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Empirical Research Paper

Communication of project risk assessment information through visuals

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ABSTRACT

Risk assessment is aimed at providing necessary risk-related information to decision-makers for formulating risk mitigation strategies. Poor communication of its context and outputs may lead to misperceptions and wrong judgements. In this research, the role of visualization as an enabler of better communication of risk assessment information is explored using a design science approach. A questionnaire was carried out with project management professionals using the risk report of a case project to understand challenges in interpretation of risk assessment outputs, information and visualization requirements for making better sense of project risk. Based on the findings from the questionnaire, a visual representation, the Risk Box was developed and further tested by semi-structured interviews. Findings reveal that visuals are not only needed for better understanding of probabilistic information but also the context of risk assessment such as relations between individual risks, risk-prone variables, assumptions, scenarios and mitigation strategies.

1. Introduction

In the project management domain, risk is used to imply uncertain conditions, factors and/or events that may have a positive or negative impact on project objectives. Project risk management (PRM), which mainly requires identification, analysis, mitigation, monitoring and learning from risks, is flagged as a key component of effective management of projects within the project management bodies of knowledge promoted by associations such as the Project Management Institute (PMI) and Association for Project Management (APM). APM (2019) defines PRM as a process that allows individual risk events and overall risk to be understood and managed proactively, highlighting the importance of holistic assessment of risks and seeing the overall risk picture (Dikmen and Hartmann, 2020). Risk identification is a vital step of PRM as it provides the initial sketch, i.e. the risk map that informs the subsequent steps to draw the overall risk picture. Using the identified risk factors, risk assessment (RA) is aimed at understanding uncertainty regarding project outcomes under different risk occurrence scenarios, which provides an input for risk management plans. RA is a knowledge-intensive process (Dikmen et al., 2008). During RA, various forms of data, such as the statistical data and expert knowledge are used to produce a risk model that simulates the project performance under different scenarios. The risk model depends on various assumptions about project vulnerability, resilience and risk allocation between the parties. RA provides valuable input for risk management plans, if the knowledge input, embedded assumptions and RA outputs are interpreted and communicated effectively.

The PRM literature features existence of two theoretical lenses; one is based on the traditions of engineering, reliability and safety, whereas the other is rooted in social sciences viewing RA as a sense-making process. Dominant perspective of RM considers risk as an objective criterion that requires analytic mode of thinking (Zhang, 2011). The so-called analytic system that aims to develop algorithms and normative rules relies on predictions using statistical data, machine learning algorithms, and expert systems. The experiential mode, risk as feelings perspective by Slovic et al. (2004) considers risk as an intangible construct that is linked to the way that decision-makers perceive it based on their mental models (Jasanoff, 1983). This requires a sense-making perspective for PRM (Winch & Maytorena, 2009). It relies on subjective judgements and system heuristics for understanding of mental models and assumptions in RA.

Although PRM literature is very rich in terms of analytic models and quantitative methods that can be used for RA (Taroun, 2014), there is a notable scarcity in studies addressing information requirements and communication of RA findings (Thompson and Bloom, 2000; Bradac, 2001; Winch and Maytorena, 2011; Lin et al., 2017; Kaufmann and Ramirez-Andreotta, 2020; Green and Dikmen, 2022; Hoti, 2023). Construction projects is not an exception. Due to their high complexity,

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exposure to external conditions such as weather and geological conditions, involvement of high number of stakeholders, capital intensiveness and long durations, construction projects have been identified as high risk undertakings requiring RA and risk management during their life cycle (Siraj and Fayek, 2019). RA via matrices, which are based on clustering the risks according to their likelihood and impact are commonly used in the construction industry, but criticised heavily in the literature due to over simplification and mischaracterization of risk scenarios (Aven, 2017; Qazi and Dikmen, 2021). Quantitative RA, proposed to be used in construction projects include methods such as Analytic Hierarchy Process (AHP) and Analytic Network Process (ANP), scenario analysis, sensitivity testing, Monte Carlo Simulation (MCS), Bayesian Belief Networks and fuzzy risk assessment. Among the most widely used probabilistic methods in practice is MCS, which is a computational *algorithm that uses random sampling to estimate the probability of occurrence* of a range of project outcomes (Jepson et al., 2020; Kwak and Ingall, 2009; Rezaie et al., 2007). It is used to generate scenarios by defining probability distributions of risk-prone variables, randomly selecting a value from each distribution at each step and carrying out these steps many times to get the probability distribution of the output (such as project cost, time or internal rate of return) which can be used to find expected/mean value, percentile values (such as 95%) and coefficient of variation as an indicator of variability/risk in a project. MCS is usually used in combination with risk ratings and matrices, and expert judgements are needed to define probability distribution functions as statistical data is usually unavailable. It is widely used in mega projects at the project evaluation phase as the financial package and contingency plans should be based on realistic cost-time estimates considering probability of occurrence of alternative scenarios. In this study, we focus on the construction industry and MCS as the most widely utilized RA method in practice, to explore information requirements of decision-makers to make risk-based decisions, utilization of probabilistic outputs of MCS to make sense of project risk and finally, whether better communication of risk information via visuals provides an enhanced understanding of risk in projects. Literature review on communication of RA information and role of visualization are depicted in the next section.

2. Literature review on risk communication and visualization

Difficulties regarding interpretation of probabilistic information for risk-informed decision-making have been discussed by several authors such as Kwak and Ingall (2009), and Hess et al. (2011). The difficulty in interpretation may stem from the problem of understanding background information behind probabilistic outputs as well as lack of prior knowledge of decision-makers on statistics (Thompson and Bloom, 2000). Lack of understanding background information is particularly critical in PRM because RA is generally carried out using subjective probabilities due to lack of statistical data on projects. Subjective probabilities are based on expert judgement, which reflect degree of belief about an uncertain issue based on personal experience and values (Aven, 2017). 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 the uncertainties, it becomes crucial to convey the knowledge underpinning these probabilities during the interpretation of RA results (Aven, 2016, Aven & Thekdi, 2022).

Gigerenzer (1991) argues that inability to understand statistical information is not a mental deficiency but also due to poor representation. He proposes the theory of probabilistic mental models, suggesting that decision-makers first construct a mental model to arrive at a reasonable guess that consists of a reference class and probability (learned frequencies of co-occurrences). The difficulty of understanding probabilistic risk information may arise from lack of understanding of mental models leading to ambiguity about the context. Anjum and Rocca (2019) argue that the interpretation of probability is a controversial issue in both philosophy and risk science, emphasizing the importance of local context when interpreting probability and predicting the future. The local context depends on experience, knowledge, imagination and assumptions of the person/group of people who are trying to explore what may happen in the future due to uncertainties (Markus et al., 2012). In the existence of uncertainties, the inclination of individuals to seek information as a means of reducing uncertainties is commonly argued (Griffin et al., 1999; Hoti, 2023). Communication of probabilistic findings and risk information within their local context has a potential to enhance risk-based decision-making.

Visualization can serve as a method for enhancing understanding and eventually improving decision-making process (Vrouwenvelder et al., 2001; Huang et al., 2008; Bostrom et al., 2008; Moore, 2017; Kimiagari & Keivanpour, 2019; Killen et al., 2020). Grainger et al. (2016) highlight the role of visual representations to reach explicit information rapidly. Londsdale and Londsdale (2019) express visualization's capability to represent vast amount of data and also textual information acknowledging its role for storytelling enabling the user to see the story behind data by revealing their relations, correlations, changes, and patterns (Lonsdale and Lonsdale, 2019). Thus, visualization does not only present data but it forms coherence between data points to come up with meaningful results, assisting the decision-making process. With the help of visuals, the risk-informed decision-making process can be improved in terms of comprehension capability by seeing data tied around a risk narrative. Chandra et al. (2008) approach visualization as a process of helping the decision-maker form a mental model of the problem, reinforcing its role on perception of risk as associated with a narrative. Considering that risk reports contain various pieces of information regarding the magnitude and consequences of risk as well as the project risk context, visual representations may reveal realistic stories about what can happen in a project.

Although difficulties of interpreting risk knowledge and communication have been widely discussed in literature, there are limited studies that investigate role of visualization for RM. Some empirical studies that explore the role of different visual presentations for risk-based decision making include Chua et al. (2006), Kontio et al. (2004), and Dikmen et al. (2018). Chua et al. (2006) showed that pictorial nature of a graphical risk display can affect decisions by increasing risk avoidance. Kontio et al. (2004) compared different risk communication methods and concluded that visualization enhances users' willingness to conduct detailed conversations about risk and can present higher amount of information, if used efficiently. Dikmen et al. (2018) conducted an empirical study to demonstrate that confidence level of the participants on risk ratings increases after visualization of risk-related data. There are some studies that demonstrate how specific graphical representations can enhance decision-making. Causal maps and influence diagrams have emerged as useful methods to illustrate risks and their relationships. As described by Ackermann et al. (2014), using causal maps to elicit systemic risk can help engage stakeholders and build a more comprehensive view of the risks faced by an organization or community. Williams (2017) studied causal maps as a method for visualizing risks in complex projects which help in understanding the relationships between various risk factors and their consequences, highlighting the importance of such visualizations in comprehending the complexities and dependencies of risks in project management. Similarly, Ackermann and Alexander (2016) emphasized on the value of causal mapping as a systems perspective tool in researching complex projects, allowing stakeholders to identify and analyze the interconnections between various elements in the system. Proto et al. (2023) studied the risk matrices, particularly how colored cells affect the risk perceptions of the users. There have been no research in PRM domain about visualizing probabilistic data and subjective risk ratings, which presents a research gap that is targeted in the current study.

It must also be reminded that visualization of risk information demands careful handling since it may significantly affect risk perception and judgments (Kumar, 2016). The opportunity created by visuals on

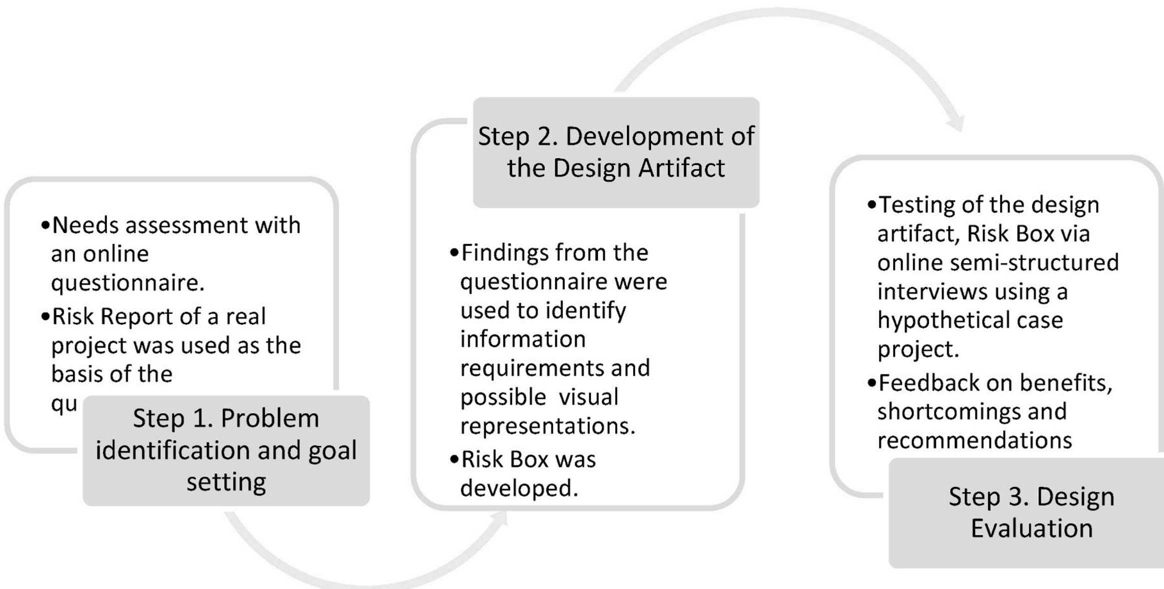

Fig. 1. Research steps.

the representation of vast data may pose a danger if the visual is not established in an efficient manner which may end up with losing the data, losing the meaning, over-simplification, bias, and ignorance of some points (Bier, 2001; Lurie and Mason, 2007; Kumar, 2016; Engin and Vetschera, 2017). Eppler and Aeschimann (2009) developed a set of guidelines to avoid dangers like distortion and manipulation of data by giving examples from several applications. The visual shall be shaped in coherence with the audience and in accordance with information requirements to serve its purpose. First, the critical information needed for a task should be identified and visualization technique that directs participant's attention to this information should be utilized. Design science methodology provides a useful framework for this purpose.

Within this context, the aim of the study is to explore information requirements, challenges of decision-makers in understanding RA information, particularly probabilistic information depicted in risk reports, and test whether alternative visual representations can help decision-makers to make better sense of risk in projects. Research questions are formulated as follows.

1. What kind of information is needed for risk-based decision-making in projects ?
2. How effectively do the decision-makers utilize probabilistic data to make sense of risks ?
3. Can better visualization of information improve risk understanding and enhance decision-making ?

In the next section on Research Methodology, we will discuss how design science methodology is used to respond to these research questions.

3. Research Methodology

Design science paradigm, that serves as the methodological framework for this study is extensively employed in information systems research, functions as a problem-solving paradigm that seeks to create innovations that define ideas, practices and products by design, implementation and utilization of information systems (Hevner et al., 2004; Markus et al., 2012). Design science paradigm that focuses on creation and evaluation of artifacts to solve decision-making problems provides an appropriate theoretical framework for our study as the research aim is to explore challenges with understanding RA information and design a visualization tool to support risk-based decision-making. Based on this framework, the research process unfolded across three steps; problem identification and goal setting, development of the design artifact and design evaluation as given in Fig. 1. In the initial step, we conducted a needs assessment via a questionnaire study using the actual RA report of a construction project. The findings from this step were used to respond to research questions 1 and 2. In the next step, based on questionnaire findings on needs and expectations, a search process was carried out to develop an artifact to represent the required project risk information in a way that is easy to understand and use to make risk-based decisions. In the final step, semi-structured interviews were carried out with professionals to test the artifact and receive feedback for further developments. Findings from step 2 and step 3 were used to answer the third research question. This approach, aligning with the design science paradigm, ensured a thorough exploration of the problem, as well as the development and evaluation of a tailored solution to enhance decision-makers' comprehension of risk.

Each research step is summarized in the below subsections.

3.1. Problem Definition and goal setting by a case project

In this research, our initial focus centers on whether decision-makers can correctly interpret probabilistic information, use the MCS outputs and related information in RA reports to comprehend risk in projects. For this purpose, a questionnaire study was carried out. Within the questionnaire, the risk report of a real project, a tunneling project in Turkey which had an investment cost more than 1 billion USD, designed, built and operated by an international joint venture (JV), was used. Risk reports serve as a means to communicate findings of RA to decision-makers, usually top managers, facilitating critical bidding and investment decisions. The risk report of the case project, prepared by an international consultancy firm at the pre-planning stage, mainly comprised of a qualitative risk assessment part detailing 84 risk factors with P–I ratings assigned by the experts through a risk checklist, and a quantitative part that depicts outputs of MCS analysis showing the likelihoods of achieving as-planned completion date (estimated by the JV) and the contractual completion date. Results of MCS were presented in the form of tables, frequency charts (probability distribution graphs) and tornado graphs that present sensitivity analysis findings about risk-prone variables that have the highest impact on duration. The questionnaire form included a summary of the risk report (project

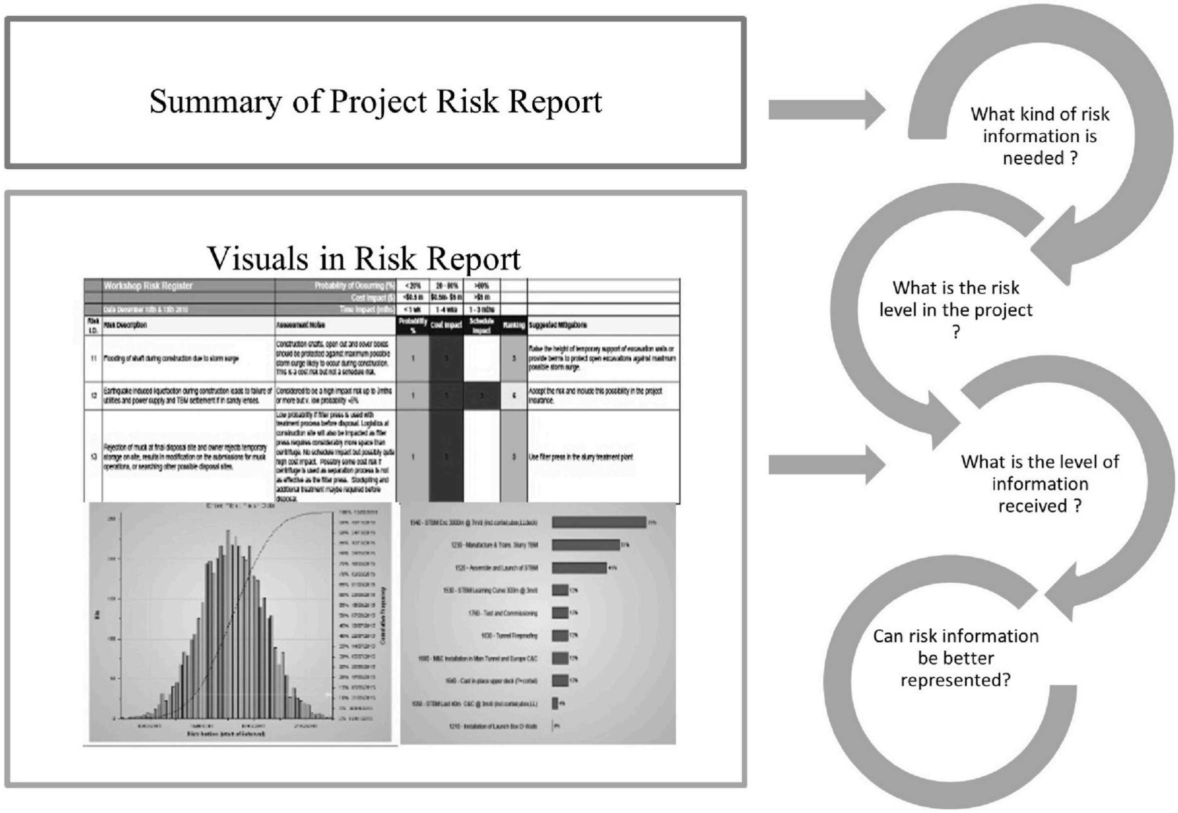

Fig. 2. Outline of the questionnaire.

Table 1
Profile of respondents involved in the online questionnaire.

ID	Gender	Country	Occupation	Education	Years of Experience	Title	Familiarity with Probabilistic RA Methods
P1	M	Germany	Civil Engineer	MSc, MBA, PMP	25+	Project Director	F
P2	M	UK	Civil Engineer	MSc	25+	Project Planning and Control	F
P3	M	Turkey	Civil Engineer	MSc	20+	Company Manager	U
P4	F	Turkey	Civil Engineer	MSc	30+	Company Manager	U
P5	M	Turkey	Civil Engineer	MSc, MBA	25+	Contracts Manager	F
P6	M	Turkey	Civil Engineer	MSc	25+	Chief Executive Officer	U
P7	M	Russia	Civil Engineer	MSc, Global Finance	25+	Deputy CEO	F
P8	M	Turkey	Civil Engineer	BSc	10+	Project Coordinator	U
P9	M	Turkey	Civil Engineer	BSc	10+	Project Coordinator	U
P10	M	Turkey	Civil Engineer	BSc	10+	Project Coordinator	U
P11	F	Turkey	Civil Engineer	PhD	10+	Head of Tendering	F
P12	M	Turkey	Civil Engineer	MSc	25+	Project Director	U
P13	M	Turkey	Civil Engineer	PhD,PMP, FCIArb, LLM	10+	Senior Planning and Claims Engineer	F
P14	M	Canada	Mechanical and Civil Engineer	PhD, PMP, EIT	20	Senior Project Scheduler	F
P15	M	Turkey	Civil Engineer	BSc	10+	Project Coordinator	U

characteristics, contract conditions, aims, contents, risk assessment method used and assumptions made) to familiarize the respondents with the project, risks and aims/contents of RA. Then, in the first part of the questionnaire, respondents were asked to share their insights on the kind of information they would like to see in a risk report so that they can make sense of level of schedule risk in the project and formulate strategies to minimize the risk of delay. In the subsequent part of the questionnaire, parts of risk report including the risk checklist and findings of the quantitative risk assessment, mainly the frequency chart and Tornado graph were provided and respondents were asked to answer some questions based on these visuals, such as "What is the probability of finishing the project on or before the contractual completion date?", "What are risks/risk-prone variables that the duration is most sensitive to?" to find out if respondents could interpret the visuals in a correct way. They were also asked to comment on the level of risk in the case project. In the final part of the questionnaire, respondents were invited to envision a visual (such as a visual metaphor, map, graph etc.) that would provide an effective representation of schedule risk in this project and comment on visuals commonly used for this purpose. The outline of the questionnaire is summarized in Fig. 2. The expected time to complete the questionnaire was 15–20 min.

This survey was distributed via e-mail to 25 professionals that had professional contacts with the authors of this paper due to previous research collaborations. Each respondent possessed a background in project management and had been involved in different steps of PRM such as attending risk identification sessions, conducting a risk

Table 2
Information requirements.

Items requested to be in a schedule risk analysis report	Occurrence	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15
Familiarity with risk		**F**	**F**	**U**	**U**	**F**	**U**	**F**	**U**	**U**	**U**	**F**	**U**	**F**	**F**	**U**
Overall impact of risks (expected cost-duration)	66,7%	X		X	X			X		X	X	X		X	X	X
Individual risks (key risks, risk register etc.)	60,0%	X	X	X	X				X		X	X			X	X
Current strategies to handle risks & costs	33,3%			X					X			X		X		X
Probability of risks	26,7%	X	X		X							X				
Best-Worst Case Scenarios	26,7%				X				X			X			X	
Sensitivity info	20,0%					X						X			X	
Mitigated vs. unmitigated risk impacts	13,3%		X	X												
Timing of risks	13,3%										X				X	
Key assumptions	6,7%		X													
Residual and secondary risks	6,7%											X				

assessment process or evaluating risk reports during feasibility and/or tendering steps. All respondents had hands-on involvement in decision-making processes that encompass risk and had previously evaluated similar risk reports for construction projects akin to the case project under examination. Furthermore, all participants have an engineering background ensuring a solid foundation about statistics/probability.

The questionnaire was responded by 15 participants as outlined in Table 1. Despite the respondents' knowledge on PRM and probability concepts, that not all could be equally familiar with MCS. Therefore, the respondents were requested to identify themselves as either familiar (F) or unfamiliar (U) considering their expertise in probabilistic RA methods. Seven respondents classified themselves as F (will be indicated as "F respondents" in this paper) while eight respondents acknowledged being less familiar or as U (indicated as "U respondents" in this paper).

3.2. Design of the artifact: the risk box

Based on the identified requirements from the questionnaire findings that will be presented in section 4, the concept of Risk Box was articulated as a visual that comprises of several informational graphics (Dikmen and Hartmann, 2020). The Risk Box is designed as a three-dimensional "box" having complementary risk-related data at different faces regarding the findings from RA and contextual risk information. The "box" shape provides six faces that serve as visualization areas. It integrates different sources of information about risk mainly individual risk factors, risk-prone variables, scenarios, statistical information on decision criterion, sensitivity information and assumptions. A team of three experts, including two academic experts on RA and one professional PRM consultant was involved in the design process of the Risk Box that took around 6 months to complete (Karakocak, 2021).

3.3. Design evaluation

In order to explore how users utilize Risk Box and receive their feedback on its benefits and shortcomings for risk-based decision-making, an observational study based on semi-structures was carried out. During the semi-structured interviews, interviewer presented the Risk Box of a hypothetical project showing the findings of MCS and then monitored how interviewees engaged with different faces to give a decision. The observational study was slightly different than traditional method as the process was interactive. It is believed that blended observation with interaction and feedback collection provided a rich data set which is valuable for the purpose of this research. The study involved 5 semi-structured interviews. The profile of the respondents is given in Table 4. The respondents involved in this step were different than those attended the initial step of the study but both groups have a similar profile. They are all experienced in project management but have different varying levels of knowledge on probabilistic risk assessment, particularly MCS. During the online interviews, interviewees were introduced to a case project (a hypothetical factory project), and given the task of evaluating its economic feasibility using the Risk Box. During design evaluation, the interviewees were asked to put themselves in the place of an investor and evaluate economic feasibility of the project considering that payback period should be less than 6 years for a feasible project according to the preferences of the hypothetical investor company. Choosing a standard project and a simple task helped us to concentrate on the tool itself rather than risks in a complex project. In both of the real case project used in the needs assessment and the hypothetical project used for design evaluation, a decision is expected to be given under uncertain conditions based on RA findings. The decision criterion was "duration" in the real case project used in the questionnaire, whereas it was "payback period of investment" in the hypothetical factory project used during the interviews. Although the projects and design criteria were different, this does not create an inconsistency as the same RA process using MCS were used in both steps. During the semi-structured interviews, the Risk Box constructed for the hypothetical factory project was shown to the interviewees face by face. They were given sufficient time to review faces, interpret the information, comment on how the information provided by the Risk Box can be used to give a decision. The interviewer closely monitored the way Risk Box was utilized by the interviewees to arrive at a decision for the feasibility of the factory project and formulate strategies. General questions were also posed about the Risk Box concept. These questions encompassed inquiries about which face(s) provided the most important information for decision-making, positive and negative attributes of the Risk Box and how it can be improved. Interviews took 40–50 min to complete.

4. Discussion of findings

Findings from each step shown in Fig. 1 are presented in the below subsections.

4.1. Findings from the needs assessment (step 1)

4.1.1. Findings about information needs

In the questionnaire, respondents were presented an open-ended question asking them about the type of information they would need to make a reliable decision (that the decision-maker believes that it is based on strong evidence, thus accurate) and formulate strategies for the given case project. The findings are summarized in Table 2. Majority of the respondents pointed out the need of information regarding "individual risk factors" and their "overall impact" on the project. This insight underscores a critical aspect while probability distribution, as an output of MCS, illuminates the "consequences" of risk events or variables, it may not reveal the underlying "sources of uncertainty" (i.e., individual risk factors). This finding points out the importance of establishment of a link between MCS outputs and individual risk factors enabling decision-makers to make sense of alternative scenarios. Approximately one third of the respondents expressed the need for information on mitigation strategies (together with their cost), probability of individual risk factors/events, and best-worst case scenarios about delay. This indicates a clear interest of respondents in understanding the risk response

Table 3
Information received (0, 1, 2 and 3 denote no, low, medium and high levels of information, respectively).

Factors	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15
Familiarity with risk	**F**	**F**	**U**	**U**	**F**	**U**	**F**	**U**	**U**	**U**	**F**	**U**	**F**	**F**	**U**
Level of uncertainty (risk level) of project completion date	3	1	2	2	1	2	2	1	2	1	2	2	1	1	1
Possible project completion dates and their probabilities	0	1	3	3	3	3	3	1	3	1	3	2	3	3	1
Confidence level regarding the contract/tender duration	3	1	2	0	3	2	2	1	2	1	3	1	2	1	0
Significant risk factors/events	1	1	1	0	3	3	3	2	3	0	1	2	3	1	1
Most likely, optimistic and pessimistic scenarios	3	0	0	0	2	2	1	0	2	1	2	2	2	1	2
Impact of individual risk factors on project completion date	2	1	0	3	2	3	3	0	1	0	1	3	2	1	2

Table 4
Profile of interviewees.

	I1	I2	I3	I4	I5
Education Level	PhD	PhD	MSc	PhD	MSc
Total Years of Exp. in Constr. Industry	20+ years	10+ years	20+ years	10+ years	20+ years
Current Job Title	Project Management Consultant	Chief Risk Officer	Executive Manager	Project Manager	Executive Manager
Familiarity with risk analysis and probability	F	F	U	F	U
Duration of Interview	47 min	50 min	40 min	50 min	50 min

strategies (risk control, finance, transfer etc.) “assumed to be utilized” during the calculations and impact of mitigation strategies on the level of risk.

4.1.2. Findings about difficulties in interpreting MCS outputs

When the respondents were asked questions related with the probability of delay, and factors that the duration is most sensitive to by referring to given visuals, majority of the respondents gave correct answers. However, it is also found that almost half of the respondents faced some level of difficulty in understanding the charts irrespective of their familiarity with MCS. Table 3 illustrates the survey findings about the level of information that can be extracted from MCS outputs and visuals. Responses were assessed using a 0–3 scale where “0” denotes undecided, 1 low, 2 medium and 3 signifies strong levels. It is apparent that the major aim of probabilistic schedule risk assessment is to unveil the “level of uncertainty” regarding the project completion date. Although the variance can be easily read from the frequency chart as well as different percentile values, half of the respondents argued that information they can get from RA outputs regarding risk level of the project is “low”. This indicates that while majority can find correct probability values from the frequency charts, they doubted whether this information conveyed enough background about the level of risk. Some respondents were even undecided about most likely, optimistic and pessimistic scenarios which could be directly seen from the frequency charts. It can be hypothesized that this uncertainty stems from the fact that frequency charts only illustrate the outcomes of some risk occurrence scenarios whereas the risks leading to these consequences are not apparent in the charts. Conflicting views were also present about the most significant risk factors and impact of individual risk factors on schedule risk, even though this information could be directly gathered from the sensitivity chart. In conclusion, while respondents could extract some critical information such as the probability of completion of the project before a certain date, they were not sure about what these visuals truly convey about the actual risk level of the project.

When the respondents were asked to comment on the level of schedule risk in the case project, almost half of them were undecided.

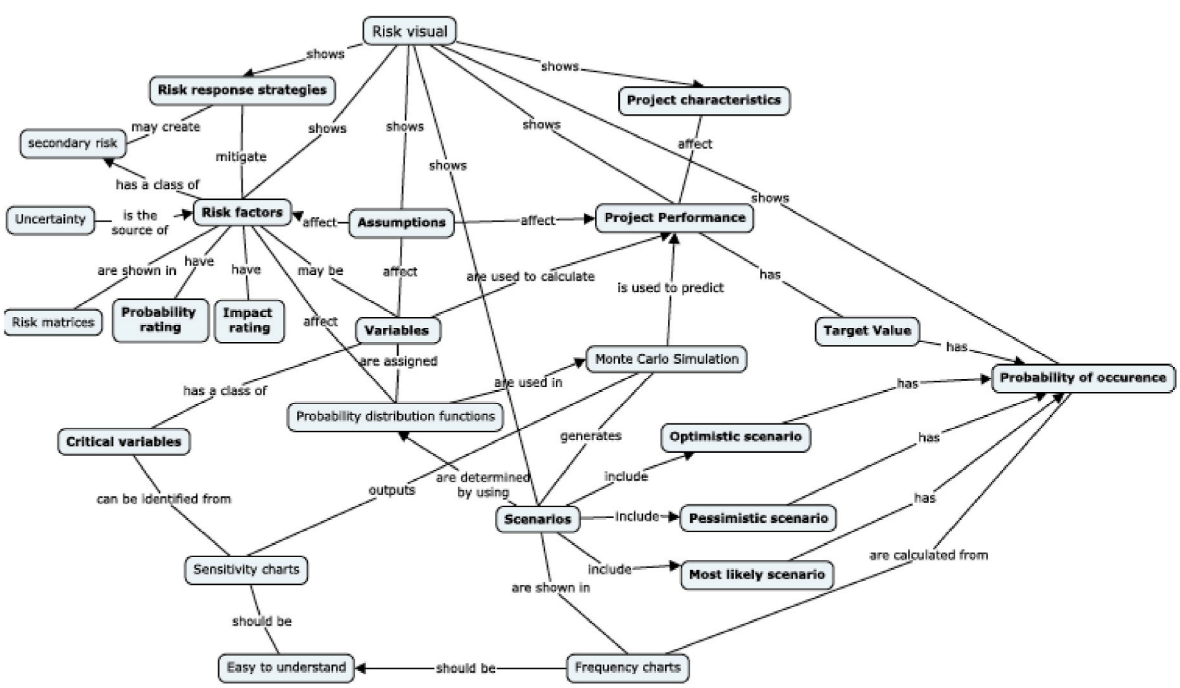

Fig. 3. Concept map regarding expectations of users on risk visualisation.

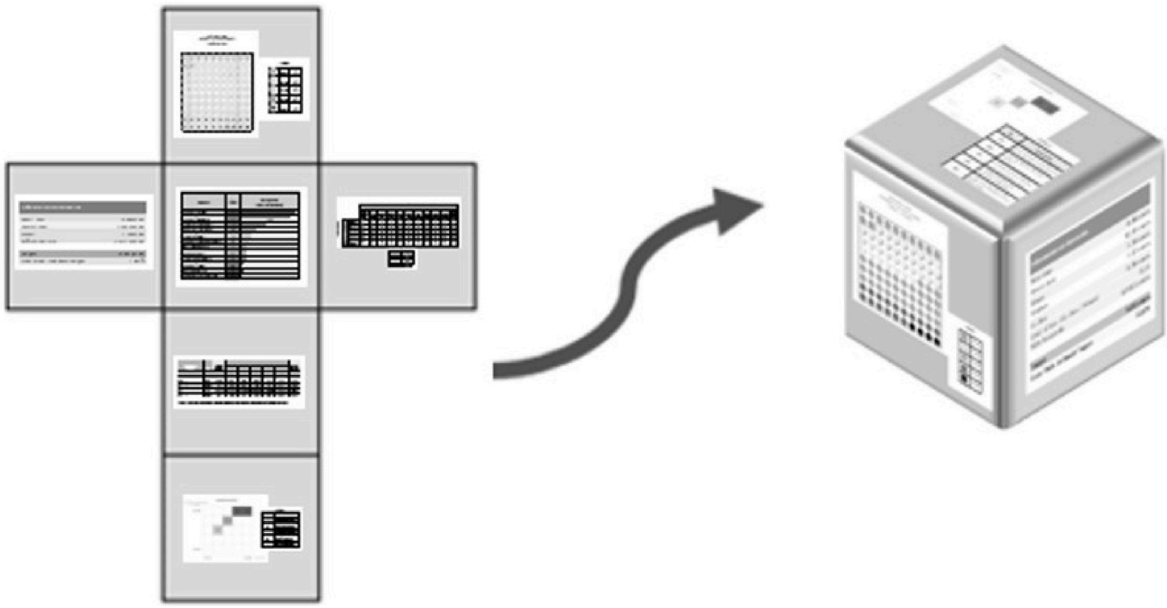

Fig. 4. Unfolding the risk box.

The shape/steepness of the probability distribution gives a clear indication of uncertainty (variability) of duration. Notably, the frequency chart reveals a 96% probability of completing the project by the contractual deadline and coefficient of variance is around 10% which implies a “low risk” situation for a risk-neutral decision-maker. Although results might have been affected from different risk perceptions of respondents and bias, there is a significant difference between F respondents and U respondents on this aspect. Among the F respondents, 43% identified schedule risk as “low” aligning with the expectations. However, only 13% of U respondents perceived the schedule risk as "low”, indicating that U managers that are less acquainted with MCS concepts may face greater challenges when interpreting MCS results compared to their more familiar counterparts.

4.1.3. Findings about communication of MCS findings

Nearly half of the respondents mentioned that they could make a better decision if they were provided with better visuals and tables. There was only one respondent, out of fifteen, who believed that risk report and visuals were enough for them to decide on the risk level. The majority indicated a demand of more information about the mitigation

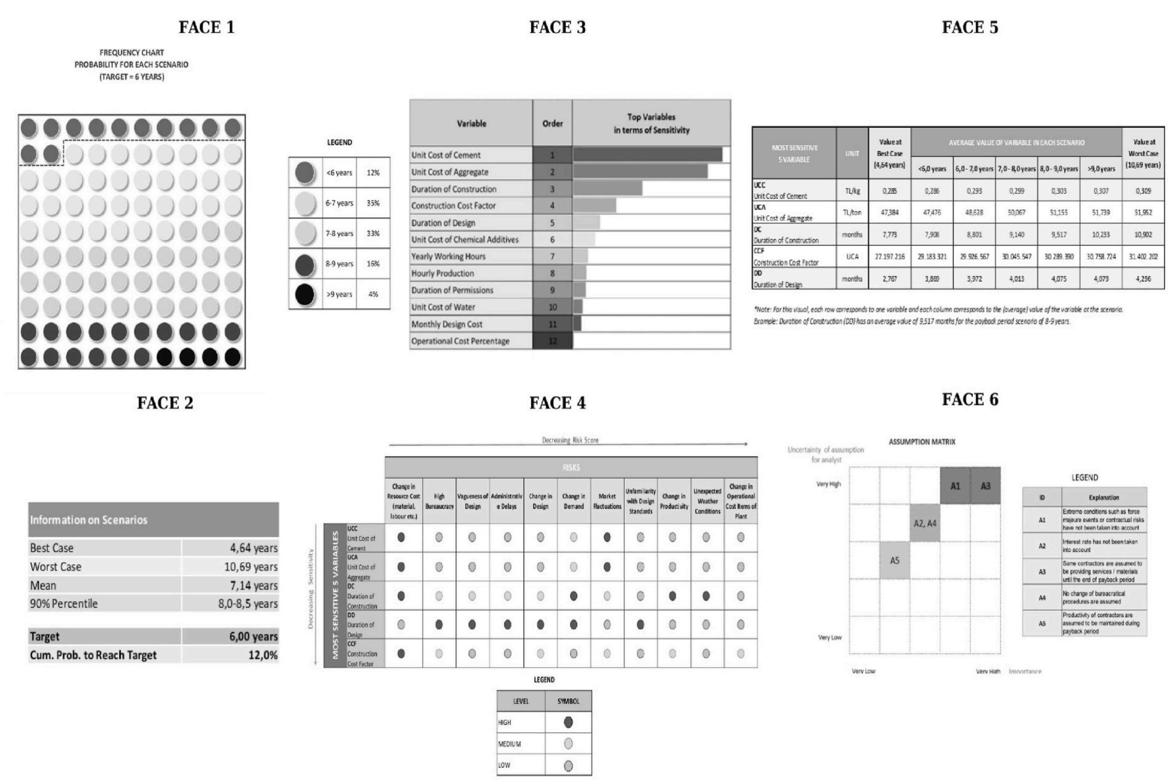

Fig. 5. Examples about faces of the risk box.

strategies and assumptions, especially how the schedule risk may change with different strategies and under different assumptions. Respondents also pointed out the importance of including comparative results of alternative risk occurrence scenarios in reports (such as before and after implementing a strategy).

Two respondents mentioned about the deficiency of MCS in providing information about individual risk factors (or risk events) which cannot be seen in the probability charts, and they commented that a visual representation that shows risk factors as well as scenarios (combination of risk factors) would be highly beneficial. It was also interesting to observe that almost half of the respondents referenced risk matrices when they were asked about a visual metaphor about risk in a project. Although risk matrices have been criticized due to mischaracterization of information, they are favored by the respondents as they help visualize individual risks in an effective and simple way. One of the respondents proposed an interactive visual where the decision-makers can observe risks and their impacts on project performance by changing model parameters and alternative strategies.

In summary, the questionnaire findings reveal the challenges decision-makers face in interpreting the outputs of MCS, especially for those who are not familiar with probabilistic assessment. Improved visuals are not only needed for simplifying MCS outputs and enhanced probabilistic reasoning, but also linking the information on risks, strategies, assumptions and performance criteria to reveal a clear risk picture. Risk reports depicting probability and sensitivity charts along with risk checklists may have limited value for decision-making if information on causal relations, assumptions and strategies are not provided to the decision-makers. Simple visuals are needed to reveal the required information in an effective way. Findings from the questionnaire were summarized as a causal map (Fig. 3) providing guidance for the forthcoming step, which is the development of a visual representation of RA information.

4.2. Development of the risk box (step 2)

Based on the findings from needs assessment, the design team worked on the development of a design artifact that could meet with the expectations as presented in Fig. 3. The visual was expected to integrate several pieces of information in an effective way, and should be able to simulate how the value of decision criterion tend to change with a possible change in assumptions and mitigation strategies. This required a dynamic and interactive visualization process reflecting the sequential steps of RA, risk identification, assessment and mitigation with feedbacks between the steps. The idea of Risk Box came from the requirement of dynamic display of the required information, filling the information gaps between each step, especially revealing the hidden link between risks (Risk matrices) and scenarios (Probability Charts) highlighted in the questionnaire. The unfolding feature of the box allows for a sequential display and update of the related faces, presenting information in a step-by-step manner such as first displaying the risks and then risk-prone variables, rather than overwhelmingly giving all the information at the same time. Each Risk Box is formed for a given set of assumptions and selected strategies, and its faces are updated with the change in these factors, emphasizing the iterative nature of decision-making process. The box's geometric shape is intended to create a solid image on users' minds while representing the required information in a simpler and consequential way. Hence, the metaphor of "unfolding the risk box" simulates the process of displaying risk-related information to a decision-maker in steps and finally showing the overall risk picture (Fig. 4).

Fig. 5 illustrates the faces of an example Risk Box, which was further used in the design evaluation step. MCS calculations were carried out using @Risk (Version 8.0; Palisade, 2020).

Face 1 serves an alternative for conventional frequency chart (Lonsdale and Lonsdale, 2019) emphasizing the existence of alternative scenarios and allowing users to assess the probability of occurrence of a given scenario by simply counting the number of different colored circles within the square, which is easier to understand than the probability distribution charts. Statistical information, including the most likely, best and worst case scenarios are given in a tabular format at Face 2, enabling decision-makers to directly see the results rather than searching for the data within the probability charts. Face 3 depicts sensitivity information, mainly the risk prone variables ranked according to their impact on output. The color code given in the bar chart provides an indication of critical variables, providing insight into areas that demand attention to decrease overall uncertainty. Face 4 features a risk matrix that decision-makers are very familiar with during risk evaluations, as understood from the questionnaires. This matrix links the most critical risk-prone variables with risk factors, showing how the risk-prone variables are affected from different risk sources, which was identified as a problem by the questionnaire respondents. Face 5 lists the average values of risk-prone variables in each scenario, fostering a "what happens if" perspective. It offers an indication about the approximate values of risk prone variables under different scenarios, including optimistic and pessimistic scenarios, so as to give users an evidence of how each scenario is related with risk-prone parameters. Face 6 presents an assumption matrix to reveal the underlying assumptions under which the RA is carried out. These assumptions can relate to the future, risk ratings, as well as strategies to be implemented. Users can identify the assumptions with the highest impact on output along with the most vulnerable (uncertain) ones, which can be challenged and revised in the subsequent iterations, if necessary. By examining the Risk Box, decision-makers can consider applying new strategies or making new assumptions and need to monitor changes in variability of project outputs. The simulation can be re-run for updating the original risk box, allowing a comparative analysis (such as impact of mitigated and unmitigated risks on the outcome). It is important to note that the numbering of faces does not necessarily reflect the steps of RA process. Users have the flexibility to start from any face and navigate back and forth several times to arrive at a decision. On the other hand, it is important to acknowledge that the Risk Box concept is just one of the several possible visualization alternatives that could be developed in the light of questionnaire findings, and may not be the best visualization template that aligns with all possible user needs.

4.3. Findings from design evaluation (step 3)

The design evaluation step that involved online interviews with 5 professionals showed that Risk Box can be used effectively to make sense of risk and formulate mitigation strategies in the hypothetical project. Some findings on the utilization of Risk Box are summarized below.

- All of the participants found Face 1 easy to understand and refer to the information given in Face 1 while making decisions. All of the participants correctly pointed out that as the expected payback period is 7–8 years, the target of 6 years is not realistic and if 6 years is a strict target, alternative risk mitigation strategies should be searched to understand whether it is possible to increase probability of achieving this target.
- Sensitivity information depicted in the Risk Box were effectively used to formulate risk mitigation strategies. For example, Interviewee1 denoted that as the most sensitive variables are unit cost of concrete, unit cost of aggregate and the duration, they could consider making contracts to fix the unit cost of concrete and aggregate for a certain amount of time and/or define strict liquated damages for contractors to avoid delay.
- Face 5 and Face 4 were also deemed informative for strategy formulation. Interviewee 1 denoted that, to achieve a payback period less than 6 years, duration of construction must not exceed the anticipated duration. It was also emphasized that individual risk factors such as adverse weather and poor productivity should be mitigated to decrease delay risk.

Table 5
Summary of evaluations of risk box.

	Informative, aesthetically appealing	Neat Representation of Useful Data (Better than Reports)	Some Explanations Are Needed	Willingness to Use İn Practice	Decisions and/or Stages of a project Risk Box can be used
I1	✓	✓		✓	Planning Cost Estimation Presentation of Data
I2	✓	✓	✓	✓	Cost Estimation
I3	✓	✓	✓	✓	Investment Presentation of Data
I4	✓	✓	✓	✓	Investment Bidding/Tendering
I5	✓	✓		✓	Investment

- The assumption matrix was effectively used by the participants while developing strategies. As an example, Interviewee 3 mentioned the criticality of contract conditions and assessment of contractual risks for economic feasibility.

For the overall evaluation of the Risk Box, participants were asked to provide scores based on four attributes: ease to understand (clearness), informativeness, efficiency (usefulness for decision) and aesthetic appearance. The attribute "informative" received the highest score, attaining at least 4 out of 5. Notably, there were no scores less than 3 out of 5 for any attribute. Table 5 also depicts that all of the interviewees found Risk Box informative and expressed a willingness to use it in practical applications. On the other hand, three interviewees mentioned that some additional explanations could be still necessary for decision-makers particularly for Face 5. Regarding the potential utilizations of Risk Box during different phases of the project, participants identified planning stage, cost estimation, presentation of data to decision-makers, investment decisions and bid preparation/tendering. A major bottleneck in the current application of Risk Box was requirement of an analyst to run the MCS and transfer its findings to Risk Box to update information. The calculations should be automated by linking the Risk Box with Monte Carlo simulator so that benefits due to interactive and dynamic features can be captured, which was the major recommendation made by the interviewees.

As a result, Risk Box can be considered as an alternative visual to communicate RA information in a simple way, present overall risk picture to decision-makers and assist them in formulating risk management strategies. However, it stands as an example about how visual aids can be used to improve risk communication rather than a generic tool that provides the best visual representation for all contexts. Risk Box may serve as a visualization prototype that can be tailored according to different user needs.

5. Conclusions

While project management literature offers an abundance of quantitative methods that can be used for RA (Taroun, 2014), there are limited studies that explore how RA findings are practically utilized to make sense of risk by decision-makers. In this research, it is hypothesized that decision-makers encounter challenges in comprehending RA findings, particularly, those arose from probabilistic MCS outputs. Findings suggest that better visualization of risk information may enhance their ability to make sense of project risk. Using a design science paradigm, information needs and challenges were identified by a questionnaire using the risk report of a real project. Case project findings reveal that visuals are not only needed for better representation of probabilistic findings but also linking pieces of information on individual risks, risk-prone variables, scenarios, strategies, assumptions and project performance. Findings pointed out the need for iterative processes and charts to reveal how project risk changes with underlying assumptions and implementing different risk response strategies. Building on user requirements, an alternative visual representation was developed. The metaphor of "unfolding the Risk Box" was employed, with informational graphics developed as the faces of the box, presenting information complementary to each other to provide a complete picture of the project risk level. Semi-structured interviews point out that Risk Box may facilitate interpretation of MCS findings and can be effectively used to develop strategies. The Risk Box holds a potential for application in cases where MCS is used as a RA method. Risk Box can be utilized during risk identification workshops to communicate risk information in a clear and concise way. Despite the fact that in its current form, MCS calculations and Risk Box are not integrated, it has a potential for future enhancements including automated MCS calculations to enhance its usability.

This research is among the limited studies exploring the impact of information visualization on risk-based decision-making. It is envisioned that findings of this study, especially about the information and visualization requirements of project management professionals can guide other researchers to explore alternative methods and technology for better risk communication across different domains. While this study demonstrates the role of visualization for better communicating RA information, it is important to note that findings reflect opinions of a limited number of respondents and cannot be generalized. Although findings provide some useful insights, they are not statistically significant. The Risk Box should not be considered as a generic visualization template that would be useful for all kinds of projects and types of users. Further research is necessary to explore risk information requirements, and develop alternative visualization tools to enhance risk communication throughout different phases of projects considering varying needs of users and advances in data visualization technologies.

CRediT authorship contribution statement

Irem Dikmen: Writing – review & editing, Supervision, Project administration, Conceptualization. **Elif Karakocak:** Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **M. Talat Birgonul:** Writing – review & editing, Supervision, Resources.

Declaration of competing interest

No potential conflict of interest was reported by the authors.

Data availability

Data will be made available on request.

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