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Raising risk awareness in multi-criteria design decisions for integrated design and construction tenders

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ABSTRACT
Awareness of design risks is essential for preparing integrated design and construction tenders as decisions in this phase can have serious consequences once the project is awarded. The practice of multi-criteria decision analysis (MCDA) promises to support contractors in dealing with risks in the decision-making process. However, due to limited time and resources in a tender, risks involved in design alternatives are often overlooked and the selection of alternatives is mainly based on the decision-makers' knowledge and experience. This raises the question how decision makers can become aware of the risks in the tender phase of projects. Following a design science research approach three interventions to raise risk awareness are identified and validated in the context of an infrastructure tender in the Netherlands. These interventions are (1) a general list of defined criteria to identify those criteria that correspond with the characteristics of the tender; (2) mapping identified project risks on criteria and assign a bandwidth score; (3) evaluation of the quality of the decision process by scoring elements of decision quality. Based on these interventions three design rules are proposed to increase the transparency of decision problems and the understanding of choices and, by doing so, create awareness for risks involved in design alternatives.

KEYWORDS
Risk awareness; infrastructure tender; multi-criteria decision analysis; decision making

Introduction

Construction companies tendering for projects with a large integral design and construction scope have to make a multitude of early design decisions to find the most economically feasible solution that is likely to be accepted by the client. At the same time, they need to carefully account for the risks involved in the decisions. Overestimating these risks can lead to a higher bid and thus a lower chance of winning the tender. Underestimating the risks can increase the chance of getting the project awarded but can negatively affect the result during realization in terms of project delays and cost overruns (Morris *et al*. 2011, Fellows and Liu 2018).

Risk is an inherent characteristic of decisions in construction tenders and can be defined as the extent of uncertainty about whether these decisions will produce potentially significant and/or disappointing project outcomes (cf. Sitkin and Pablo 1992). Although there is a significant amount of literature on risk and risk assessment in construction (e.g. Baker *et al*. 1998, Laryea and Hughes 2008, Carvalho and Rabechini Junior 2014, Taroun 2014, Siraj and Fayek 2019), a main prerequisite for an effective risk management has been largely neglected. In order to assess risks, decision-makers need to be aware of possible risks. They need to perceive a decision situation as risky, comprehend the meaning of risk in this situation, and make a projection of the possible impact of risks to the future (cf. Endsley 1988). Risk awareness is the result of individuals sharing and reflecting on potential causes and outcomes of their behaviour and actions in decision situations (Braumann 2018).

While preparing a bid and making early design decisions, contractors can easily lose their sense for the involved risks for three interacting reasons. First, the multidisciplinary and integral scope of alternatives combined with the high value of projects increase the solution space of alternatives. This requires that the overall evaluation of alternatives is decomposed into

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sub-evaluations on a number of usually conflicting criteria relevant to the problem (Durbach and Stewart 2012). Second, next to the total costs of a project, factors that increase the cost-quality ratio need to be considered to make a bid. As a result, the number of criteria that need to be considered in design decisions has increased. Besides price, other criteria such as social, economic, environmental and aesthetic factors have to be included (Ballesteros-Pérez *et al*. 2012). Third, time and resources of contractors are capped. This constrains the required iterative design process and forces contractors to quickly choose between feasible alternatives without completely knowing the entire construction requirements, the environment of operation, future design decisions and the emergent construction behaviour (Aughenbaugh and Paredis 2004, Van Der Meer *et al*. 2015). To cope with these constraints in tenders, engineers narrow down their field of attention by processing less information, reverting back to known behaviour in a rigid way (Klapproth 2008) or by relying on their experience and intuition when making decisions (Laryea 2013). As a consequence, risks related to design alternatives are easily overlooked at the time the assessment is made.

In order to support the evaluation of conflicting objectives in design decisions, a variety of multi-criteria decision analysis (MCDA) tools and methods are available and used in daily practice (Jato-Espino *et al*. 2014, Bueno *et al*. 2015, De Almeida *et al*. 2016, Tscheikner-Gratl *et al*. 2017). However, their main focus is on defining "what" is required for structuring the decision problem and dealing with involved risks. They fall short in addressing the situational complexity of decisions and explicating "how" decision makers could structure the decision problem and become aware of the risks (Van Der Meer *et al*. 2020). Particularly for decisions under time and resource constraints this shortcoming can create the illusion of consistent and rational choices (Polatidis *et al*. 2006, Scholten *et al*. 2015). Research on decision-making in construction in general and MCDA in particular has mainly focussed on specific decision problems but has largely neglected the conditions under which these decisions are made. This is surprising, since previous research has shown that the way decisions are derived depends on the decision situation and the characteristics of the decision maker which can include time available (Benhabib *et al*. 2010), processing capacity (Weber and Johnson 2009) and risk attitude (Han *et al*. 2005, Kahneman 2011).

Thus, the aim of the paper is to investigate how engineers can become aware of the risks while making design decisions during the tender phase. Following a design science research approach (Wieringa 2014) we first analyze the design decision-making process in an ongoing tender for a multidisciplinary infrastructure project in the Netherlands. Based on the effects of using a trade-off matrix in the tender three interventions are identified to increase the transparency of decision problems and the understanding of the rationality of choices and, by doing so, the awareness of risks involved in design alternatives. The identified interventions are validated during a workshop with engineers involved in the tender and translated into three design rules for raising risk awareness in the project context.

Design decisions in infrastructure tenders

During the tendering phase of large scale and integrated infrastructure projects with a long-term involvement of the contractor, various design options are evaluated by the tender team of the contractor. The design options are mostly based on either a preferred design or prescribed functional requirements given by the client. In both situations the design options reflect different and sometimes conflicting client's needs (Kim and Augenbroe 2013). The design task relates to "a decision-making process for the purpose of generating a specification of an object based on the environment in which the object exists, the goals ascribed to the object, the desired requirements and the constraints that together limit the acceptable degrees of freedom of alternatives" (Ralph and Wand 2009, p. 125). Design decisions in the tender context are often made without knowing the emergent behaviour of the solution (Laryea 2013, Van Der Meer *et al*. 2015), and without a sufficient problem understanding. The integral and multidisciplinary nature of the design problem makes it hard to predict the effects of decisions. Difficulties in forecasting how one criterion, for example buildability, influences other criteria, for example project costs, and whether these effects remain stable over time hinder the identification and assessment of risks and often lead to their ignorance (Kutsch and Hall 2005).

Risks in design decisions

Design risks in construction tenders refer to the variability in the scoring of different design alternatives on several design criteria. In other words, the effect of design alternatives on important criteria and thus project outcomes is uncertain. The consequences of design decisions will depend on future events. These uncertainties relate to the external project environment and are outside the control of the decision maker (Durbach and Stewart 2012). Stakeholders are, for example, able to exert more influence on the design and construction process which have led to more non-traditional design objectives, such as sustainability, reliability, availability, and maintainability. These objectives need to be taken into account by incorporating, for example, social, economic, environmental and aesthetic criteria in the decision making of infrastructure projects (Ballesteros-Pérez *et al*. 2012).

However, whether and how design risks are identified and assessed will be influenced by uncertainties related to the internal project environment. These uncertainties are caused by the process of problem structuring and analysis, imprecision of criteria meaning, and vague judgmental inputs required for a decision (Stewart and Durbach 2016) , but also from strategic considerations about how a project should be gained. Ideally, these internal uncertainties should be resolved as far as possible during the evaluation of alternatives through problem structuring and/or appropriate sensitivity and robustness analyses (Stewart and Durbach 2016). In the tender context with limited time and resources available for the design tasks and in an attempt to reduce the negative return-on-investments from lost bids these internal uncertainties are not easily resolved. At a basic level, decision-makers should become aware of internal and external uncertainties related to their decision-making to be able to identify the involved design risks.

MCDA for risky design decisions

Design decisions in infrastructure tenders need to consider a number of conflicting criteria. A multitude of MCDA methods and tools have been developed to support such decisions (for overviews of MCDA methods in construction see Jato-Espino *et al*. 2014, De Almeida *et al*. 2016, Chen and Pan 2021). Decision makers employ these tools and methods to prioritise important criteria or parameters, reduce uncertainty and enhance the quality of decisions (Mardani *et al*. 2016). The methods can be used for two types of problems: (i) selecting from discrete alternatives or (ii) selecting from a continuous set of options. In infrastructure tenders one alternative is often chosen from a finite set of alternatives. Appropriate methods for this type of problem (De Montis et al. 2000) are the weighted-sum method (Triantaphyllou 2000), the analytical hierarchy process (Wind and Saaty 1980), outranking or multiple attribute utility theory (Keeney 1988, Belton and Stewart 2003). Despite the large number of available methods, none of them is considered the best for all kinds of decision-making problems (Guitouni and Martel 1998). Each method has its own properties with respect to the assessment of criteria, the application and computation of weights, the mathematical algorithm utilized, the model to describe the system of individual preferences, the level of uncertainty embedded in the data set and the ability for stakeholder participation (De Montis *et al.* 2000).

Previous research also has shown that situations like construction tenders have an influence on how MCDA methods and tools are used and that using an MCDA in these situations does not necessarily ensure consistent and rational decisions (Van Der Meer *et al*. 2020). Decision uncertainties and risks can be rather masked than revealed. One reason is that the application of substantiated probability distribution to address the risk-related external uncertainty of decision criteria is a time-consuming and methodological-demanding process (Velasquez and Hester 2013). Often there is a lack of historical data while available data and information is too imprecise, incomplete, conflicting, and scattered (Mardani *et al*. 2016). The design iterations in the tender context are restricted by the tender duration. In such cases of weaker states of data and information, decision-makers rather apply MCDA tools and methods in a deterministic way (Pries-Heje and Baskerville 2008, Antucheviciene *et al*. 2015). They take shortcuts in their judgement by immediately form ideas about possible solutions and solely rely on recent experiences and intuition (Zimmerman 2001, Laryea and Hughes 2008). As a result, risks remain hidden during the evaluation of design alternatives and subjective interpretations are dominating the judgements of decision-makers (Van Der Meer *et al*. 2020). Here, insights from behavioural science suggests that the way of presenting a decision, the so-called choice architecture, can influence the outcome of decisions (Thaler *et al*. 2012). It draws attention to the cognitive biases of decision-makers that lead to non-rational decisions, and shows how an intentionally arranged choice architecture may help in raising risk awareness by, for example, highlighting uncertainties involved in decisions (Van Buiten *et al*. 2016).

Another reason for inconsistencies of MCDA supported decisions in construction tenders is that the decision quality cannot be measured because decision outcomes are not accessible prior to the decision and it is impossible to determine the actual consequences of the decision (Van Der Meer *et al*. 2020). MCDA methods and tools are then often used to create the

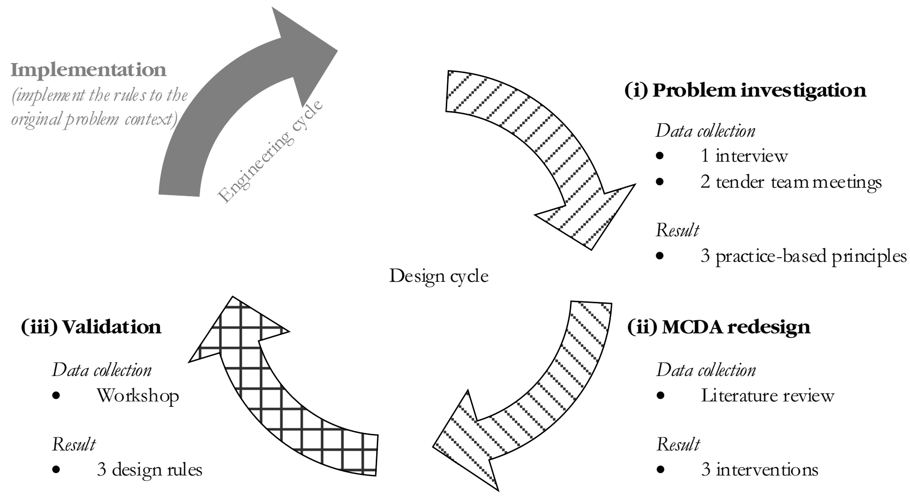

Figure 1. Design cycle.

impression of soundly underpinned evaluations of design alternatives "while ignoring the incomplete and uncertain information underlying the decision" (Van Der Meer *et al*. 2020). However, what can be assessed is the quality of the analysis while making the decision (Keren and De Bruin 2005). This includes whether there is an appropriate frame for structuring the analysis, creative and feasible alternatives are developed, reliable and unbiased information is available, desired outcomes are formulated, the decision follows a certain logic, and whether there is commitment to action (Spetzler *et al*. 2016, Van Der Meer *et al*. 2020). The evaluation of the quality of the analysis should initiate a discussion about what is required to ensure the desired quality of the decision process, how uncertain it is to achieve this, and thereby raise the risk awareness of engineers.

Research design

This study adopts a design science approach (Wieringa 2014) to investigate how the design decision process using MCDA could be set up in construction tenders to create risk awareness of decision-makers. Design science connects the scientific knowledge of scholars to the pragmatic, action-oriented knowledge of practitioners, in order to develop so-called design rules (Romme and Endenburg 2006). A design rule is "a chunk of general knowledge linking an intervention or artefact with an expected outcome of performance in a certain field of application" (Van Aken 2005, p. 23). In this research, design rules are proposed for raising risk awareness in the project context. They are based on the analysis of the decision-making practice in a construction tender and the underlying practice-based principles that led to the disregard of risks. These principles were addressed by three interventions which were developed with the support of scientific literature. The validation of the interventions in a workshop with tender participants then generated the knowledge on how to raise risk awareness when making design decisions under tender conditions.

The infrastructure tender covered the engineering and construction of a stacked tunnel in a densely populated city in the Netherlands. The stacked tunnel consisted of a bicycle tunnel on a fast-traffic tunnel replacing a railroad-crossing. Besides the stacked tunnel, the scope of the project included two other engineering objects (ecoduct and viaduct) and the construction of a road connecting the highway with the city. The budget was capped at about 50 million euros. The tender team of the construction firm participating in the tender comprised of a design manager, a technical manager, a cost specialist, a planner, a geotechnical engineer and the tender manager. The rationale for choosing this tender is that it represents a "typical case" (Yin 2003) for engineering and design tenders in the Dutch infrastructure sector. A contractor is responsible for integrating the engineering and construction of infrastructure composed of multiple objects, a multi-disciplinary team is involved in the design process, the project has an average size, and the preparation time is limited to five months. The tender team applied an MCDA by using a trade-off matrix (ToM) as tool to compare and score design options on various criteria. The exploratory character of the study and the intention to make first theoretical advancements of understanding risk awareness in the project context provided the rationale for studying the tender as a single case (cf. Flyvbjerg 2006).

The research process followed the design cycle (Wieringa 2014) and consisted of three main steps: (i)

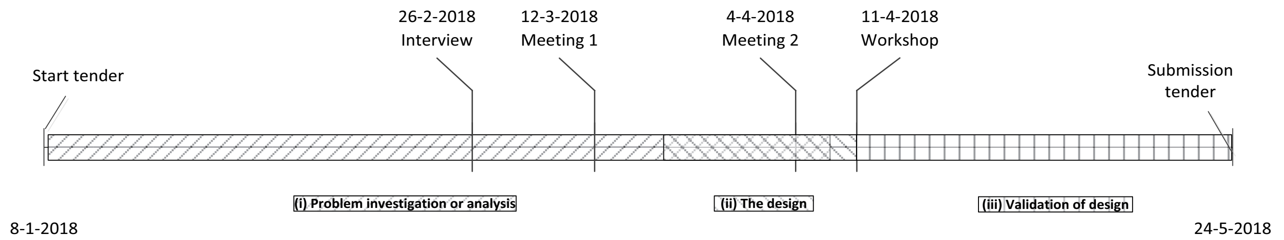

Figure 2. Timeline of tender including the three research steps.

problem investigation or analysis, (ii) the design itself and (iii) the validation of the design (Figure 1). The first two steps partially overlapped in time to be able to start the validation step directly after the last tender meeting (Figure 2).

Problem investigation

In the first step, the current practice of an MCDA using a trade-off matrix (ToM) in the infrastructure tender was analyzed to identify the principles of dealing with risks underlying this practice. Data was collected by conducting one interview with the design and technical manager and observing two tender team meetings (Figure 1). The interview gathered information about the scope of the tender, the decision problem and design of the ToM including how the criteria were selected. The first tender team meeting took place three months after the start of the tender. During the meeting the tender team explained the possible alternatives for the construction of the stacked tunnel to external specialists. In the second meeting, four weeks after the first meeting, the tender team again explained their chosen alternative to external specialists and members of the project board. Both meetings were audio recorded (2 hours each) and notes were taken during both meetings. The recordings were transcribed and analyzed. The meetings were analyzed to identify whether newly introduced risks during the meetings changed the ToM (e.g. values, criteria, alternatives) and influenced the decision-making process, e.g. did the tender team ignore, reject or adopt (newly) identified risks in their decision process. The changes made in the ToM were traced back to the transcription and vice versa. The observations aimed at collecting data about how the tender team performed the MCDA, reacted on comments or questions and dealt with involved uncertainties in their decision-making. The observations were compared with the used ToM and the technical documentations including technical drawings, soil parameters, and technical analyses of the soil to assess the extent to which risks were determined on available information or experiences. The design of the ToM together with how it was reviewed during the meetings resulted in the formulation of the first practice-based principle. The analysis of how the risks were included in the ToM revealed the second practice-based principle. The last practice-based principle emerged from the analysis of the impact of changes made to the ToM on the final decision.

MCDA re-design

In the second step of the research process the MCDA was redesigned with the identified practice-based principles as starting point. Based on literature covering multi-criteria decision making, behavioural sciences and risk assessment three interventions were developed that change the practice-based principles to raise risk awareness in infrastructure tenders. The interventions represented propositions of how the MCDA should be designed that were not yet tested in practice but grounded in science (Romme 2003).

Validation of the design

In the third research step the interventions were validated in a workshop setting and design rules were defined. A workshop setting was chosen because it created the possibility to repeat the design decision using the alternatives, information and knowledge gathered during the tender while observing the decision-making process. To be able to work with the time limitations of a workshop, the ten alternatives were reduced to the three alternatives with the highest value. The validation aimed at identifying the effects of the designed interventions on the MCDA process and their potential to increase risk awareness. The workshop took place one week after the second tender meeting. The tender team attended the workshop and included design manager (1), planner (2), cost specialist (3), geotechnical engineer (4) and technical manager (5). The first author functioned as workshop leader and another researcher took notes, facilitated

Table 1. MCDA process in tender and during workshop.

MCDA-process	Tender	Workshop
Determine alternatives	• Alternatives are determined by the team.	• Alternatives are determined by the team.
Determine criteria	• General format of ToM is used with predetermined criteria. • Criteria are adjusted by design manager.	• General format of ToM is used with predetermined criteria. • Distinctive criteria are determined using a predetermined list of criteria. • Determine definition per criterium.
Determine scoring	• Scoring is prefilled by design manager.	• Link the impact of risks with criteria. • Score each criterium using a most likely, minimum and maximum value (bandwidth score).
Determine decision	• Determine the total score for each alternative. • Choose the alternative with highest total score.	• Determine the total score (most likely, minimum and maximum) for each alternative. • Evaluate the quality of decision process. • Choose the alternative with a total score that best relates to the desired risk profile.

the discussion at the end of the workshop, and acted as a neutral observer for triangulation reasons.

The workshop started with a short introduction and a questionnaire in which the participants wrote down their interpretation of each criterion considered in the ToM that was used before the workshop. After finishing the questionnaire, the participants started the MCDA using an empty version of the ToM which was filled with additional criteria, descriptions of the criteria, values and the chosen alternative. At the end of the workshop, the participants elaborated on their analysis and scored the decision quality (Spetzler *et al.* 2016). This last step also resulted in discussing the lessons learned by the tender team.

Additional data was collected through 3.5 hours of video and audio recordings during the workshop. The recordings were transcribed. The transcripts were coded by relating every step of the MCDA with how it stimulated the discussion and influenced risk awareness. The ToM served as means to analyze the result of the decision process and determine the impact of the interventions. The impact of the first intervention was analyzed by comparing the definitions of criteria given in the questionnaire with the definitions given during the workshop. Different interpretations of a criterion indicated an ambiguous problem definition and subjectivity in judgements. Discussing different interpretations between engineers widens the view of participants and thereby increases the chance that engineers better comprehend the meaning of risks and their impact on future project phases. The likelihood of considering relevant information increases if criteria are well defined and understood by all participants (Weick *et al.* 2005). Then, the effects of the second intervention were identified using the transcripts. Risk awareness was indicated by the extent to which additional risks were identified and the impact on future project phases was identified. The identification of additional risks is a way to measure the perception of how risky a solution is. In addition, it was analyzed how the impact on future project phases was evaluated during the decision-process. The third intervention was assessed by discussing how the decision process could be improved (Spetzler *et al.* 2016). This discussion revealed the gap between what was considered and what was preferred in the decision-making process and thereby raise the risk awareness of engineers.

Results

Problem investigation

The followed MCDA process (Table 1) structured the decision problem and evaluated conflicting criteria such as cost and schedule. During the MCDA process the tender team first determined various alternatives, followed by the criteria that needed to be considered. Then, a value for each criterion was given and the values per alternative were calculated to derive the best alternative. The tender team applied the weighted-sum method using a trade-off matrix (ToM) as tool for comparing and scoring ten alternatives. The alternatives differed in the method for constructing the tunnel walls and included a cutter soil mix wall, a diaphragm wall and a cement bentonite wall. The analysis of the MCDA revealed three practice-based principles of dealing with risks:

Use standard criteria and adjust them to the characteristics of the tender

The evaluated criteria were based on a general format of the ToM used within the construction company (Table 2). The criteria described in this format were

Table 2. Format of the ToM used in the tender.

Main criteria Sub-criteria	Weight	Alternative *n* Explanation of value	Score	Alternative *n* + 1 Explanation of value	Score
Short description of the alternatives					
Phasing/working method					
Critical requirements					
Requirements	…	…	Value	…	Value
Technical aspects					
Design complexity	…	…	Value	…	Value
Permits	…	…	Value	…	Value
Buildability	…	…	Value	…	Value
Safety	…	…	Value	…	Value
EMVB (economically most viable bid)					
Sustainability	…	…	Value	…	Value
Nuisance reduction	…	…	Value	…	Value
Specific client risks reduction					
Schedule					
Preparation time	…	…	Value	…	Value
Construction time	…	…	Value	…	Value
Costs					
Absolute costs	…	…	Value	…	Value
Percentage	…	…	Value	…	Value
Risks					
Costs	…	…	Value	…	Value
Time	…	…	Value	…	Value
Quality	…	…	Value	…	Value
Safety	…	…	Value	…	Value
Environment	…	…	Value	…	Value
Maintenance	…	…	Value	…	Value
Chances					
Score	…	…	Value	…	Value
Time	…	…	Value	…	Value
Quality	…	…	Value	…	Value
Decision					
Score			Total score		Total score
Comments					

adjusted and merged by the design manager based on the specific characteristics of the tender. For example, the criteria "critical functional requirements" and "critical aspect requirements" were merged into "critical requirements". The criteria "design complexity" and "permits" were added. Values for each criterion were assigned and then multiplied by the corresponding predetermined weights and finally summarized in a total score per alternative. The design manager determined the initial value for each criterion and sent criteria and values to the team for a review. The values were based on a four-point scale ranging from "–" (bad), "-"(unfavourable), "+" (neutral) to "++" (favourable). The review within the team took place before the first meeting. During this internal review no attention was given to the scope and uncertainty of each criterion or the format of the ToM. During the first meeting possible new alternatives were discussed. In the second meeting the chosen alternative was challenged by the external specialist on technical details. Both the team and the reviewers did not change the predetermined criteria of the design manager (values for the criterium "safety" and "permits" changed, see subsection iii) nor the identified risks. According to the team, the criteria represented the specific characteristics of the tender. The non-traditional criteria (e.g. reliability, availability, maintainability), that make the decision problem more complex, were not included in the ToM (Table 2).

Score the criterion "risk" for each alternative

Concerning the three wall constructing methods combined with various methods to construct the floor of the tunnel led to three main risks: (i) a higher leaking rate than expected for the wall-floor connection, (ii) having a floor that is not watertight when using e.g. underwater concrete, and (iii) the alternative requires more diving work than expected to place all the rebar in the floor. The main criterion "risk" was scored with a single value that represented the possible impact that the specific alternative had on the risk factors. This single value conflated the identified risks. The other criteria were also scored using a single value which represented the preferences of the engineers. The ToM was, along with other documentation, part of the input for both meetings and was used to identify the best alternative. External specialists were invited to the first review-session to reflect on the choices made by the tender team. During this meeting the specialists paid no attention to the presented

Table 3. Proposed interventions for raising risk awareness.

Current practice		Proposed intervention	Risk awareness mechanism	Underlying literature
(i) Use standard criteria and adjust them to the characteristics of the tender.	A.	A description of the criteria and a general list of criteria to identify those criteria that correspond with the characteristics of the tender.	Enable engineers to understand each other's interpretations of criteria, to discuss the criteria from a multidisciplinary view and to set clear boundaries of all criteria. This should increase risk awareness by discussing the rationale of including criteria and the scope of the criteria.	Decision objectives (Bond *et al.* 2008) Behavioural decision theory (Morton and Fasolo 2009)
(ii) Score the criterion "risk" for each alternative.	B.	Explicitly mapping the identified project risks on the criteria and assign a bandwidth score (most likely, minimum and maximum score).	The cumulative bandwidth value of each alternative can lead to overlapping values which means that the decision-maker is triggered to choose between riskier and less riskier alternatives. This should increase risk awareness	Choice architecture (Thaler and Sunstein 2008) Highlighting uncertainty (Van Buiten *et al.* 2016)
(iii) Prefer the alternative with the highest cumulative value.	C.	Evaluation of the quality of the decision process by scoring the elements "relevant and unbiased information", "desired outcomes" and "logic" of decision quality.	The evaluation of these three elements should reveal differences between engineers about their used information, their preferred outcomes, or their applied logics which should raise risk awareness.	Decision Quality (Spetzler *et al.* 2016) Outcome information (Hershey and Baron 1992) Decision Quality (Keren and De Bruin 2005)

ToM. Instead, the specialists came up with other solutions to connect the wall with the floor and required further explanation about technical details of existing alternatives. The newly proposed solutions to connect the floor with the wall be possible measures to reduce or mitigate the identified risks belonging to the connection between the floor and the wall. The tender team first defended their alternatives but eventually discussed the new proposed alternatives. The meeting resulted in homework for the team to explore the new alternatives, however no additional risks were identified.

Prefer the alternative with the highest cumulative value

After the first meeting, the values of the sub-criteria "safety" and "permits" were adjusted based on review-comments about the connection of the diaphragm wall with the reinforced under water concrete floor. The sub-criterion "safety" was given a more negative value as the execution of the floor-wall connection seemed more dangerous than expected in terms of water tightness. The sub-criterion "permits" was given a more positive value as the external specialists commented that the construction of the diaphragm wall combined with a floor of reinforced under water concrete complied with the required water permit. These adjusted values did not result in a different value of the main criterion "risk" or led to additional risks used in the decision process. The engineers did not discuss the link between changing the value of the sub-criterion "permit" and the identified risk of the higher leaking rate and the risk of a floor that is not watertight. In addition, they did not think about the possibility that the effects of both risks could also change the value of other criteria. Despite the detailed technical questions during the review-moments, the preferred alternative by the tender team remained the best alternative. The used information that resulted in the initial values of all criteria, including the risks, were not explicitly reviewed by the team.

MCDA re-design

The overall aim of the interventions is to make engineers more aware of the risks involved in design alternatives and to stimulate a discussion to bring these risks to the foreground. The three proposed interventions address the identified practice-based principles and intend to explicate the "how" in structuring the decision problem (Van Der Meer *et al*. 2020). The principles resulting from the case study are further confronted with insights from literature. The interventions are presented in Table 3 and described in the following sections.

Intervention A: description and general list of criteria

The selection of criteria is an important step in an MCDA. The analysis of the current situation showed that general and predetermined criteria were used in the ToM and adjusted to the characteristics of the tender. Engineers did not discuss the scope of the criteria and create a common understanding of criteria. The

Table 4. Redesigned format for ToM.

			Alternative n					Alternative $n+1$				
						Score [step 3]					Score [step 3]	
Criteria	Definition [step 2]	Weight	Explanation of score	Related risk	Min	Most likely	Max	Explanation of score	Related risk	Min	Most likely	Max
Criteria n	…	…	….	…	Value	Value	Value	….	….	Value	Value	Value
Criteria $n+1$	…	…	….	…	Value	Value	Value	….	….	Value	Value	Value
				Sum	Score	Score	Score			Score	Score	Score

adjustment of the criteria by the design manager left the engineer with the impression that the criteria soundly represented the problem and were well defined. This prevented engineers from discussing their interpretation of criteria and identifying possible risks related to interpretation differences.

Experimental work suggests that when people are asked for criteria in some substantive decisions problem, the number which they generate is much smaller than the number of criteria which they can recognize as relevant from a list (Bond *et al*. 2008). The number of selected criteria from a list will increase when a list of predetermined criteria is used in an MCDA. According to Morton and Fasolo (2009), this provides some support for the use of a comprehensive checklist. To incorporate all criteria in the decision problem for infrastructure tenders, a comprehensive list of predetermined criteria relevant for general decision making in infrastructure was designed and tested in infrastructure projects by Van Der Meer *et al*. (2020). However, increasing the number of criteria in an MCDA can overwhelm decision-makers and force decision-makers to simplify their decision by focussing on a few familiar criteria while neglecting others. Decision-makers focus only on those criteria that are most prominent or salient (Bond *et al*. 2008). Focussing on the most familiar criteria requires less cognitive effort of decision-makers and allows them to better understand information and weight important information (Peters *et al*. 2007, Johnson *et al*. 2012).

The aim of the first intervention is to enable engineers to understand each other's interpretation of criteria, to discuss the criteria from a multidisciplinary view and to set clear boundaries for all criteria and thereby to increase risk awareness. Discussing variations in the interpretation of criteria should help to increase the understanding of the presented information while the differences between interpretations show possible risks in scope. Setting clear boundaries should help to find distinctive criteria for the decision problem. Therefore, the first intervention changes the format of the ToM by introducing a description of criteria next to the list of distinctive criteria itself (Table 3). It is expected that creating a common understanding of each criterion based on the exchange of knowledge and experience supports engineers in broadening their perspective. The different interpretations help engineers to perceive a situation as being riskier and thereby raise risk awareness.

Intervention B: bandwidth value for criteria

The analysis of the current situation also showed that a single value is assigned to the criterion risk comprising the identified impact of alternatives for several criteria. Using a single value decouples impact on criteria from the uncertainty of other criteria creating this impact. It also conflates several different risks with different probabilities and effects. As a consequence, uncertainties involved in the possible impact of criteria on other criteria remain hidden. Risk awareness could be raised by discussing the possible consequences and impact of the risks on each criterion. It supports engineers to better comprehend the meaning of risks in the specific situation.

The second intervention aims to explicitly link risks to single criteria by first stating which risks are associated with which criteria. Then, the most likely, the minimum and maximum value (bandwidth score) of the criteria impact are assigned which invites engineers to discuss the wider causes of identified risks (Table 4). Once all criteria have been scored, decisions-makers should try to understand the ranking of the alternatives using the cumulative bandwidth value of each alternative. The cumulative bandwidth value of each alternative can lead to overlapping values which means that the decision-maker is triggered to choose between riskier and less riskier alternatives. Riskier decisions opt for alternatives with more uncertain criteria impact, that is more difficult to achieve or includes the possibility of extreme consequences.

Intervention C: evaluation of decision quality

New information and new insights (e.g. about the floor-wall connection) during the review meetings changed the values of the criteria "permits" and "safety" in the ToM but did not change the preferred alternative. The presented values in the ToM were not questioned by the external specialists or explained by the tender team. Whether the values given at the start

Table 5. Results of collective scoring on decision-making quality.

Decision quality element	Score [0–100%[a]]
Relevant and unbiased information	50%
Desired outcomes	50%
Sound reasoning or logic	100%

[a]Benefits outweigh the cost – costs outweigh the benefits.

of the MCDA represented the available knowledge about the alternatives at the end of the tender was not evaluated. Whether the presented values were based on limited or biased information was not evaluated. Evaluating the quality of the decision process is expected to raise risk awareness as it indicates what risks are not considered when making the decision. Decision-makers are made aware of possible new risks which is a first step to be able to assess the risks.

The third intervention is to evaluate the quality elements "relevant and unbiased information", "desired outcomes" and "logic". The elements "appropriate frame" and "creative and feasible alternatives" are not evaluated (Table 5). The former element is already evaluated by the first intervention. The latter element is considered a boundary condition to perform an MCDA. The evaluation of the three elements should start a discussion about what is required to raise quality of the decision process based on the used information, the preferred outcomes, and the applied logics of the decision. During the evaluation engineers should together evaluate each element by allocating percentages ranging from 0 to 100% (Howard 1988, Spetzler *et al*. 2016). A percentage of 100% represents a situation in which additional costs to improve the quality outweighs the achieved benefits. A percentage of 0% represents a situation in which additional benefits will outweighs the costs to improve the quality.

Validation of the design

This section describes the decision-making process during the workshop in which the interventions were validated. Table 6 summarizes the workshop results.

Intervention A: description and general list of criteria

The use of the predetermined list of criteria resulted in adding the criterion "acceleration possibilities" in the ToM after a discussion about the appropriateness for this tender. Other criteria were also discussed but were not added. For example, participant 3 indicated that "maintenance" was not defined as criterion, participant 1 indicated that "culture and expertise" of the construction company should be included and participant 2 stated that "acceleration possibilities" in the working method should be included. All team members agreed to only add this latter criterion in the MCDA as distinctive criterion.

This discussion increased the understanding of the engineers' interpretations of the criteria and supported engineers in voicing their individual view. It also supported the definition of clear boundaries for the criteria. Through the discussion engineers became aware that they interpreted the sub-criteria belonging to the criteria "technical aspects" and "risks" differently. This included the sub-criteria "design complexity", "permits", "buildability", "safety", and "schedule". For example, the criterion "design complexity" was interpreted by participant 1 as "the technical feasibility of the design" while participant 5 interpreted this criterion as "the complexity of the design based on the chosen construction method". Participant 1 considered the (technical) design part, where participant 5 only considered the construction method. The criterion "permits" was interpreted by participants 4 and 5 as "can we comply with the requirements" while participant 2 interpreted this criterion as "can the solution comply with the requirements and is the time required for application feasible". The scope of the criterion "permits" was adjusted to solve this overlapping scope.

This intervention intensified the interaction between participants. Discussing and defining the criteria prevented overlapping scope of criteria. Defining a common interpretation of the criteria was helpful in setting clear boundaries which were used during the scoring of criteria and the evaluation of the outcome. Risk awareness emerged through the scoping of the problem and the associated information need. Clear definition of the problem scope by defining each criterion revealed uncertainties in scope. This was key in clearly defining the problem frame and increased the likelihood that relevant information was used. It also showed what information was missing or required.

Intervention B: bandwidth value for criteria

This intervention resulted in discussing the scope of the identified risks. Participants became aware that the criterion "risk" is not a separate criterion but relates to other criteria. Variations in the scope of the risks emerged while linking the predefined risks to various criteria. For example, the safety related risk of alternatives which involve much diving-work was interpreted by some participants as diving being an unsafe activity that cannot be eliminated. Other participants interpreted the risk as a situation in which much more diving is required in comparison to the

Table 6. Validation outcomes of risk awareness interventions.

Intervention	Effect	Result	Role of the intervention
A. Introduce a description of the criteria and use a general list of criteria to identify those criteria that correspond with the characteristics of the tender.	Discussion about the appropriateness of the predetermined criteria based on the individual interpretations of criteria. Discussion about how decisions are made and what level of detail is required to decide on the most preferable alternative.	Adding the criterion "acceleration possibilities" and identification of overlapping scope of criteria "permits" and "schedule". Opinions of engineers were adjusted and the tender team defined definitions in order to prevent overlapping scope of criteria. Participant became aware of their decision-making behaviour and their influence on the outcome of decision	The discussion and specification of the criteria's definition was key to clearly define the problem frame. The intervention intensified the collaboration, sharing of interpretations to identify overlapping, conflicting or missing criteria and created new information.
B. Explicitly map the identified project risks on the criteria and assign a bandwidth score (the most likely, the minimum and maximum score).	Discussion in which participants became aware that the criterion "risk" is not a criterion in itself but that risks should be included in all criteria instead. Exchanging experiences and knowledge about the water tightness of the walls in theory and practice when bandwidth score was determined Discussion about the bandwidth score created new insights resulting from experiences and knowledge of the participants.	Acceptance of possible risk consequences leading to increased risk perception. Determining the bandwidth score of the criteria "permits", "sustainability" and "EMVB" based on the scope of each criterion including the allocated risks. Defining a bandwidth score based on new insights for the criteria "buildability", "preparation time" and "possibility to accelerate".	The intervention intensified the discussion about the scoring method. The team noticed that small changes in the values resulting from increased uncertainty awareness can have significant effect on the outcome.
C. Evaluation of the quality of the decision process by scoring the elements "relevant and unbiased information", "desired outcomes" and "logic" of decision quality.	Discussion about the scores of each decision quality element. Not only for the workshop session but also for the tender itself.	Determining the quality of the decision process resulted in the awareness that more effort was required for 1) the exchange of information and knowledge, 2) for updating the costs of all alternatives and 3) understanding the end result.	The intervention allowed the team to reflect on their decision-making process after the workshop.

calculated diving work. The first interpretation only related to the criterion "buildability" while the second interpretation also linked to the criterion "schedule". The participants allocated this risk to the criterion "buildability" and the discussion created a better understanding of the defined scope and related value.

Through the discussion about scope and scoring of the bandwidth engineers exchanged knowledge and experiences which had not taken place during the tender. For example, the water tightness of the alternatives was discussed. All alternatives included in the MCDA were supposed to be watertight. During the workshop it became clear that the water tightness of the alternatives also depends on the quality of execution. The impact of the quality of execution was not included in the original ToM. Other examples are discussions about the scope of the criteria "permits", "sustainability" and "EMVB". The design acceptance by the authorizing body was not part of the criterion "permit" and thus not included in the original value. The original value was based on whether a permit could be authorized. "Sustainability" was defined as described in the contract. Despite this definition, participant 3 suggested a value based on the sustainability defined by the construction company. Participant 4 reminded on the defined scope of "sustainability" and was against a different value. The team was encouraged to stick to the predetermined definitions and defined values accordingly.

The scoring of the criterion "buildability" led to new insights. Specific setting and vibration requirements for constructions under the railway were discussed. This included the risk that the construction underneath the railway might not comply with the specific vibration requirements. The uncertainty caused by this risk was incorporated in the bandwidth score. New insights also emerged during the scoring of the criterion "preparation time". During the workshop a discussion about the required time to start the production process of the cutter soil mix wall (CSM) wall started. As a result, the bandwidth value of the criterion "preparation time" included the production process risks of an CSM wall. This production process risk was not included in the value given in the tender. Scoring the new defined criterion "possibility to accelerate" created new insights about the required steps to prepare the production. This was valuable information because it showed the acceleration possibilities in case of delay. The team discovered that the CSM-alternative scored better on this criterion than the other alternatives. Surprisingly, this discussion had not taken place during the tender although a robust schedule was part of the strategy-to-win.

The bandwidth score encouraged the team to discuss and exchange knowledge leading to new insights. It created problem transparency and better understanding of the rationality of the decision making. Individual experiences and knowledge were transformed into more collective knowledge and thereby created new decision information and raised risk awareness for all engineers. The team noticed that small changes in the scoring could have significant effects on the outcome. For example, participant 2 stated that it is important to discuss the values because a small change can have large consequences when variations between alternatives are small. Participants changed their opinion based on the discussions and thus changed their scoring. Or as participant 4 summarized it: "it is always important to understand the distinctive factors between alternatives, and to understand the importance of the factors because the values should be in line with these factors".

Intervention C: evaluation of decision quality

Providing feedback about the quality of the decision-making process created awareness that more time and resources should have been spent on (i) the exchange of information and knowledge, (ii) updating the costs of all alternatives and (iii) understanding the end result of the MCDA. The scores in Table 6 represent the perceived decision quality for the three elements "relevant and unbiased information", "desired outcomes" and "logic" that the tender team collectively determined and agreed upon. This intervention allowed the team to reflect on their decision-making process during the workshop, but it did not allow them to improve the quality because the limited time between the workshop and submission of the tender.

The evaluation of "relevant and unbiased information" resulted in agreement between engineers that the exchange of knowledge during the tender should get more attention. Participant 1 indicated that it is important to discuss and determine the criteria together to exchange experiences and knowledge. The added criterion "acceleration possibility" in the decision-making process is an example. Participant 5 pointed out that the collaboration within the team increased through the discussion about the scope of each criterion combined with presenting the alternatives. Participant 2 added that the awareness about uncertainty increased by using the bandwidth score and that it is necessary to accept the presence of uncertainty and risk. He also added that the bandwidth scoring should "not only be used for scoring criteria, but also for determining both schedule and budget. Both are surrounded with uncertainties and thus biased if uncertainty is not discussed." Participant 1 explained that "the total costs of each alternative must be updated for all alternatives if more detail is provided on one alternative to ensure that the costs are based on the same level of detail. Especially when cost differences between alternatives are minimal, more time should be spent on determining an equal level of detail in the cost-estimates."

The evaluation of "desired outcomes" resulted in a discussion about the importance of uncertainty in the scoring to understand the outcome of the MCDA. The values represent the experience and knowledge of the involved engineers and discussing the values supports to understand the differences between the alternatives. The bandwidth scoring supported the team to understand these differences or as participant 2 explained: "it is impossible to rely on a single value with a lot of uncertainty because it does not represent reality". Participant 5 further stated that "I do not fully understand the current outcome. I expected a higher value for the cement bentonite (CB) alternative because the current outcome does not match with my perception and past-experience". Participant 2 reacted by stating that "they (the tender team) just analyzed the values to better understand the differences" which resulted in adjusting the bandwidth of the CB-alternative. "So, the outcome seemed odd at the start, but after analyzing the values we started to understand the consequences. This means that you can never rely on a single value with high uncertainty". Trying to understand and explain the outcome based on given values becomes important to make decision-makers aware of the involved risks, which do not always match with their past experiences.

Discussion

The decision process supported by an MCDA in an infrastructure tender was redesigned to increase the understanding of the decision problem and the reasoning behind choices and, by doing so, to increase the risk awareness of engineers. Infrastructure tenders are characterized by limited time and resources and a certain design complexity stemming from the multidisciplinary scope, integrative character and high value of projects. This quickly can lead to undetected risks that become manifest in later project phases. Although risk and risk assessment in construction have gained much attention in literature, risk awareness as a main prerequisite for the management of risks has been largely neglected. To be able to assess risks construction professionals need to perceive a decision situation as risky, comprehend the meaning of risk in this situation and make a projection of the possible impact. The results of our study show how risk awareness can be created in the design phase of infrastructure tenders. The three interventions designed in this study triggered and structured discussions and helped to gain insight into the perceptions and reasoning of professionals. The emerging general design rules represent first ingredients towards an action-oriented theory for creating risk awareness in the project context. They extend research on judgement and decision-making by offering actionable knowledge based on professional experiences with design decisions. In the following we discuss the three design rules which address (i) the structuring of the decision problem, (ii) the visualization of risks, and (iii) the evaluation of the decision-process.

Jointly define criteria to increase a common understanding of criteria and the use of relevant information

The first design rule states that engineers require tools or processes that increase the common understanding of criteria and thereby increase the use of relevant information. In this sense, generating criteria defines a structure for "how" to specify the criteria next to the "what" that is required in terms of structuring the problem. To account for the different interpretations of engineers it is important to openly discuss the problem framing, develop a common interpretation of criteria and make sense of the criteria before alternatives are compared. This is relevant because engineers see, interpret and respond to circumstances differently (Vaughan and Seifert 1992) and it influences engineers' preferences about how to change the situation (Vickers 1965, Shafir and Leboeuf 2004). Individuals focus on the information that is most prominent (Bond *et al*. 2008). The most prominent information in the intervention was the given interpretations in the questionnaire because participants used their interpretation as scope-boundary of the criteria. All participants had an individual perspective on the evaluation of alternatives based on their individual expertise. The intervention revealed to the participants that their thinking was not as coherent as they might thought. Participants with different backgrounds used different frames and different information, preferred different outcomes and applied different logics. The perspective of decision-makers on the problem framing will be widened when criteria are jointly defined. Broadening the perspective includes the exchange of various criteria interpretations which, in turn, point out the risks in the problem scope and increase risk awareness.

Highlight or visualize the uncertainty in criteria scoring to trigger discussion about risks

The focus of this design rule is on the presentation of choices to the decision-maker and can be seen as a form of choice architecture (Thaler *et al*. 2012). The smart redesign of decision-making tools is a low-cost method with relatively small barriers to implementation but with potentially large effects on the decisions made (Shealy and Klotz 2015). The implemented intervention changed the representation of risk from an overall numeric value to bandwidth scores for each criterion. The bandwidth scores influenced the perceived risks and stimulated discussion among participants about the best- and worst-case scenario using their tacit knowledge. The structure of defining both best- and worst-case scenarios requires information about possible future events which enhances the ability to deal with uncertainty (Amer *et al*. 2013). Participants were supported in making a well-considered decision given the identified risks and uncertainties. They became aware that there is not a single best alternative due to the involved uncertainties represented in the bandwidth. The bandwidth explicated the subjective interpretations underlying the judgements of participants and facilitated the discussion about which alternative matches with the amount of risks the construction company was willing to take. The fact that participants had to voice their interpretations, write down their conclusions and explain the possible interrelatedness of design issues stimulated their collaboration. This interaction with each other can be seen as an attempt to produce meaning by shaping and balancing interests and actions (Kaplan 2008).

There might be other ways of changing the choice architecture to trigger a discussion about risks. This can include the description of choices (Johnson *et al*. 2012), the use of graphical expressions of risk information as opposed to numerical representations (Stone *et al*. 1997, Lipkus and Hollands 1999), the shift of defaults (Johnson *et al*. 2012) to focus on the worst- or best-case scenario's, or the provision of feed-back loops which can shape the quality of the decision (Kluger and Denisi 1996). Not all choice architectures are grounded in theory, but for every decision it can be useful to think about how choices are presented and what might possible effects on the decision (Keller and Wang 2017). As Jato-Espino *et al*. (2014) acknowledge, the adaption of MCDA to easily understandable and manageable formats where users only need to express their preferences in a conventional semantic can support decision making problems where experience and speed are relevant factors.

Reflecting on the decision-making process through the evaluation of decision quality

The focus of this design rule is on the evaluation of the decision process leading up to the scoring of criteria instead of focussing on the cumulative value of alternatives. This evaluation should point out areas of the decision process that are still risky. It supports decision-makers to reflect on the logical implications of judgements and to isolate and explain clashes between the MCDA and their intuitive judgement (Morton and Fasolo 2009). This effort can take the form of thinking about what matters (to oneself and to others), confronting trade-offs (to the extent that getting more of one thing requires giving up something else), or searching for additional (more comprehensive) and higher quality (more complete or precise) information (Pidgeon and Gregory 2004).

The intervention implemented put engineers in the position to discuss those parts of the decision-making process which could make the outcome more certain. In this respect, the intervention provided insights in the quality of the decision-making process by evaluating the used information, the underlying reasoning and the interpretation of the outcome. The design rule pays attention to the subjectivity of problem structuring, values, and probabilities and attempts to incorporate a wider range of values and concerns in modelling MCDA (Pidgeon and Gregory (2004). Many models that deal with risk assessment and interpretation tend to focus on mathematical and algorithmic details rather than providing transparency to the decision maker (Durbach and Stewart 2012). Taroun (2014) demonstrates that the conventional rules of aggregation, the averaging or the weighed sum, are not always suitable ways for obtaining a representative project risk level due to their underlying assumptions. He suggests that revealing practical experience is key in extending risk modelling. The design rule facilitates the exchange of practical experience because decision makers with varied specialties are supported in more structured social interaction and discussion about the underlying reasoning, interpretation and uncertainties of the outcome of the decision-making process.

Limitations and further research

Despite the thoroughness of the methodology used in this research, it is not without limitations. One limitation is related to designing and testing the interventions based on a single tender. The single case provided opportunities to develop an in-depth understanding of the decision-making process, but it limits the generalizability of the findings. More cases could help to meaningfully validate the design rules through the same or similar interventions. The generalizability of the findings is further limited because the interventions are tested in a context of complexity belonging to this type of project. The applicability for cases with more or less detailed designs or more or less complex projects is encouraged.

A second limitation is that the interventions were implemented in a workshop at the end of the tender. This limited the possibility to integrate potential improvements in the tender for example for those areas that were classified as average quality and then study the effect on risk awareness once these areas are improved. This would require a tender in which the design rules are implemented and the quality of the decision-making process is used to find and improve areas of average or low quality. The adequate level of quality was determined based on the assessment of the participants. A more structured approach could be beneficial to explore design rules that support a high-quality decision process. We encourage further research into the practical use of MCDA methods and tools under tender conditions to not only increase risk awareness but also to increase the quality of the decision process itself or the quality of the scoring method. Nevertheless, evaluating decision quality at the end of a tender is also beneficial to justify a decision-to-bid and to learn for next tenders.

Conclusions

Risk awareness plays an important role for decision-making in construction projects (Laryea and Hughes 2008, Van Der Meer *et al*. 2020). The results of our study on the early stages of a design process in a construction tender suggest that risks remain concealed if decision-making practices of tender or project teams are based on hidden subjective interpretation of imprecise decision criteria and vague judgmental inputs. Although MCDA tools such as trade-off matrices support decision-making by structuring the decision problem, they insufficiently address the non-transparency of reasoning and sense-making of team members in decision-making processes. Our research shows how the individual judgement of decision alternatives can be externalized and the awareness of risks involved in these alternatives can be raised. We propose three design rules that primarily encourage discussion in tender and project teams and through this discussion bring forward the underlying reasoning and interpretation of decision criteria. They foster a more transparent problem understanding between decision makers and more rational choices, even though choices are based on experiences. The decision-support tools can capture the outcome of discussions and can create a logbook that decision-makers can use to find previous contributions when defining the problem frame. In this way, decision-makers in infrastructure tenders can revert to experience and expertise when (historical) information is scarce as long as they become aware of the risks involved in their decisions.

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