

1 Article

2 A hybrid MCDM technique for risk management in 3 construction projects

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17 **Abstract:** Multi-stakeholder based construction projects are subject to various risk factors due to
18 dynamic business environments. These risks affect project activities which indirectly impact
19 construction costs, resulting in delays and poor building quality. So, managing these project risks
20 requires suitable risk mitigation strategies to evaluate and analyse their severity. Hence, risk
21 evaluation and assessment of construction projects is a multi-criteria decision making (MCDM)
22 problem. In present real-life problems, evaluation of project risks is often uncertain and even
23 incomplete, and the prevailing methodologies fail to handle such situations. To address the
24 problem, this paper extends the analytical network process (ANP) methodology in the D number
25 domain to handle three types of ambiguous evaluations, viz. complete, uncertain, and incomplete,
26 and assesses the weight of risk criteria. The D number based approach overcomes the deficiencies
27 of the exclusiveness hypothesis and completeness constraint of Dempster-Shafer (D-S) theory. Here,
28 preference ratings of the decision matrix for each decision-maker are determined using a D number
29 extended consistent fuzzy preference relation (D-CFPR). An extended multi-attributive border
30 approximation area comparison (MABAC) method in D number is then developed to rank and
31 select the best alternative risk response strategy. Finally, an illustrative example from construction
32 sector is presented to check the feasibility of the proposed approach. For checking the reliability of
33 alternative ranking, a comparative analysis is performed with different MCDM approaches (D-
34 COPRAS, D-ARAS, D-MABAC, and D-TOPSIS). Based on different criteria weights, a sensitivity
35 analysis of obtained ranking of the hybrid D-ANP-MABAC model is performed for verify the
36 robustness of the proposed method.

37 **Keywords:** D number, Analytical Network Process (ANP), MABAC, Multi-criteria decision making
38 (MCDM), Consistent fuzzy preference relation (CFPR), Construction project risk, Risk Management.
39

40 1. Introduction

41 In recent decades, projects in the construction sector have become more complex and risky due
42 to the diverse nature of activities among global companies [1–8]. In comparison to other sectors,
43 construction projects encounter more risks due to uncertainties occurring because of various
44 construction practices, working conditions, mixed cultures and political conditions between host and
45 home countries [9–12]. Thus, in this scenario, risk management can be considered a vital part of the
46 decision making process in construction projects. These projects may involve many stakeholders, in

47 addition to uncertain socio-economic conditions at the project site, bringing big challenges to
48 practitioners of the industry in recent decades [13–14]. Construction project failure may cause higher
49 costs and time over-runs, requiring a systematic risk assessment and evaluation procedure to classify
50 and respond to changes [15–16].

51 Thus, prioritisation among construction based risk portfolios, and finding suitable risk
52 mitigation strategies for construction projects, can be introduced as multi-criteria decision making
53 (MCDM) problems. Researchers have recently proposed new methods for prioritising risks in
54 construction based projects [10, 17–19]. Also, the increasing dynamism of construction projects have
55 resulted in extensive impreciseness and subjectivities in this risk investigation procedure. With
56 respect to the identification of risk criteria, a methodology is needed to sort and prioritise criteria
57 weights, based on specific environments and domain experts' judgment. In the real world, since
58 various uncertainties occur in the decision making process due to subjective and qualitative judgment
59 of DMs, so it is essential to develop a more optimised technique that can handle various types of
60 uncertainties [15, 20–24].

61 In this scenario, a proper decision making methodology is required to solve multiple conflicting
62 interdependent criteria when evaluating risks in construction projects. In recent years, the number of
63 papers related to analytic hierarchy process (AHP) and analytic network process (ANP) methods,
64 considering supplier selection procedure, has increased substantially [25–29]. But increasing the
65 number of criteria or comparison levels causes confusion in decision makers' (DMs) judgments,
66 resulting in incomplete decision making and inconsistency in the evaluator's judgments, thus
67 reducing strategy selection ability. Under these circumstances, Herrera-Viedma et al. proposed
68 consistent fuzzy preference relations (CFPR) to evade inconsistency in the decision making process
69 [30], and thus models have been developed with CFPR structuring of the problem of multi-criteria
70 knowledge based strategy selection both with AHP [31] and ANP [32, 33]. The CFPR methodology
71 requires less time, has computational simplicity, and also guarantees consistency of decision matrices.
72 But as CFPR is based on complete and certain information, there always exists a possible
73 inconsistency risk due to the inability of DMs to deal with overcomplicated objects [34].

74 It is obvious that the approaches mentioned above can play a vital role under some special
75 circumstances, but it also reveals more uncertainties due to the subjective judgment of experts'
76 assessment. For fuzzy set theory it is difficult to determine in advance membership function values
77 before making any decision in an uncertain and vague environment [8, 23]. Interval theory has the
78 same deficiency. Also the frame of discernment and basic probability assignment (BPS) present in
79 Dempster-Shafer (D-S) evidence theory limits its ability to represent incomplete information in
80 uncertain situations [34, 35]. In order to overcome the above shortcomings and effectively handle
81 various uncertain and incomplete information, *D* number [36], a special kind of random set, is applied
82 in the construction of CFPR. The *D*-CFPR method expresses the expert's linguistic preference values
83 using *D* number's, and can also be converted to traditional CFPR [34]. In recent years, papers related
84 to *D* number based MCDM methods have begun to appear, viz. *D*-VIKOR [37], *D*-GRP (grey
85 relational projection) [38], *D*-AHP [39, 40], *D*-CFPR [34], *D*-TOPSIS [41], and *D*-DEMATEL (*D* number
86 based decision making trial and evaluation laboratory) [42].

87 Besides managing the many risks associated with construction projects, this study also attempts
88 to categorise and assess their risk mitigation strategies, thus setting up a proper framework which is
89 accountable to investors in construction sectors. Thus, a survey on risk mitigation strategies is
90 performed, based on the work [9, 23, 43], to alleviate construction projects risks. Based on the above
91 considerations, this paper also develops an extended version of the MABAC methodology in an
92 uncertain and incomplete decision environment, to evaluate risk mitigation strategies in construction
93 based projects. Some papers related to MABAC have been published in recent years, viz. traditional
94 DEMATEL-MABAC [44], Pythagorean fuzzy MABAC [45], interval type 2 fuzzy MABAC [46],
95 interval valued intuitionistic fuzzy MABAC [47], and the fuzzy AHP-MABAC model [48].

96 Thus, the key motivation of this paper is to develop a *D* number based ANP-MABAC decision
97 making methodology for prioritising construction project risks, and to find suitable mitigating
98 strategies in uncertain and incomplete decision environments. In this paper, we choose the ANP

99 methodology due to its ability to represent the potential interactions, interdependences, and feedback
100 among the risk based criteria and sub-criteria. Hesamamiri et al. developed a systematic framework
101 combining ANP and CFPR to properly assess and select a knowledge management strategy [33].

102 In this paper, CFPR is taken into the decision matrix under D-ANP to find the priority vectors
103 of the criteria for *uncertain* and *incomplete* environments. Thus the main objectives of this research are
104 as follows:

- 105 • Categorise and describe proper risk issues concerning various socio-economic,
106 technical, and geo-political based sectors correlated to construction projects.
- 107 • Develop a logical structure incorporating a D-CFPR based ANP model for risk
108 prioritisation during construction.
- 109 • Identify and prioritise risk response factors in the construction industry based on the D-
110 MABAC methodology.

111 This paper is organised as follows: Section 2 offers an outline of construction projects along with
112 a review of risk assessment in the sector. Section 3 briefly discusses the preliminaries of D-S evidence
113 theory and *D* number theory, along with their properties. In Section 4, algorithmic methodologies of
114 D-CFPR, D-ANP, and D-MABAC are discussed. Section 5 demonstrates the effectiveness of the above
115 methodology by presenting a numerical example on risk prioritisation and responses in the
116 construction sector. A discussion based on sensitivity analysis is given in Section 6. Finally, the
117 conclusions and future direction of the present research are given in Section 7.

118 2. Risks in construction projects

119 2.1. An overview

120 The construction industry in general, as well as individual construction projects, deals with
121 various threats which are called risks. Risk assessment in construction projects has been applied
122 differently from project to project (using various models of risk assessment) to evaluate the risk in
123 certain activities of the project [49]. However, the socio-economic complexity involved in
124 construction events makes it more risk prone, so that there may be negative effects on project
125 sustainability [23]. Due to various complex factors, the construction industry is highly diverse and
126 heterogeneous, experiencing a great deal of dynamic change with global sourcing and increasing
127 price competition [50].

128 To overcome these risks contractors have generally used high mark-ups, but this approach is no
129 longer effective as their margins have become smaller [51]. In recent decades, the stages involved in
130 construction projects have become far more complex in nature, due to technological upgrading and
131 stakeholder pressure, and are characterised by a number of uncertainties which have a negative
132 influence on the projects [52]. As risk free construction projects are impossible in real life, a controlled
133 risk assessment procedure is required to manage various risks in the projects. The aim of this study
134 is to highlight the main risks that construction projects face and the risk mitigation strategies used to
135 manage them.

136 2.2 Previous studies on risk assessment in construction projects

137 There have been substantial developments over the last four decades in research related to
138 construction project management. Projects have been considered that are either exposed to risks, or
139 have apparently inherited risk due to the participation of several stakeholders (as owners, contractors
140 and designers); see [53] among others. For classifying and managing risks effectively, many
141 methodologies have been suggested in the literature. In this section, a list of the existing approaches
142 to construction project risk management are now briefly summarised.

143 Wang et al. developed an Alien Eyes' Risk Model, categorising the project risks and their mutual
144 relationships, and proposing a qualitative risk mitigation framework [4]. Schieg adopted a risk
145 management process in construction project management, concentrating more on personal area risks
146 [17]. Zavadskas et al. presented risk assessment based on the MCDM method and applying TOPSIS
147 grey and COPRAS-G [23]. Wen integrated rough sets and artificial neural networks for risk

148 evaluation of construction projects [54]. Fouladgar et al. proposed a risk evaluation outline faced
149 during tunnelling operations based on fuzzy TOPSIS methodology [55]. Taroun and Yang hybridised
150 the Dempster-Shafer (D-S) theory of evidence and evidential reasoning algorithm for structuring
151 personal experience and professional judgment with a spreadsheet-based decision support system
152 [56]. Mohammadi and Tavakolan combined fuzzy logic and AHP in traditional Failure Mode Effect
153 Analysis (FMEA) for construction project risk assessment [25]. Serpella et al. applied a knowledge-
154 based approach, based on a three-fold arrangement and risk management function, to address project
155 risks in the construction management sector [18]. Ebrat and Ghodsi identified the risks in
156 construction projects based on the adaptive neuro fuzzy inference system and stepwise regression
157 model for the evaluation of project risks [14]. Taylan et al. proposed hybrid methodologies combining
158 fuzzy AHP and fuzzy TOPSIS and applied the relative importance index method to prioritise the
159 project risks based on the data obtained [15]. Iqbal et al. considered two types of risk management
160 technique during project execution, viz. preventive techniques (to manage risk before the start of the
161 project) and remedial techniques (after occurrence of the risk) [9]. Vafadarnikjoo et al. developed an
162 intuitive fuzzy decision making trial and evaluation laboratory (DEMATEL) to prioritise risks
163 associated with construction projects by using the risk breakdown structure [24]. Ahmadi et al.
164 analysed the criteria for prioritising potential risk events and quantified it using fuzzy AHP [27]. The
165 best response action for a risk event is then identified with respect to the same criteria using a scope
166 expected deviation index. Santos and Jungles evaluates the completion of construction project risk
167 by considering the correlation of delay and the schedule performance index along with any time over-
168 run [19]. Shin et al. made a comparative analysis of AHP and fuzzy AHP to evaluate the potential
169 risk factors at the construction site of a nuclear power plant [28]. Kao et al. proposed an integrated
170 fuzzy ANP based balanced scorecard system for evaluation of relevant bilateral factors in Taiwanese
171 construction projects [57]. Burcar Dunovic et al. assessed large infrastructure projects by integrating
172 the risk impact cumulative distribution curve based MCDM approach [58]. Yousefi et al. proposed a
173 neural network model for predicting emerging time and cost claims applied to Iranian construction
174 projects [59]. Valipour et al. presented a fuzzy cybernetic ANP model for proper identification of
175 public-private partnership project based risks [60]. Ulubeyli and Kazaz developed a fuzzy based sub-
176 contractor selection model (CoSMo) for global based construction projects [61]. Rajakallio et al.
177 analysed the solution delivery from a network perspective in integrated business model renewal. For
178 assessing risk in deep foundation excavation [62], Valipour et al. developed a SWARA-COPRAS
179 framework to analyse Iranian construction project uncertainty [63]. Khanzadi et al. solved the dispute
180 resolution problem in the construction sector by considering a grey number based discrete zero-sum
181 two-person matrix game model [64]. Keshavarz Ghorabae et al. presented the hybrid fuzzy SWARA-
182 EDAS model for assessment of the construction equipment by taking sustainability into account [65].

183 3. Preliminaries

184 3.1. Dempster-Shafer (D-S) evidence theory

185 To deal with real world information, which may be ambiguous, various imprecise decision
186 making models based on probability theory, fuzzy set theory, and (D-S) evidence theory have been
187 developed [66]. D-S evidence theory directly express uncertain information by allocating the
188 probability to the multiple object based subsets in lieu of individual items [67]. Due to its ability to
189 compare pairs of evidence or belief functions when deriving new ones, and its superiority in an
190 uncertain environment, evidence theory has been widely applied in various domains [22, 34, 39,
191 68–70].

192 Certain basic definitions are now presented. Let U denote the frame of discernment representing
193 a collective set of exhaustive and mutually exclusive events, and each element of 2^U (a power set in
194 U) represents a proposition [22]. Based on these, basic probability assignment (BPA) is defined as
195 follows:

196 *Definition: Basic probability assignment (BPA)*

197 A finite non-empty set of mutually exclusive and exhaustive hypotheses for any problem
 198 domain is called *its frame of discernment*. In lieu of a D-S evidence framework, the BPA is defined on
 199 a frame of discernment to express the imprecise judgements of experts [39]. Thus, if 2^U denotes the
 200 power set of a finite non-empty set U then a BPA is defined as a mapping m satisfying (1) and (2):

$$m : 2^U \rightarrow [0,1], \quad (1)$$

$$m(\emptyset) = 0 \text{ and } \sum_{A \in 2^U} m(A) = 1 \quad (2)$$

201 where \emptyset is an empty set and A is any element of 2^U . If $m(A) > 0$, A is called its *focal element*, and
 202 the union of all focal elements is the core of the mass function.

203 *Example:* Suppose there exists a task to assess a project. In the frame of D-S theory, the frame of
 204 discernment is the proposed project set $B = \{b_1, b_2, b_3\}$.

205 As per the expert view, a BPA can be created to express their assessment result:
 206 $m(\{b_1\}) = 0.2$; $m(\{b_2\}) = 0.7$; $m(\{b_2, b_3\}) = 0.1$ where $b_1 = [0, 40]$, $b_2 = [41, 70]$, $b_3 = [71, 100]$. Also,
 207 the set $B = \{b_1, b_2, b_3\}$ is a frame of discernment in D-S theory with
 208 $m(\{b_1\}) + m(\{b_2\}) + m(\{b_2, b_3\}) = 1$.

209 3.2. *D number theory*

210 Although D-S evidence theory is operative in the data fusion problem, it is restricted to handling
 211 semantic information where linguistic variables are not mutually exclusive [39, 70]. Intuitively, if
 212 some hypotheses of D-S theory is removed reasonably, the ability to represent and handle uncertain
 213 information may greatly improve. Overall, in many practical scenarios, the experts fail to have
 214 complete information, and the assessment is done solely on the basis of partial information, resulting
 215 in an incomplete BPA. Based on this idea, Deng proposed *D numbers theory*, a generalisation of
 216 evidence theory, in order to characterise ambiguous data, as defined in (3) and (4) below [36]:

217 *Definition: D number* [36]

218 Let Ω be a finite nonempty set, *D number* is defined by a mapping:

$$D : \Omega \rightarrow [0,1], \quad (3)$$

$$\text{with } \sum_{B \subseteq \Omega} D(B) \leq 1 \text{ and } D(\emptyset) = 0 \quad (4)$$

219 where \emptyset is an empty set and B is a subset of Ω .

220 Compared with D-S evidence theory, the *D number's* concept has the advantages that [39, 34,
 221 42, 71]:

- 222 • *Firstly*, *D number's* with *nonexclusive hypothesis* in each element of the frame of
 223 discernment is more applicable for linguistic assessment.
- 224 • *Secondly*, for an evidence theory, a normal BPA must be *complete*, implying that the sum
 225 of all focal length elements in BPA is 1. *D number's* allows the experts to input *incomplete*
 226 *and uncertain information* to the framework resulting in an incomplete BPA, thus
 227 releasing the completeness constraint. Thus, if $\sum_{B \subseteq \Omega} D(B) = 1$, the information is said to be

228 complete, and for $\sum_{B \subseteq \Omega} D(B) < 1$, the information is said to be incomplete.

229 *Example:* Let an expert give their assessment on the condition of a bridge, using *D numbers*, in a scale
 230 interval of [0,100]. The expert gives a BPA to express their assessment as follows:

$$231 \quad D(\{a_1\}) = 0.5; \quad D(\{a_2\}) = 0.3; \quad D(\{a_1, a_2, a_3\}) = 0.1$$

232 where, $a_1 = [0, 60]$, $a_2 = [45, 75]$, and $a_3 = [65, 100]$.

233 Hence the set of $\{a_1, a_2, a_3\}$ is not a frame of discernment, because the elements in the above set
 234 are not mutually exclusive. Also, since $D(\{a_1\}) + D(\{a_2\}) + D(\{a_1, a_2, a_3\}) = 0.9 < 1$, the above
 235 information is incomplete. This example shows that the definition of D number is similar to the
 236 definition of the mass function.

237 *Definition: D numbers for a discrete set* [36]

238 For a discrete set $\Omega = \{b_1, b_2, \dots, b_i, \dots, b_n\}$, where $b_i \in R$ and $b_i \neq b_j$ ($i \neq j$), a special form of
 239 D numbers can be expressed as:

$$\left\{ \begin{array}{l} D(\{b_i\}) = v_i \quad (i = 1, 2, \dots, n) \\ \text{or denoted as,} \\ D = \{(b_1, v_1), (b_2, v_2), \dots, (b_i, v_i), \dots, (b_n, v_n)\}, \\ \text{where } v_i > 0 \text{ and } \sum_{i=1}^n v_i \leq 1. \end{array} \right. \quad (5)$$

240 *Definition: Permutation invariability* [22, 71].

241 Two D numbers $D_1 = \{(b_1, v_1), \dots, (b_i, v_i), \dots, (b_n, v_n)\}$ & $D_2 = \{(b_n, v_n), \dots, (b_i, v_i), \dots, (b_1, v_1)\}$

242 are said to be invariable if:

$$D_1 \Leftrightarrow D_2 \quad (6)$$

243 *Example:* If there are two D numbers:

244 $D_1 = \{(0.0, 0.7), (1.0, 0.3)\}$ and $D_2 = \{(1.0, 0.3), (0.0, 0.7)\}$, then, $D_1 \Leftrightarrow D_2$

245 *Definition: D numbers integration* [6, 36].

246 Let $D = \{(b_1, v_1), (b_2, v_2), \dots, (b_i, v_i), \dots, (b_n, v_n)\}$ be a D number, then the integration

247 representation $I(D)$ of the D number is defined as:

$$I(D) = \sum_{i=1}^n b_i v_i \quad (7)$$

248 *Example:* Let $D = \{(1, 0.3), (2, 0.4), (3, 0.1), (4, 0.2), (5, 0.2)\}$, then

249 $I(D) = 1 \times 0.3 + 2 \times 0.4 + 3 \times 0.1 + 4 \times 0.2 + 5 \times 0.2 = 3.2$

250 4. Methodology

251 4.1. D-CFPR: D numbers extended CFPR

252 Based on the additive transitive property, put forward the consistent fuzzy preference relation
 253 (CFPR) for structuring a $n \times n$ decision matrix [30], which requires only $(n-1)$ pair wise
 254 comparisons. Preserving both the reciprocity and transitivity properties, CFPR is constructed only on
 255 complete and certain information, but fails to deal with cases containing insufficient information [34,
 256 36]. Citing the same deficiency as in the case of fuzzy preference relations, Deng et al. proposed the
 257 concept of a D numbers preference relation encompassing the fuzzy preference relations of the D
 258 numbers domain [39]. Also, considering the insufficiency in traditional CFPRs, Zuo et al. proposed a
 259 D number consistent fuzzy preference relation matrix, abbreviated as D-CFPR matrix. In the

260 following steps, we will discuss the algorithmic methodology of D-CFPR, where distribution
261 assessments are assessed under incomplete or missing information [42].

262 *Step 1: Construct a D-CFPR matrix (R_D).* The D number extended CFPR is advocated to reinforce the
263 capability of CFPR to express uncertain and incomplete information. A D number based preference
264 relation on a set of criteria $C = \{C_1, C_2, \dots, C_n\}$ is characterised by a $n \times n$ matrix $R_D = [D_{ij}]_{n \times n}$ on the
265 product set $C \times C$, whose elements are formulated as per Eqn. (8), and represented in matrix form (9).
266 $R_D: C \times C \rightarrow D$

$$R_D: C \times C \rightarrow D, \quad (8)$$

$$R_D = \begin{matrix} & C_1 & C_2 & \dots & C_n \\ \begin{matrix} C_1 \\ C_2 \\ \vdots \\ C_n \end{matrix} & \begin{bmatrix} D_{11} & D_{12} & \dots & D_{1n} \\ D_{21} & D_{22} & \dots & D_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ D_{n1} & D_{n2} & \dots & D_{nn} \end{bmatrix} \end{matrix}, \quad (9)$$

267 where, $D_{ij} = \{(b_{ij}^1, v_{ij}^1), (b_{ij}^2, v_{ij}^2), \dots, (b_{ij}^p, v_{ij}^p), \dots\}$, $D_{ji} = \neg D_{ij} = \{(1 - b_{ij}^1, v_{ij}^1), (1 - b_{ij}^2, v_{ij}^2), \dots, (1 - b_{ij}^p, v_{ij}^p), \dots\}$,
268 $\forall i, j \in \{1, 2, \dots, n\}$, $b_{ij}^p \in [0, 1]$, $v_{ij}^p > 0$, $\sum_p v_{ij}^p = 1$.

269 Obviously, $D_{ii} = \{(0.5, 1.0)\} \forall i \in \{1, 2, \dots, n\}$ in R_D .

270 In Eqn. (9), is R_D called a D-CFPR as it is constructed based on $(n-1)$ pair wise comparisons,
271 denoted as $\{D_{12}, D_{23}, \dots, D_{(n-1)n}\}$ representing a set of D numbers. Considering the set
272 $B = \{D_{ji}, 1 \leq i < j \leq n\}$, the elements of which are denoted $D_{ji} = \{(b_{ji}^1, v_{ji}^1), (b_{ji}^2, v_{ji}^2), \dots, (b_{ji}^k, v_{ji}^k), \dots\}$, can
273 also be represented as follows:

$$274 \quad D_{ji} = \frac{j-i+1}{2} - D_{i(i+1)} - D_{(i+1)(i+2)} - \dots - D_{(j-1)j}$$

275 where every component (b_{ji}^k, v_{ji}^k) is obtained by:

$$\left. \begin{aligned} b_{ji}^k &= \frac{j-i+1}{2} - b_{i(i+1)}^x - b_{(i+1)(i+2)}^y - \dots - b_{(j-1)j}^k, \forall (x, y, \dots, z) \\ v_{ji}^k &= \sum_{(x, y, \dots, z) \in \Omega} v_{i(i+1)}^x \times v_{(i+1)(i+2)}^y \times \dots \times v_{(j-1)j}^z \end{aligned} \right\}, \quad (10)$$

276 where $\Omega = \left\{ (x, y, \dots, z) \mid b_{ji}^k = \frac{j-i+1}{2} - b_{i(i+1)}^x - b_{(i+1)(i+2)}^y - \dots - b_{(j-1)j}^k \right\}$, $(b_{i(i+1)}^x, v_{i(i+1)}^x)$ is the x^{th}
277 component of $D_{i(i+1)}$, $(b_{(i+1)(i+2)}^y, v_{(i+1)(i+2)}^y)$ is the y^{th} component of $D_{(i+1)(i+2)}$, $(b_{(j-1)j}^z, v_{(j-1)j}^z)$ is the
278 z^{th} component of $D_{(j-1)j}$

279 Thus, based on the reciprocal property, the rest of the entries in D-CFPR (9) are calculated as per
280 Eqn. (11) as follows:

$$D_{ji} = \neg D_{ij}, \forall i, j \in \{1, 2, \dots, n\}. \quad (11)$$

281 As per Eqns. (9)–(11), a D-CFPR can be constructed based on $(n-1)$ pair wise comparisons
282 $\{D_{12}, D_{23}, \dots, D_{(n-1)n}\}$. In the D-CFPR generated above, some values of the b_{ij} 's in
283 D_{ij} , $i, j \in (1, 2, \dots, n)$ that fall in the interval $[-a, 1+a]$, $a > 0$, need to be transformed using Eqn.
284 (12):

$$f: [-a, 1+a] \rightarrow [0, 1], \quad f(r) = \frac{r+a}{1+2a}, \quad (12)$$

285 The transformation function (12) works as a normalisation, which transforms the values of b_{ij} 's
286 from $[-a, 1+a]$ to the interval $[0, 1]$.

287 *Step 2: Determine the crisp matrix R_c .* Convert the matrix $R_D = [D_{ij}]_{n \times n}$ in (9) to a *crisp matrix*
288 $R_c = [c_{ij}]_{n \times n}$ (13) using the integration representation of D numbers [as per Eqn. (7)], where each
289 element $c_{ij} = I(D_{ij})$ $i, j = 1, 2, \dots, n$.

$$R_c = [c_{ij}]_{n \times n} = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{nn} \end{bmatrix}, \quad (13)$$

290 *Step 3: Construct a probability matrix R_p .* Based on the crisp matrix R_c (13), construct a probability
291 matrix $R_p = [p_{ij}]_{n \times n}$ (14), representing the preference probability between a pair wise set of n criteria

292 $C = \{C_1, C_2, \dots, C_n\}$:

$$R_p = [p_{ij}]_{n \times n} = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix}, \quad (14)$$

293 In R_p , the element $p_{ij} = \Pr(C_i \succ C_j), \forall i, j \in \{1, 2, \dots, n\}$, where " \succ " represents "prefer to". Based
294 on (13), a set of rules is suggested to generate R_p .

- 295 • For the elements satisfying $c_{ij} + c_{ji} = 1.0$,
 - 296 ○ If $c_{ij} > 0.5$, then $\Pr(C_i \succ C_j) = 1$ and $\Pr(C_i \prec C_j) = 0$,
 - 297 ○ If $c_{ij} \leq 0.5$, then $\Pr(C_j \succ C_i) = 1$ and $\Pr(C_i \succ C_j) = 0$.
- 298 • When $c_{ij} + c_{ji} > 1.0$: $c_{ij} \geq 0.5$ and $c_{ji} \geq 0.5$,
 - 299 ○ If $c_{ij} \geq 0.5$, then $\Pr(C_i \succ C_j) = 1$ and $\Pr(C_j \succ C_i) = 0$,
 - 300 ○ If $c_{ji} \geq 0.5$, then $\Pr(C_j \succ C_i) = 1$ and $\Pr(C_i \succ C_j) = 0$.
- 301 • When $c_{ij} + c_{ji} < 1.0$: $c_{ij} < 0.5$ and $c_{ji} < 0.5$,

302 In this condition, the unallocated preference (*up*) is $c_{up} = 1 - (c_{ij} + c_{ji})$. The probability of one
303 criteria outperforming another criteria is as follows:

- 304 ○ If $c_{ij} < 0.5$, then $\Pr(C_i \succ C_j) = 1 - \frac{(0.5 - c_{ij})}{c_{up}}$,
- 305 ○ If $c_{ji} < 0.5$, then $\Pr(C_j \succ C_i) = 1 - \frac{(0.5 - c_{ji})}{c_{up}}$.

306 *Step 4: Construct a triangular probability matrix R_p^T .* Rank the criteria using the triangularisation
307 procedure, viz. by maximising the sum of the values above, the main diagonal in the $n \times n$ square
308 matrix in the final order is given as:

- 309 • First, sum up of each row of the $n \times n$ matrix and determine the row number with
310 maximum value.

- 311 • Then, assuming the obtained row number is k , delete the k -th row and k -th column in
 312 the matrix.
 313 • Replicate the above two procedures until the matrix is empty.

314 Thus, by applying this defined row deletion order operation on the matrix $R_p = [p_{ij}]_{n \times n}$ (14),

315 construct the triangular probability matrix R_p^T , shown in (15):

$$R_p^T = [p_{ij}^T]_{n \times n} = \begin{bmatrix} p_{11}^T & p_{12}^T & \cdots & p_{1n}^T \\ p_{21}^T & p_{22}^T & \cdots & p_{2n}^T \\ \vdots & \vdots & \ddots & \vdots \\ p_{n1}^T & p_{n2}^T & \cdots & p_{nn}^T \end{bmatrix}, \quad (15)$$

316 *Step 5: Construct triangulated crisp matrix R_c^T .* Firstly, the crisp matrix R_c (13) is triangulated based on
 317 the triangular matrix R_p^T (15). From that step, the triangulated crisp matrix R_c^T (16) is derived:

$$R_c^T = [c_{ij}^T]_{n \times n} = \begin{bmatrix} c_{11}^T & c_{12}^T & \cdots & c_{1n}^T \\ c_{21}^T & c_{22}^T & \cdots & c_{2n}^T \\ \vdots & \vdots & \ddots & \vdots \\ c_{n1}^T & c_{n2}^T & \cdots & c_{nn}^T \end{bmatrix}, \quad (16)$$

318 Secondly, for elements satisfying $R_c^T(i, j) + R_c^T(j, i) < 1$, a new "polishing operation" (17) is
 319 implemented to obtain a triangulated crisp matrix R_k^T (18):

$$R_k^T(i, j) = R_c^T(i, j) + \frac{1 - [R_c^T(i, j) + R_c^T(j, i)]}{2}, \quad (17)$$

$$R_k^T = [k_{ij}^T]_{n \times n} = \begin{bmatrix} k_{11}^T & k_{12}^T & \cdots & k_{1n}^T \\ k_{21}^T & k_{22}^T & \cdots & k_{2n}^T \\ \vdots & \vdots & \ddots & \vdots \\ k_{n1}^T & k_{n2}^T & \cdots & k_{nn}^T \end{bmatrix}, \quad (18)$$

320 *Step 6: Calculate the relative priority weights of the criteria.* Assume that the weight vector is $W = (w_i)^T$,
 321 where $w_i (i=1, 2, \dots, n)$ are the weights of criteria $C_i (i=1, 2, \dots, n)$. The elements above and alongside the
 322 main diagonal of the matrix $R_k^T = [k_{ij}^T]_{n \times n}$ (18), indicate the weight relationship of the criteria. Thus,
 323 by adding some necessary constraints, a set of equations (19) is formed:

$$\begin{cases} \lambda(w_2 - w_1) = k_{22}^T - k_{12}^T \\ \lambda(w_3 - w_2) = k_{33}^T - k_{23}^T \\ \dots & \dots & \dots \\ \lambda(w_n - w_{n-1}) = k_{nn}^T - k_{(n-1)n}^T \end{cases}, \quad (19)$$

324 where λ indicates the *granular information* about the pair wise comparison, which reveals the
 325 expert's perceptive competency. The value of each weight $w_i (i=1, 2, \dots, n)$, subjected to the
 326 parameter λ , relates to the expert's cognitive aptitude. The values of λ highly depend on the
 327 influence of the experts' judgment and belief function. Thus, a feasible outline (20) is obtained as
 328 follows:

$$\lambda = \begin{cases} \lceil \frac{n}{2} \rceil, & \text{The information has high credibility} \\ n, & \text{The information has medium credibility} \\ \frac{n^2}{2}, & \text{The information has low credibility} \end{cases} \quad (20)$$

329 where $\underline{\lambda}$ signifies the lower bound of λ , $\lceil \underline{\lambda} \rceil = \min\{k \in \mathbb{Z} | k \geq \underline{\lambda}\}$, and n is the number of
 330 alternatives. The concrete priority weight value of each criteria is calculated here when $\lambda = n$.

331 *Step 7: Inconsistency for the D-CFPR.* The traditional CFPR is fully consistent when constructed
 332 under the transitivity property for $n-1$ preference values. The D number based CFPR is *consistent*,
 333 but when reduced to classical CFPR it shows inconsistency under *uncertain or incomplete* information.
 334 Thus, to express this inconsistency of D-CFPRs, an inconsistency degree (ID) (21) is defined, based
 335 on the triangular probability matrix R_p^T (18), as follows:

$$I.D. = \frac{\sum_{i=1, j < i}^n R_p^T(i, j)}{n(n-1)/2}, \quad (21)$$

336 here, $R_p^T(i, j)$ is an element of R_p^T , and n is the number of comparison objects. This emphasises that
 337 the inconsistency of the D matrix, and its acceptable level, is decided by the DMs, whose subjective
 338 requirement regulate the tolerance level of the aforementioned inconsistency.

339 4.2. Evaluating the risk criteria weight using D-ANP

340 The evaluation of D-ANP methodology is composed of two phases.

341 The first phase emphasises the formation of pairwise judgments for every dependent
 342 relationship among given criteria $C_i (i=1, 2, \dots, n)$, and determination of their priority weight. The
 343 priority weights thus obtained are input to the system-with-feedback supermatrix for computing the
 344 network influences amongst the different relationships.

345 The second phase, namely supermatrix evaluation, incorporates five steps: formation of the
 346 unweighted supermatrix, formation of the weighted supermatrix, normalisation of the weighted
 347 supermatrix (a column stochastic matrix), and finally convergence to a solution using the limited
 348 supermatrix.

349 The converged supermatrix will provide us with the relative priorities for each of the criteria (or
 350 *sub-criteria*) considered within clusters of the decision framework. Thus the following algorithmic
 351 steps of D-ANP are as follows:

352 *Step 1: Model construction and problem structuring.* First, we properly outline the decision problem
 353 with detailed criteria and sub-criteria (if taken) and then delimit the cluster's (*dimension's*) network
 354 and elements (*criteria set*) within the given clusters. Next, we decide which inter- and inner-
 355 dependencies will prevail in the decision problem and clusters of the over-all feedback system.

356 *Step 2: Pairwise comparison matrices and priority vectors.* The expert inputs prerequisite for the ANP
 357 method are the pairwise judgments of the elements within each cluster, from which inter-and-inner-
 358 dependence matrices are formed. Primarily three categories of pairwise comparisons are formed.
 359 First, the inner dependence comparison matrix, based on the criteria of different clusters
 360 (dimensions), is used to get the priority weight vector. Then, the pairwise comparison matrices
 361 obtained from criteria with respect to other factors (criteria) of the same cluster (dimension). Finally,
 362 the pairwise comparison matrix is developed by considering the factor (criteria) of a cluster
 363 (dimension) among factors (criteria) of the other cluster (dimension), which affect the criteria.

364 These pairwise comparison matrices, along with their valuation elicitation, constitute a modified
 365 version of D-AHP [22] and D-CFPR [34]. Based on Section 4.1, a brief summary for getting the priority
 366 weight of any pairwise comparison matrix is given below, the graphical description of which is
 367 shown in Figure 1.

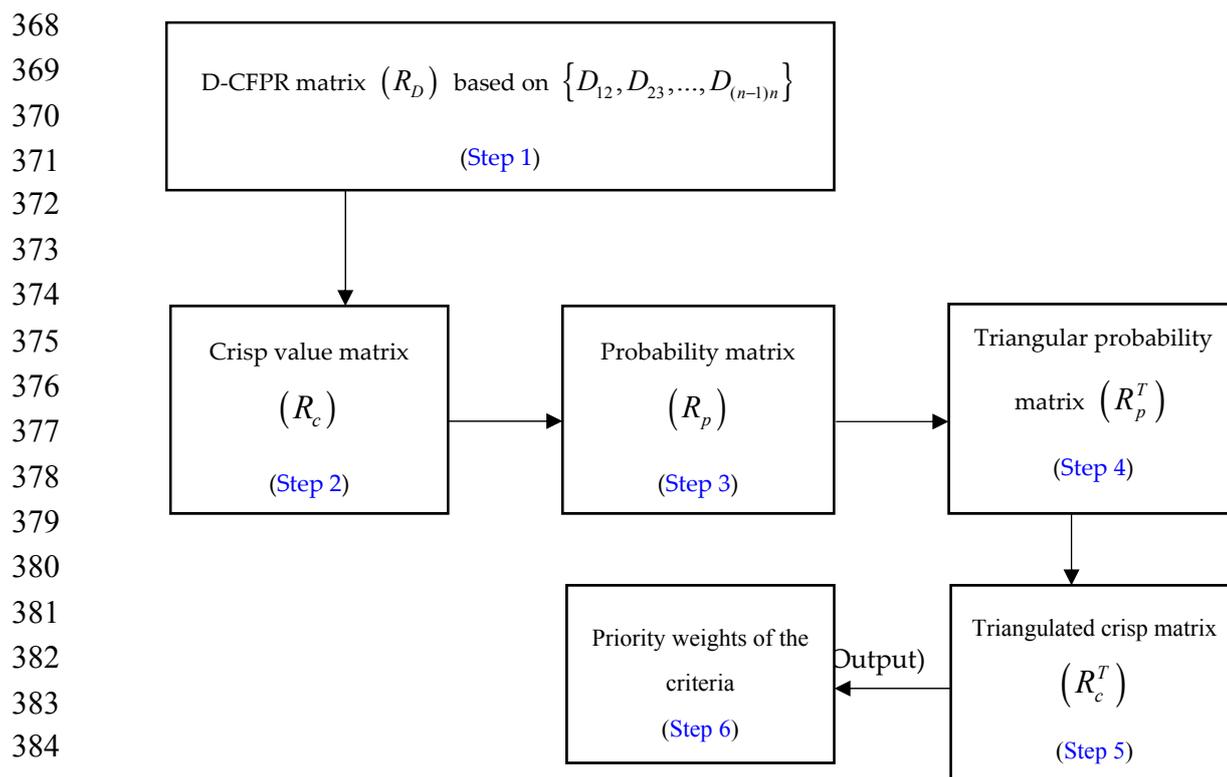


Figure 1. Procedure to obtain priority weights of criteria based on D-CFPR.

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- In the first step, the D-CFPR matrix $R_D = [D_{ij}]_{n \times n}$, is constructed for n criteria, by considering the system as an input using Eqns. (9)–(12).
 - The D-CFPR matrix formed (R_D), is converted to a crisp matrix $R_c = [c_{ij}]_{n \times n}$, using the integration representation of D number, shown in Eqn. (13).
 - The probability matrix $R_p = [p_{ij}]_{n \times n}$ is then constructed based on the derived crisp matrix (R_c) using Eqn. (14), and it satisfies a set of rules in Step 3 of Section 4.1.
 - In the next step, using Eqn. (15), triangularisation $R_p^T = [p_{ij}^T]_{n \times n}$ is applied to the probability matrix using local information that contains the preference relations of pairwise criteria.
 - Lastly, applying Eqns. (16)–(19), the crisp based triangular matrix $R_c^T = [c_{ij}^T]_{n \times n}$, is obtained, and relative priority weights $w_i (i = 1, 2, \dots, n)$ of each criteria $C_i (i = 1, 2, \dots, n)$, based on clusters (*dimensions*) are calculated, thereby checking its inconsistency as per Eqn. (21).

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Step 3: Formation of the unweighted supermatrix. The local priority weights resulting from the pairwise comparison are used as input in suitable columns of the unweighted constructed supermatrix, to obtain the global priorities in a system. As a result, a supermatrix takes the form of a partitioned matrix, each segment of which represents an association between two clusters in the given system. Thus, the supermatrix W [Eqn. (22)] formed is represented by sub-matrices W^{ij} as $W = [W^{ij}]_{n \times n} (i, j = 1, 2, \dots, n)$. The size of the sub-matrix W^{ij} [Eqn. (23)] depends on the compared factors (criteria). Interdependency between clusters is illustrated in Eqn. (22) by analysing both inter- and intra-relations among clusters.

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Arrange all priority vectors, representing the impact of a given set of elements in a cluster on another element in the network, as sub-columns of the corresponding column of an unweighted

410 supermatrix W as in Eqns. (22)–(23). This is composed of k clusters $\{D_1, D_2, \dots, D_k\}$, and linkages of
 411 these clusters $\{e_{k1}, e_{k2}, \dots, e_{kn_k}\}$, are elements of the cluster D_p ($p = 1, 2, \dots, k$). Each column of the sub-
 412 matrix W^{ij} [Eqn. (23)] is the priority vector acquired from the identical pairwise judgment,
 413 indicating the significance of the elements in the i^{th} cluster with respect to an element in the j^{th}
 414 cluster.

$$W = \begin{matrix} & \begin{matrix} D_1 & D_2 & \dots & D_k \\ e_{11}e_{12}\dots e_{1(n_1)} & e_{21}e_{22}\dots e_{2(n_2)} & \dots & e_{k1}e_{k2}\dots e_{k(n_k)} \end{matrix} \\ \begin{matrix} D_1 \\ \vdots \\ D_2 \\ \vdots \\ D_k \end{matrix} & \begin{bmatrix} W^{11} & W^{12} & \dots & W^{1k} \\ W^{21} & W^{22} & \dots & W^{2k} \\ \vdots & \vdots & \ddots & \vdots \\ W^{k1} & W^{k2} & \dots & W^{kk} \end{bmatrix} \end{matrix} \quad \text{where } \sum_{j=1}^k (n_j) = n \quad (22)$$

$$W^{ij} = \begin{bmatrix} W_{11}^{ij} & \dots & W_{1j}^{ij} & \dots & W_{1n_j}^{ij} \\ \vdots & & \vdots & & \vdots \\ W_{i1}^{ij} & \dots & W_{ij}^{ij} & \dots & W_{in_j}^{ij} \\ \vdots & & \vdots & & \vdots \\ W_{n_i1}^{ij} & \dots & W_{n_ij}^{ij} & \dots & W_{n_in_j}^{ij} \end{bmatrix} \quad i, j = 1, 2, \dots, k' \quad (23)$$

415 *Step 4: Determine the normalised weighted supermatrix.* If there is no linkage between clusters D_k
 416 and D_l , then the sub-matrix W^{kl} equals zero. We compute the weighted supermatrix $W^a = [\tilde{W}^{ij}]_{n \times n}$,
 417 by multiplying the unweighted matrix $W = [W^{ij}]_{n \times n}$, [(Eqn. (23))] by priority of dimensions
 418 V_j ($j = 1, 2, \dots, n$), in this stage. As the weighted supermatrix (W^a) needs to be stochastic, we normalise
 419 each column of it, and develop meaningful limiting priorities for determining overall cluster
 420 influences. This normalisation procedure ensures that the weighted supermatrix is column stochastic;
 421 it is finally represented by matrix $\hat{W} = [\hat{W}^{ij}]_{n \times n}$.

422 *Step 5: Compute the limiting priorities for criteria weights.* Finally, the column stochastic weighted
 423 supermatrix is raised to an appropriately large power until it converges. Thus, the weighted
 424 supermatrix \hat{W} , is raised to limiting powers $(\hat{W})^{2m+1}$, m being an arbitrarily large number, to attain
 425 a steady-state limiting matrix W^q . Details are shown in Eqn. (24):

$$W^q = \lim_{k \rightarrow \infty} (\hat{W})^{2m+1}, \quad (24)$$

426 The priority weight of criteria for the corresponding clusters (dimensions) can now be found in
 427 the rows of the limiting supermatrix W^q . The limiting supermatrix provides the priority information
 428 for the elements of each individual cluster. The strategy outcome with the highest value should be
 429 selected from the cluster of criteria. Other priority rankings in different clusters are also provided.

430 4.3. D-MABAC for ranking alternatives

431 The MABAC methodology was developed by Pamucar and Cirovic to handle problems in
 432 MCDM [44]. D numbers is a new representation of uncertain information that can denote the more
 433 imprecise based conditions. So, the combination of MABAC and D number is a new experiment to
 434 make decisions in an uncertain environment. The basic setting of the MABAC technique is revealed

435 in the definition of the distance of the criterion function of each of the observed alternatives from the
 436 approximate border area [72]. The algorithmic steps displays the execution process for the aforesaid
 437 D-MABAC methodology in six steps as follows:

438 *Step 1: Constructing the initial decision matrix M .* Initially, the assessment of m alternatives in
 439 respect of n criteria is carried out. The alternatives are represented in vector form
 440 $A_i = (d_{i1}, d_{i2}, \dots, d_{in})$, where d_{ij} ($j=1, 2, \dots, n$) denotes the value (in D numbers format) for the i
 441 alternative ($i=1, 2, \dots, m$) according to j criteria for matrix $M = [d_{ij}]_{m \times n}$. Details shown in decision-
 442 matrix (25).

$$M = \begin{bmatrix} d_1(\{1\}) = d_{11} & d_1(\{2\}) = d_{12} & \cdots & d_1(\{n\}) = d_{1n} \\ d_2(\{1\}) = d_{21} & d_2(\{2\}) = d_{22} & \cdots & d_2(\{n\}) = d_{2n} \\ \cdots & \cdots & \ddots & \cdots \\ d_m(\{1\}) = d_{m1} & d_m(\{2\}) = d_{m2} & \cdots & d_m(\{n\}) = d_{mn} \end{bmatrix}, \quad (25)$$

443 Next applying Eqn. (8), (i.e. integration representation of D numbers) on the elements d_{ij}
 444 ($i=1, 2, \dots, m; j=1, 2, \dots, n$) of decision matrix $M = [d_{ij}]_{m \times n}$, crisp decision matrix $X = [I(d_{ij})]_{m \times n}$ is
 445 formed as per Eqn. (26) as follows:

$$X = \begin{bmatrix} I(d_{11}) & I(d_{12}) & \cdots & I(d_{1n}) \\ I(d_{21}) & I(d_{22}) & \cdots & I(d_{2n}) \\ \cdots & \cdots & \ddots & \cdots \\ I(d_{m1}) & I(d_{m2}) & \cdots & I(d_{mn}) \end{bmatrix}_{m \times n} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \ddots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}_{m \times n} \quad \text{where } x_{ij} = I(d_{ij}), \quad (26)$$

446 *Step 2. Normalisation of the elements of the initial matrix X .* The elements of the normalised matrix
 447 $N = [t_{ij}]_{m \times n}$, are obtained using the following expressions:

$$N = \begin{bmatrix} t_{11} & t_{12} & \cdots & t_{1n} \\ t_{21} & t_{22} & \cdots & t_{2n} \\ \cdots & \cdots & \ddots & \cdots \\ t_{m1} & t_{m2} & \cdots & t_{mn} \end{bmatrix}, \quad \text{where} \quad (27)$$

$$t_{ij} = \begin{cases} \frac{x_{ij} - x_i^-}{x_i^+ - x_i^-}, & \text{for "benefit type" criteria} \\ \frac{x_i^+ - x_{ij}}{x_i^+ - x_i^-}, & \text{for "cost type" criteria} \end{cases}, \quad (28)$$

448 where $x_{ij} = I(d_{ij})$ and the components $x_i^+ = \max(x_1, x_2, \dots, x_m)$, $x_i^- = \min(x_1, x_2, \dots, x_m)$ of the decision
 449 matrix (X) represent the maximum and minimum values of the criteria C_j ($j=1, 2, \dots, n$), by
 450 alternatives A_i ($i=1, 2, \dots, m$).

451 *Step 3. Calculation of the elements of weighted matrix (V).* The elements of the weighted matrix
 452 $V = [v_{ij}]_{m \times n}$, are calculated using the following equations:

$$V = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1n} \\ v_{21} & v_{22} & \cdots & v_{2n} \\ \cdots & \cdots & \ddots & \cdots \\ v_{m1} & v_{m2} & \cdots & v_{mn} \end{bmatrix}, \quad (29)$$

$$v_{ij} = w_j \cdot (t_{ij} + 1), \quad (30)$$

453 where t_{ij} are the elements of the normalised matrix $N = [t_{ij}]_{m \times n}$ and $w_j (j = 1, 2, \dots, n)$ the weight
454 coefficients of criteria, respectively.

455 *Step 4. Determine the approximate border area matrix (G).* The elements of the border approximation
456 area (BAA) for each criterion $C_j (j = 1, 2, \dots, n)$, are determined as follows:

$$g_j = \left(\prod_{i=1}^m v_{ij} \right)^{1/m}, \quad (31)$$

457 where v_{ij} are the elements of the weighted matrix $V = [v_{ij}]_{m \times n}$, and m is the total number of
458 alternatives. After calculating the value $g_j (j = 1, 2, \dots, n)$, for each criterion, the BAA matrix (G) is
459 formed with format $n \times 1$ ($n =$ the total number of criteria, according to which the selection is made
460 from the alternatives).

$$G = [g_1 \ g_2 \ \dots \ g_n]_{1 \times n}^T, \quad (32)$$

461 *Step 5. Calculation of the distance of the alternative from the BAA for the matrix elements (Q).* The distance
462 (q_{ij}) of the alternatives $A_i (i = 1, 2, \dots, m)$ from the BAA matrix $G = [g_1 \ g_2 \ \dots \ g_n]$, is determined as the
463 difference between the elements $v_{ij} (i = 1, 2, \dots, m; j = 1, 2, \dots, n)$ in the weighted matrix $V = [v_{ij}]_{m \times n}$,
464 and the value $g_j (j = 1, 2, \dots, n)$ of the BAA (G). The distance $q_{ij} (i = 1, 2, \dots, m; j = 1, 2, \dots, n)$ are
465 elements of a matrix $Q = [q_{ij}]_{m \times n}$ and are shown in Eqn. (33):

$$Q = \begin{bmatrix} q_{11} & q_{12} & \dots & q_{1n} \\ q_{21} & q_{22} & \dots & q_{2n} \\ \dots & \dots & \ddots & \dots \\ q_{m1} & q_{m2} & \dots & q_{mn} \end{bmatrix} \quad \text{where each } q_{ij} = v_{ij} - g_j, \quad (33)$$

466 Alternative $A_i (i = 1, 2, \dots, m)$ can belong to BAA (G), upper approximation area (G^+), or
467 lower approximation area (G^-), i.e. $A_i \in \{G \vee G^+ \vee G^-\}$ and are determined as per Eqn. (34):

$$A_i \in \begin{cases} G^+ & \text{if } q_{ij} > 0 \\ G & \text{if } q_{ij} = 0 \\ G^- & \text{if } q_{ij} < 0 \end{cases}, \quad (34)$$

468 *Step 6. Ranking of the alternatives.* A calculation of the values of the criterion functions for the
469 alternatives is obtained as the sum of the distance of the alternatives from the BAA (q_{ij}). Using Eqn.
470 (35), we calculate the sum of the elements q_{ij} of matrix (Q) by rows, and obtain the final values of
471 the criterion functions $\hat{S}_i (i = 1, 2, \dots, m)$, for the alternatives $A_i (i = 1, 2, \dots, m)$:

$$\hat{S}_i = \sum_{j=1}^n q_{ij}, \quad i = 1, 2, \dots, m; j = 1, 2, \dots, n, \quad (35)$$

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474 **5. Numerical example: risk assessment in a construction project**475 *5.1. Identification of construction projects risk indicators and their mitigation strategies*

476 For categorising and managing construction project risks effectually, several methodologies are
 477 recommended in the literature [43, 73]. Keeping this in mind, we proposed the hybrid D-ANP-
 478 MABAC approach for the risk assessment of projects in the construction sector involving uncertain
 479 and incomplete information data. The authors employed a combination of questionnaire surveys
 480 involving literature reviews and subjective judgments of highly proficient experts to detect different
 481 risk response strategies that optimise the performance of construction projects. The proposed
 482 methodology incorporates the knowledge and experience of ten experts (five *technical* and five
 483 *management* based experts) for risk identification and structuring, along with proper risk mitigation
 484 strategies. The demographic profile of the respondents is given in Table 1.

485 **Table 1.** Summary of demographic profile of respondents.

Characteristics	Frequency	Percentage (%)
<i>Age group</i>		
21–31	2	20
31–39	4	40
39–45	3	30
45–58	1	10
<i>Gender</i>		
Female	4	40
Male	6	60
<i>Level of Education</i>		
Bachelor's degree	4	40
Master's degree	5	50
Higher	1	10
<i>Role of respondents</i>		
Chief personal officer	1	10
Manager or general manager	2	20
Staff or assistant manager	1	10
Project risks analyst	2	20
Purchasing manager	1	10
Construction site engineer	3	30
<i>Years of experience in construction sector</i>		
Above 15 years	2	20
10 years ~ 15 years	4	40
5 years ~ 10 years	3	30
Less than 5 years	1	10
Total available number	10	

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487 Based on the literature review of papers discussed in Table 2, the DMs consider *nine construction*
 488 *project risk criteria* identified under *three dimensions*: political instability (C₁), economic risk (C₂), and
 489 social risk (C₃). These are defined as environmental based *external risks* (D₁). Technological risk (C₄),
 490 work quality risk (C₅), and time and cost risk (C₆) are defined as construction process based *project*

491 risks (D₂). Resource risk (C₇), documents and information risk (C₈), and stakeholder's risk (C₉) are
 492 defined under intrinsic criteria based *internal risks* (D₃). The details shown in Table 3.

493 **Table 2.** Risk factors involved in construction projects.

Risk indicators in project based construction management	References
Environmental risk; political, social and economic risk; contractual agreement risk; financial risk; construction risk; project design risk; market risk.	[1]
Safety risk, quality risk, environmental risk, political risk, project site risk, project complexity risk.	[53]
Quality risks, personnel risks, cost risks, deadline risks, strategic decision risks, external risks.	[17]
Operational risk, economic risk, political risk, financial risk, legal risk, currency and inflation risk, corruption risk, tendering procedures.	[3]
Political risks, economic risk, social risk, weather risk, cost, quality risk, technical risk, construction risk, resources risk, project member risk, information risk, construction site risks.	[23]
Resources risk, inexperience of project members, lack of motivational approach, design errors risk, efficiency risk, technical risk, quality risk.	[21]
Inflation risk, Payment security risk, Programme overrun risk, subcontractor pricing risk.	[56]
Political risk, economic risk, natural risk, legal risk, contractor risk, financial risk, management risk, equipment risk, designer risk.	[25]
Management risk, project risk, design risk, financial risk, operational risk, external risk.	[14]
Information risk, cost risks, lack of coordination, project schedule risk, lack of professional planning, legal dispute risk.	[15]
Designing risk, time risk, budget risk, labour risk, political risk.	[16]
Design risk, payment delay risk, funding risk, quality risk, labour dispute risks, natural disaster risk, exchange rate fluctuation risk, political instability, site condition risks, insurance inadequacy risk.	[9]
Technical risks, organisational risks, socio-political risks, environmental risks, financial risks.	[6]
Inflation (economic) risk, environmental and geological risk, design risk, construction delay risk, inadequate managerial skills risk, resource risk.	[29]

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Table 3. Dimensions and risk criteria involved in construction projects.

Risk dimension	Risk criteria*	Brief descriptions of causes of the mentioned criteria risks
External risks (D ₁)	Political instability (C ₁)	Frequent changes in government due to disputes among political parties, change in law due to local government's unpredictable new regulations, needless influence by local government on court proceedings regarding project disputes.
	Economic risk (C ₂)	Fluctuation in currency exchange rate, unpredictable inflation due to immature banking systems, payment delays due to poor funding for project, inadequate forecasting about market demand.
	Social risk (C ₃)	Racial tension and differences in work culture and language between foreign and local partners.
Project risk (D ₂)	Technological risk (C ₄)	Risk of insufficient technology, improper design, unexpected design changes; inadequate site investigation; change in construction procedures and insufficient resource availability.
	Work quality risk (C ₅)	Corruption, including bribery, at sites; obsolete technology and practices by the local partner; low local workforce labor productivity due to poor skills or inadequate supervision; improper quality control; local partner tolerance of defects and inferior quality.
	Time and cost risk (C ₆)	Delays due to disputes with contractors, natural disasters, and lack of availability of utilities; risk of labor disputes and strikes; insufficient cash flow, improper measurements, ill planned schedules, and delays in payment; lack of proper benchmarking and monitoring of construction activities.
Internal risks (D ₃)	Resource risk (C ₇)	Difficulty in hiring suitable skilled employees; risk of defective material from suppliers; risk of labor, materials, and equipment availability; poor competence and productivity of labor*.
	Documents and information risk (C ₈)	Intellectual property protection risk from former local employees, partners, and third parties; corporate fraud including unexpected increases in turnover, unexpected resignations of financial advisers, intentional or unintentional negligence by auditors, bankers, or creditors.
	Stakeholder's risk (C ₉)	Local partner's creditworthiness: Information on local partner's accounts lucidity, financial soundness, foreign exchange liquidity, staff reliability. Termination of joint ventures (JV): unfair dividends, e.g., assets, shares, and benefits, to foreign firms by local partner upon termination of JV contract.

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*Sources: [23] [4] [9] [6] [52] [27]

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In past decades, construction businesses were constrained to use only a limited number of risk management procedures, even though they were not suitable for all situations. For example, Lyons and Skitmore found that brainstorming is the most common risk identification technique used in the Queensland engineering construction industry [50]. Forbes et al. developed a matrix for selecting

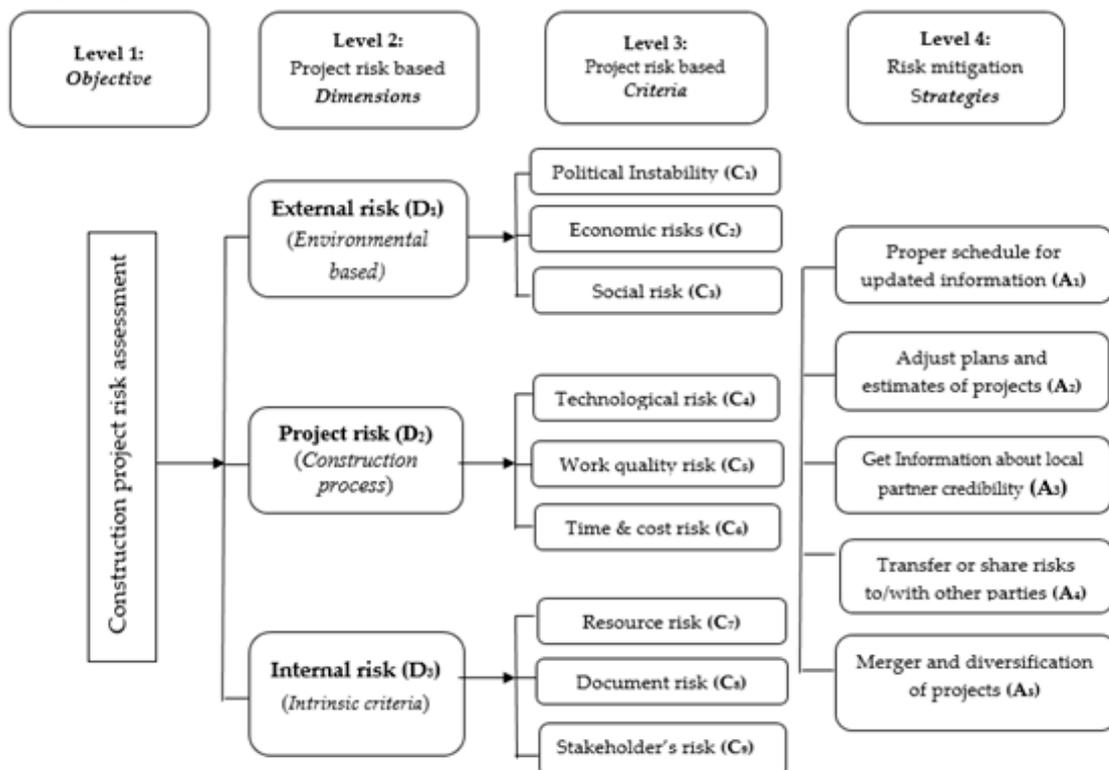
502 appropriate risk management techniques such as artificial intelligence, probabilistic analysis,
 503 sensitivity analysis, and decision trees in the built environment for each stage of risk management
 504 [74]. In this paper, based on the brainstorming method, the experts sought five alternative
 505 construction project risk response mitigation strategies, as detailed in Table 4.

506 **Table 4.** Construction risks response strategies

Alternative(s)	Preventive management techniques	References
A ₁	Proper scheduling for getting updated project information.	[9]
A ₂	Adjust plans for scope of work and estimates to counter risk implications.	[2]
A ₃	Get information about local partner's credibility from present and past business partners.	[4]
A ₄	Transfer or share risks to/with other parties.	[6]
A ₅	Merger and diversification of projects.	[23]

507 5.2. Calculating risk based criteria weight using D-ANP framework

508 In this section, the weights of the risk based criteria in construction projects are calculated by D-
 509 ANP. The ANP has substantial influence in MCDM problems involving a wide range of factors and
 510 sub-factors. In the ANP, a decision problem is transformed into a network structure that allows both
 511 inter-intra dependency and feedback among the decision clusters, and even amongst elements within
 512 the same clusters. In this phase, the decision group is asked to make pairwise comparison matrices
 513 for priority weights of three dimensions and nine criteria (as detailed in Table 3).



514

515

Figure 2. A hierarchical construction project risk breakdown structure

516 Using Steps 1–6 (of Section 4.1) of D-CFPR, the priority weights are calculated in the decision
517 matrices. The algorithmic steps of D-ANP are shown below:

518 *Step 1: Construction of the hierarchy of criteria and alternative risks strategies.* The clearly defined risk
519 based construction project model is decomposed into a logical system like a network. Based on the
520 hierarchy of Figure 2, we have five risk mitigation strategies A_i ($i=1,2,\dots,5$) in Level 4 hierarchical
521 position, three dimensions D_j ($j=1,2,3$) (external, project, and internal risk) in Level 2, and
522 corresponding to each dimension, a total of nine criteria C_j ($j=1,2,\dots,9$) in Level 3.

523 *Step 2: Determination of the pairwise comparison matrices and priority vectors within clusters.* The D
524 numbers based preference matrix is first constructed before calculating the weight of the indicators
525 using the ANP supermatrix. Here, we present the process of determining the priority weight of
526 criteria (C_1, C_2 , and C_3) for risk dimension *external risk* with respect to the criterion C_6 under dimension
527 *Project risk*.

528 *First*, we calculate the relative significance of sub-criteria (C_1, C_2 , and C_3) relative to sub-criterion
529 C_6 , to construct the inner dependence matrix built on the D numbers based preference relation
530 $R_D = [D_{ij}]_{3 \times 3}$. In this case, the preference modelled by a set of D numbers (*based on DM's choice*)
531 involving both *uncertain entry* (i.e., $D_{12} = \{(0.55, 0.7), (0.65, 0.3)\}$) and *incomplete entry*
532 $D_{23} = \{(0.75, 0.8)\}$, respectively.

$$533 \quad R_D = \begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{21} & D_{22} & D_{23} \\ D_{31} & D_{32} & D_{33} \end{bmatrix} = \begin{bmatrix} \{(0.5, 1.0)\} & \{(0.55, 0.7), (0.65, 0.3)\} & - \\ - & \{(0.5, 1.0)\} & \{(0.75, 0.8)\} \\ - & - & \{(0.5, 1.0)\} \end{bmatrix}$$

534 The standard CFPR cannot handle this case, but D-CFPR (Eqns. (9)–(12) in Section 3.1) is effective
535 to fill up the rest of the matrix elements in $R_D = [D_{ij}]_{3 \times 3}$ as follows:

$$536 \quad R_D = \begin{bmatrix} \{(0.5, 1.0)\} & \{(0.55, 0.7), (0.65, 0.3)\} & \{(0.80, 0.56), (0.9, 0.24)\} \\ \{(0.45, 0.7), (0.35, 0.3)\} & \{(0.5, 1.0)\} & \{(0.75, 0.8)\} \\ \{(0.2, 0.56), (0.1, 0.24)\} & \{(0.25, 0.8)\} & \{(0.5, 1.0)\} \end{bmatrix}.$$

537 Then, the D numbers based CFPR matrix $R_D = [D_{ij}]_{3 \times 3}$ is converted to a crisp mode,
538 $R_C = [c_{ij}]_{3 \times 3}$, using Eqn. (13), and the integration representation of D numbers [Eqn. (7)], shown
539 below:

$$540 \quad R_C = I(R_D) = \begin{bmatrix} 0.5 & 0.58 & 0.66 \\ 0.42 & 0.5 & 0.60 \\ 0.13 & 0.20 & 0.5 \end{bmatrix}.$$

541 Applying the preference rules proposed for D-CFPR (in Step 3 of Section 4.1) and using Eqn.
542 (14), the probability matrix $R_p = [p_{ij}]_{3 \times 3}$ is constructed:

$$543 \quad R_p = \begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}.$$

544 Following the process (as mentioned in section 4.1 of Step 4) of the D-CFPR methodology, we
545 obtain the triangular matrix $R_p^T = [p_{ij}^T]_{3 \times 3}$. Using the triangularisation method, the ranking of the
546 indicators is calculated and shown as: $I_1 \succ I_2 \succ I_3$, where the symbol " \succ " indicates preference,

547
$$R_p^T = \begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}.$$

548 We next evaluate the relative weights of the risk criteria. *First*, based on the ranking of the risk
 549 criteria in the triangulated matrix R_p^T , the crisp matrix R_c , is converted to a triangular crisp matrix
 550 R_c^T , as per Eqn. (16):

551
$$R_c^T = \begin{bmatrix} 0.5 & 0.58 & 0.66 \\ 0.42 & 0.5 & 0.60 \\ 0.13 & 0.20 & 0.5 \end{bmatrix}.$$

552 *Next*, for elements satisfying $R_c^T(i, j) + R_c^T(j, i) < 1$, a new polishing operation [Eqn. (17)] is
 553 executed and, by also applying Eqn. (18), a novel triangulated crisp matrix $R_k^T = [k_{ij}^T]_{3 \times 3}$ is obtained:

554
$$R_k^T = \begin{bmatrix} 0.5 & 0.58 & 0.76 \\ 0.42 & 0.5 & 0.70 \\ 0.21 & 0.24 & 0.5 \end{bmatrix}.$$

555 *Finally*, applying Eqn. (19), a group of equations is built to calculate the priority weight
 556 w_i ($i = 1, 2, \dots, n$) of each risk based criterion. Applying the weight relation of the indicators in matrix
 557 mode, and incorporating necessary constraints, the weight equations are constructed and shown
 558 below:

559
$$\begin{cases} \lambda(w_1 - w_2) = 0.58 - 0.5 \\ \lambda(w_2 - w_3) = 0.76 - 0.5 \\ w_1 + w_2 + w_3 = 1 \\ \lambda > 0 \\ w_i \geq 0, \quad \forall i \in \{1, 2, 3\} \end{cases}$$

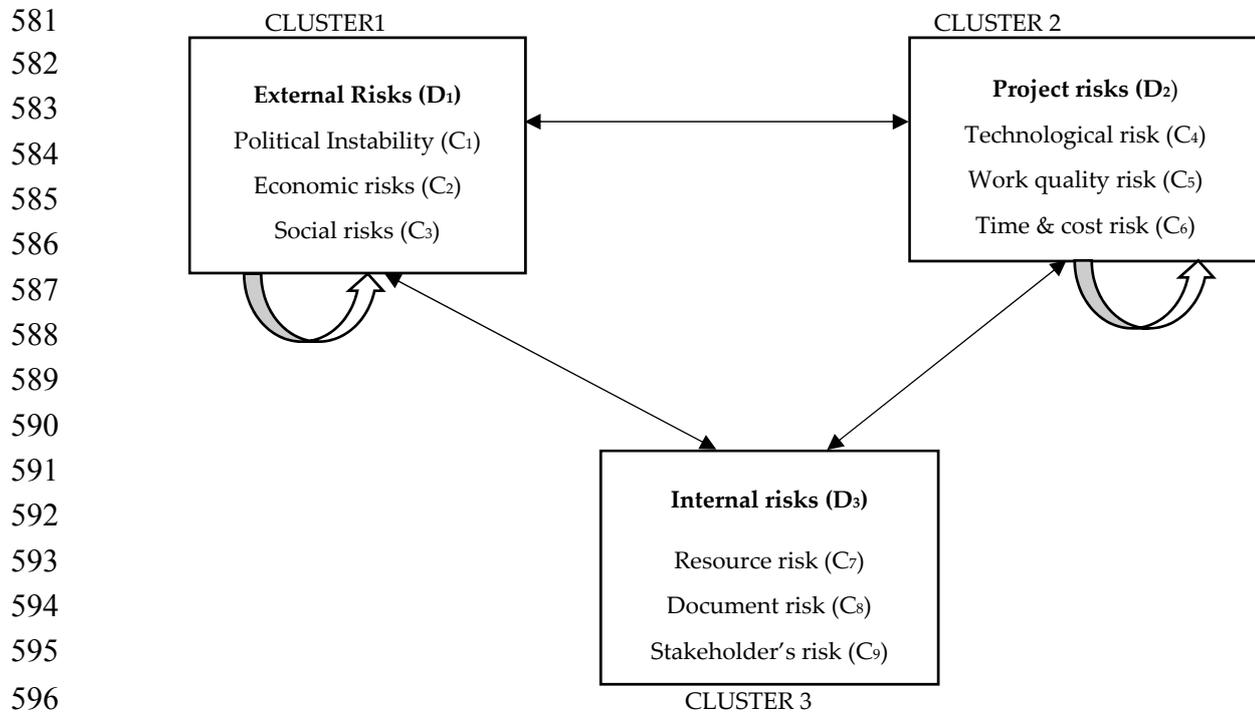
560 where w_i denotes the weight of the i^{th} indicator and λ indicates the granular information about the
 561 pairwise evaluation, which is connected to the cognitive aptitude of the experts. Setting $\lambda = 3$ and
 562 using Eqn. (20), the weight of risk criteria C_1, C_2 , and C_3 for dimension D_1 relative to C_6 of dimension
 563 D_2 are calculated as $(0.373, 0.347, 0.280)^T$, respectively.

564 For quantifying the consistency of the D-CFPR based matrix R_p^T , an ID defined for the D numbers
 565 preference relation [as defined in Eqn. (21)] is used to express such inconsistency, and for the case study
 566 taken, it is found to be consistent.

567 Similarly, using the same process, the priority weights of remaining criteria, shown in Figure 3
 568 with respect to the same dimensions and criteria of other clusters (dimensions), are calculated.

569
 570 *Step 3: Formation of unweighted supermatrix.* Arrange all priority vectors, indicating the influence
 571 of pre-set elements, in different cluster elements in the network, as sub-columns of the resultant
 572 column in an unweighted supermatrix W , which is composed of k clusters D_k ($k = 1, 2, 3$), with
 573 corresponding linkages (criteria) $\{e_{k1}, e_{k2}, e_{k3}\}$ for $k = 1, 2, 3$. Putting $k=1$, we get the first cluster
 574 (dimension) D_1 along with three elements $\{e_{11}, e_{12}, e_{13}\}$ representing three risk criteria $\{C_1, C_2, C_3\}$,
 575 respectively. For $k=2$, we get a second cluster (dimension) D_2 along with three elements

576 $\{e_{21}, e_{22}, e_{23}\}$ representing three risk criteria $\{C_4, C_5, C_6\}$. Similarly, the remaining cluster
 577 (*dimensions*) D_3 , along with its risk criteria, can be found. Thus, we get three clusters (*dimensions*)
 578 $D_k = \{D_1, D_2, D_3\}$ and nine corresponding risk criteria $C_j \{j = 1, 2, \dots, 9\}$. Based on the above, the
 579 unweighted supermatrix W is formed by placing priority vector elements in the particular column,
 580 where each criterion influences the other risk criteria. Details shown in Table 5.



597 **Figure 3.** Network structure among construction risk dimensions and criteria

598 Table 5. Unweighted supermatrix formed from every risk factor.

		External risk (D1)			Project risk (D2)			Internal risk (D3)		
		C1	C2	C3	C4	C5	C6	C7	C8	C9
External risk (D1)	C1	0.000	0.576	0.589	0.315	0.386	0.373	0.332	0.353	0.395
	C2	0.525	0.000	0.411	0.357	0.351	0.347	0.336	0.321	0.327
	C3	0.475	0.424	0.000	0.327	0.264	0.280	0.332	0.326	0.278
Project risk (D2)	C4	0.288	0.355	0.354	0.000	0.461	0.510	0.348	0.346	0.340
	C5	0.416	0.320	0.338	0.481	0.000	0.490	0.334	0.361	0.363
	C6	0.296	0.326	0.308	0.519	0.539	0.000	0.318	0.293	0.298
Internal risk (D3)	C7	0.332	0.324	0.357	0.364	0.313	0.370	0.000	1.000	1.000
	C8	0.351	0.369	0.351	0.343	0.371	0.351	1.000	0.000	1.000
	C9	0.316	0.308	0.292	0.293	0.315	0.279	1.000	1.000	0.000

599

600 *Step 4: Calculating the weighted supermatrix.* The weighted supermatrix (W^a) is calculated by
 601 multiplying unweighted supermatrix W (Table 5) by the inner dependence matrix of risk
 602 dimension $D_j (j = 1, 2, 3)$ (Table 6). Details are shown in Table 7.

603

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Table 6. Inner dependence matrix of construction project factors.

	Dimensions		
	External risk	Project risk	Internal risk
External risk	1	0.518	0.503
Project risk	0.537	1	0.496
Internal risk	0.462	0.482	1

605

Table 7. Weighted supermatrix based on supply chain risk factors.

		External risk			Project risk			Internal risk		
		C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉
External risk	C ₁	0.000	0.576	0.589	0.163	0.200	0.193	0.167	0.178	0.199
	C ₂	0.525	0.000	0.411	0.185	0.182	0.180	0.169	0.162	0.165
	C ₃	0.475	0.424	0.000	0.170	0.137	0.145	0.167	0.164	0.140
Project risk	C ₄	0.155	0.191	0.191	0.000	0.461	0.510	0.173	0.172	0.169
	C ₅	0.223	0.172	0.182	0.481	0.000	0.490	0.166	0.179	0.180
	C ₆	0.159	0.175	0.165	0.519	0.539	0.000	0.158	0.146	0.148
Internal risk	C ₇	0.154	0.150	0.165	0.176	0.151	0.178	0.000	1.000	1.000
	C ₈	0.162	0.171	0.162	0.165	0.179	0.169	1.000	0.000	1.000
	C ₉	0.146	0.142	0.135	0.141	0.152	0.134	1.000	1.000	0.000

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Step 5: Selecting the weight of criteria based on the limit matrix. To make the matrix column stochastic in Table 7, we normalise the weighted supermatrix (W^a) column wise, and the result is shown in

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Table 8. The normalised weighted supermatrix \hat{W} (Table 8) is raised to its limiting power using Eqn.

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(22), to get the limiting supermatrix W^q (Table 9). The final ranking of risk criteria weight for the

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construction project is shown in Table 10.

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613

Table 8. Normalised weighted supermatrix based on supply chain risk factors.

		External risk			Project risk			Internal risk		
		C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉
External risk	C ₁	0.000	0.288	0.294	0.082	0.100	0.097	0.056	0.059	0.066
	C ₂	0.263	0.000	0.206	0.093	0.091	0.090	0.056	0.054	0.055
	C ₃	0.238	0.212	0.000	0.085	0.068	0.073	0.056	0.055	0.047
Project risk	C ₄	0.078	0.095	0.095	0.000	0.231	0.255	0.058	0.057	0.056
	C ₅	0.112	0.086	0.091	0.241	0.000	0.245	0.055	0.060	0.060
	C ₆	0.079	0.088	0.083	0.260	0.270	0.000	0.053	0.049	0.049
Internal risk	C ₇	0.077	0.075	0.083	0.088	0.075	0.089	0.000	0.333	0.333
	C ₈	0.081	0.085	0.081	0.083	0.090	0.085	0.333	0.000	0.333
	C ₉	0.073	0.071	0.068	0.071	0.076	0.067	0.333	0.333	0.000

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Table 9. Limited supermatrix based on supply chain risk factors.

		External risk			Project risk			Disruption risk		
		C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉
External risk	C ₁	0.1062	0.1062	0.1062	0.1062	0.1062	0.1062	0.1062	0.1062	0.1062
	C ₂	0.0958	0.0958	0.0958	0.0958	0.0958	0.0958	0.0958	0.0958	0.0958
	C ₃	0.0894	0.0894	0.0894	0.0894	0.0894	0.0894	0.0894	0.0894	0.0894
Project risk	C ₄	0.0972	0.0972	0.0972	0.0972	0.0972	0.0972	0.0972	0.0972	0.0972
	C ₅	0.0996	0.0996	0.0996	0.0996	0.0996	0.0996	0.0996	0.0996	0.0996
	C ₆	0.0971	0.0971	0.0971	0.0971	0.0971	0.0971	0.0971	0.0971	0.0971
Internal risk	C ₇	0.1392	0.1392	0.1392	0.1392	0.1392	0.1392	0.1392	0.1392	0.1392
	C ₈	0.1406	0.1406	0.1406	0.1406	0.1406	0.1406	0.1406	0.1406	0.1406
	C ₉	0.1349	0.1349	0.1349	0.1349	0.1349	0.1349	0.1349	0.1349	0.1349

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Table 10. Ranking of construction project risk criteria.

Dimensions	Risk Criteria	Ranking
External risk (D ₁)	Political instability (C ₁)	4
	Economic risk (C ₂)	8
	Social risk (C ₃)	9
Project risk (D ₂)	Technological risk (C ₄)	6
	Work quality risk (C ₅)	5
	Time and cost risk (C ₆)	7
Internal risk (D ₃)	Resource risk (C ₇)	2
	Document and information risk (C ₈)	1
	Stakeholder's risk (C ₉)	3

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From Table 10 it is concluded that the third cluster (dimension) *internal risk* (D₃) has a severe risk

effect on the construction project sector. *Document and information risk* (C₈) is the most risky, followed

by *resource risk* (C₇) and *stakeholder's risk* (C₉). First cluster *External risk* (D₁) has less of a risk effect on

construction business. *Economic risk* (C₂) and *social risk* (C₃) are in 8th and 9th position, respectively.

But *political instability* attains 4th position in respect of risk category. Managers and stakeholders

should keep this in view when choosing projects in large construction sectors.

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5.3. Determination of final alternative ranking by D-MABAC

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In this phase, the evaluation and ranking of risk response alternatives is performed by the

application of a D numbers based MABAC (D-MABAC) methodology in construction project risk

management. The step-by-step computational procedure is shown below.

Step 1: First, the five *risk response* alternative vectors, with respect to nine risk criteria

C_j ($j = 1, 2, \dots, 9$), are represented as $A_i = (d_{i1}, d_{i2}, \dots, d_{i9})$ ($i = 1, 2, \dots, 5$) using *incomplete and uncertain*

numbers expressed in D numbers. Using Eqns. (23)–(24), we develop an initial decision matrix

$M = [d_{ij}]_{5 \times 9}$ (Table 11) along with its crisp form $X = [I(d_{ij})]_{5 \times 9} = [x_{ij}]_{5 \times 9}$.

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Table 11. Comparison of alternatives w.r.t risk criteria using D numbers.

	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉
A ₁	(.62, .5)	(.72, .4), (.48, .6)	(.53, .4)	(.58, .5)	(.72, .6)	(.48, .6), (.64, .4)	(.66, .6)	(.38, .9)	(.84, .2)
A ₂	(.68, .4)	(.44, .8)	(.64, .6), (.32, .3)	(.44, .9)	(.82, .9)	(.88, .6)	(.56, .8)	(.92, .8)	(.69, .4)
A ₃	(.54, .8), (.68, .2)	(.68, .3)	(.47, .9)	(.78, .8)	(.38, .7), (.59, .3)	(.68, .5)	(.29, .6), (.39, .4)	(.28, .6)	(.34, .6)
A ₄	(.72, .9)	(.49, .7)	(.78, .4)	(.86, .4)	(.88, .4)	(.47, .7)	(.64, .2)	(.62, .1)	(.56, .7)
A ₅	(.48, .1)	(.56, .9)	(.82, .7)	(.36, .1)	(.78, .7)	(.59, .9)	(.78, .7)	(.68, .3), (.49, .6)	(.44, .8)

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638

Step 2: The elements of the crisp decision matrix $X = [x_{ij}]_{5 \times 9}$ are normalised using Eqns. (24)–

639

(25) to form a normalised decision matrix $N = [t_{ij}]_{5 \times 9}$, shown in Table 12.

640

Table 12. Normalised decision matrix of alternatives w.r.t criteria.

	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉
A ₁	0.8989	0	1	1	0.7927	0	0.3589	0.5846	1
A ₂	1	0.6022	0.2597	0.6826	0	0.0744	0.2344	0	0.5179
A ₃	0.2128	1	0.4171	0	0.7642	0.9488	0.5167	0.8427	0.8393
A ₄	0	0.6263	0.7238	0.8383	1	1	1	1	0
A ₅	0.4468	0.1935	0	0.7904	0.4974	0.0605	0	0.3531	0.1786

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642

Step 3: Using Eqns. (26)–(27), the elements of the weighted normalised decision matrix

643

$V = [v_{ij}]_{5 \times 9}$ are calculated, and are shown in Table 13.

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Table 13. Weighted normalised decision matrix of alternatives w.r.t criteria.

	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉
A ₁	0.2017	0.1916	0.1788	0.1944	0.1786	0.0971	0.1892	0.2381	0.2698
A ₂	0.2124	0.1304	0.1126	0.1636	0.0996	0.1043	0.1718	0.1406	0.2048
A ₃	0.1288	0.1641	0.1267	0.0972	0.1757	0.1892	0.2111	0.2812	0.2481
A ₄	0.1062	0.1324	0.1541	0.1787	0.1992	0.1942	0.2784	0.1693	0.1349
A ₅	0.1537	0.0958	0.0894	0.1740	0.1491	0.1030	0.1392	0.1995	0.1590

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Step 4: Next, using Eqns. (28)–(29) we determine the BAA, $G = [g_1 \ g_2 \ \dots \ g_9]$ for each criterion

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$C_j (j=1,2,\dots,9)$. This is followed by calculation of the distance (q_{ij}) for matrix elements

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$Q = [q_{ij}]_{5 \times 9}$ for risk response alternatives $A_i (i=1,2,\dots,5)$ from BAA $G = [g_1 \ g_2 \ \dots \ g_9]$ using

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Eqns. (30)–(31).

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Step 5: Finally, using Eqn. (32) we calculate the sum function $\hat{S}_i (i=1,2,\dots,5)$ to obtain the

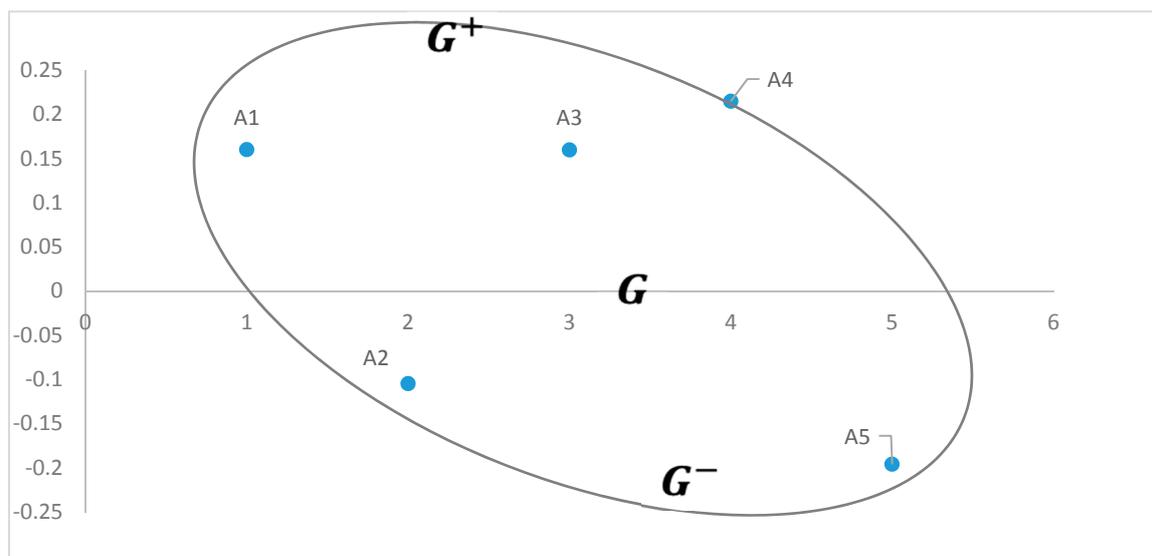
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ranking of alternatives $A_i (i=1,2,\dots,5)$. A graphical representation of the process is shown in Figure

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4. Ranking of alternative risk response alternatives (Table 14) is finalised according to values

653 calculated by D-MABAC in descending order. In this paper, the first alternative risk response was
 654 selected and implemented.
 655



656
 657 **Figure 4.** *D* number based MABAC in risk mitigation strategy selection

658 **Table 14.** Ranking of alternatives using the MABAC method.

	Alternative risk responses	Q	Rank
Risk response (A ₁)	Proper scheduling for getting updated project information.	0.2830	1
Risk response (A ₂)	Adjust plans for scope of work and estimates to counter risk implications.	-0.1161	4
Risk response (A ₃)	Get information about local partner's credibility from its present and past business partners.	0.1660	2
Risk response (A ₄)	Transfer or share risks to/with other parties.	0.0913	3
Risk response (A ₅)	Merger and diversification of projects.	-0.1935	5

659
 660 **6. Results and discussion**

661 In this section, a detailed comparative analysis of all alternative initiatives (with respect to
 662 criteria and dimensions) is conducted.

663 *6.1. Comparison of alternative ranking using different MCDM methods*

664 The hybrid MCDM methods viz. D-MABAC, D-TOPSIS, D-COPRAS, and D-ARAS were applied
 665 to the construction project based case study data to obtain the weighted normalised decision making
 666 matrix $V = [v_{ij}]_{5 \times 9}$ (Table 13). The priority order of the risk response alternatives A_i ($i = 1, 2, \dots, 5$) is
 667 compared and presented in Table 15.

668 Ranking of the risk response alternatives according to the presented MCDM methods concluded
 669 that the optimal alternative risk response is A₁ (Proper scheduling for getting updated project
 670 information), followed by A₃ (Information about local partner's credibility), A₄ (Transfer risks with
 671 other parties), A₂ (Adjust plans for scope of work). The worst performing risk response alternative is
 672 A₅ (Merger and diversification of projects).

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Table 15. Comparison of MABAC with various existing MCDM methods

Alternative risk responses	D-MABAC	D-TOPSIS	D-COPRAS	D-ARAS
A ₁	1	1	1	1
A ₂	4	4	4	4
A ₃	2	2	2	2
A ₄	3	3	3	3
A ₅	5	5	5	5

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Spearman's rank correlation coefficient (r_k) between ranks is applied for determining correlation of ranks obtained by various approaches. Here, this coefficient is applied to demonstrate the statistical importance of difference among the ranking obtained through pairwise correlation analysis of different MCDM methods. Based on the recommendation of Keshavarz Ghorabae et al. [65], all (r_k) values higher than 0.80 show considerably high correlation. As per Table 16, a strong correlation (1.000) among the MCDM approaches is shown, confirming the credibility of the proposed approach.

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Table 16. Rank correlation of various MCDM methods

Spearman's coefficient	D-MABAC	D-TOPSIS	D-COPRAS	D-ARAS
r_k	-	1.000	1.000	1.000

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6.2. Sensitivity analysis

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Ranking of results in MCDM problems are subject to the distribution of weight coefficients of the criteria. Sometimes, modifying these criteria weight coefficients may change the ranking order of alternatives, generally analysed by sensitivity analysis during the decision making process. The above weight coefficients are usually based on expert subjective perception, and thus the outcome of probable deviation of these weight values need to be properly assessed.

A sensitivity analysis was executed to measure the level of crosstalk amongst the criteria, revealing the variation in alternative rankings as per variation in criteria weight. Outcomes of the sensitivity analysis for prioritising specific project based criteria C_j ($j = 1, 2, \dots, 9$) weights are shown in Table 17, and its corresponding effect on ranking of risk response alternatives A_i ($i = 1, 2, \dots, 5$) in Table 18.

- The results (Table 17 and Figure 5) shows that assigning various weights to project based criteria C_j ($j = 1, 2, \dots, 9$) through different scenarios $\{S_1 - S_8\}$ results in changes to ranking of individual alternatives, thus proving that the model is sensitive to variations in weight coefficients.
- Analysis of the alternative ranking through eight scenarios (Table 18) showed that alternative A₁ retained its rank in five scenarios $\{S_2, S_3, S_4, S_5, S_8\}$ (*best-ranked alternative*), while in the remaining two scenarios $\{S_1, S_7\}$ it was ranked second, and third in scenario $\{S_6\}$.
- The worst-ranked alternative A₅ retained its rank in six scenarios $\{S_2, S_3, S_4, S_5, S_7, S_8\}$, while in two scenarios $\{S_1, S_6\}$ it was ranked second worst. Therefore, changing the criteria weights through different scenarios resulted in changes to the ranks of the remaining alternatives.

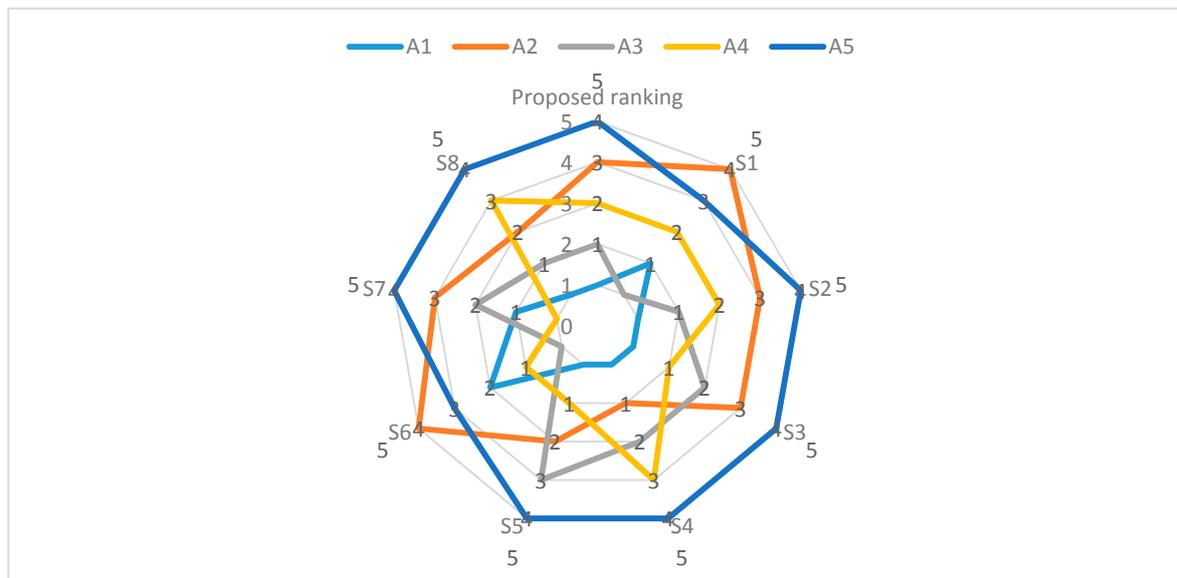
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Table 17. Scenarios for different criteria weights.

Criteria	Scenarios*							
	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	S ₇	S ₈
C ₁	0.0113	0.1482	0.0226	0.2674	0.1944	0.0795	0.0081	0.1602
C ₂	0.1578	0.1121	0.1204	0.1178	0.0914	0.0632	0.0962	0.0537
C ₃	0.0576	0.1789	0.2946	0.0001	0.1853	0.0577	0.0308	0.1054
C ₄	0.0904	0.1118	0.2655	0.1556	0.2219	0.0519	0.2032	0.0958
C ₅	0.1172	0.0033	0.0478	0.0598	0.0603	0.0703	0.0875	0.1805
C ₆	0.2016	0.0233	0.0496	0.0631	0.0322	0.3311	0.1958	0.0218
C ₇	0.0894	0.1663	0.0352	0.0937	0.0560	0.0055	0.1485	0.0223
C ₈	0.2103	0.0933	0.0030	0.0276	0.0871	0.3320	0.1191	0.0539
C ₉	0.0645	0.1628	0.1613	0.2150	0.0714	0.0089	0.1107	0.3063

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* Priority criteria are indicated in bold text for different scenarios.



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Figure 5. Sensivity analysis of the alternative ranking through different scenarios

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- In addition, from Tables 17–18, it is clear that prioritising criteria C₉ has less of an effect on ranking position of alternatives. However, prioritising criteria set {C₄, C₆, and C₇} in scenario S₇, {C₂, C₆, and C₈} in scenario S₁, along with {C₄, C₆, and C₈} in scenario S₆, all altered the positions of risk response alternatives $A_i (i = 1, 2, \dots, 5)$.

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Table 18. Sensitivity in alternative rankings for different scenarios of criteria weighting.

Alternative risk responses	Scenarios							
	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	S ₇	S ₈
A ₁	2	1	1	1	1	3	2	1
A ₂	5	4	4	2	3	5	4	3
A ₃	1	2	3	3	4	1	3	2
A ₄	3	3	2	4	2	2	1	4
A ₅	4	5	5	5	5	4	5	5

- 716 • The prioritising of criteria weight in scenarios $\{S_2, S_3, S_4, S_5, S_8\}$ has no effect on ranking of
 717 best or worst risk response alternative A_1 and A_5 , respectively, but it does have an effect on the
 718 ranking of the second best risk response alternative A_2 .

719 7. Conclusions and future research

720 In this paper, we rank uncertain risk strategies in construction projects using a D-ANP-MABAC
 721 multi-criteria decision making (MCDM) approach. In the new proposed method, the decision matrix
 722 determination from the MCDM problem is transformed to D numbers, which effectively represent
 723 the inevitable uncertainties such as incompleteness and imprecision, due to the subjective assessment
 724 of decision makers. By using D-CFPR decision matrices it allows all stakeholders (members) of a
 725 construction business to address multiple criteria involving various types of uncertainties, such as
 726 imprecision and fuzziness in the decision process. The weights of the risk criteria for any cluster are
 727 determined by the D-ANP method and alternative risk response strategy ranking is achieved using
 728 the D-MABAC method. In view of several categories of uncertainties, including incompleteness and
 729 impreciseness, the proposed technique can effectively represent and address uncertain information
 730 weighting risk criteria and alternatives in a logical way. An example of selecting risk strategies in
 731 construction risk projects is shown here to demonstrate the efficiency of the proposed approach. The
 732 assessment of a real world application of D-ANP-MABAC methodology, along with its output result
 733 of sensitivity, clearly identifies its potential to provide stable solutions to the problematic choice of
 734 laying-up positions. Based on that, the proposed risk strategy alternatives are successfully ranked.
 735 Thus, it can be concluded that the above procedure has provided an alternate approach for
 736 sustainable risk analysis and decision making in the construction sector. In future research, the
 737 theoretical framework needs to be further perfected and applied to other real-life application areas
 738 such as supplier selection problems, project portfolio management, renewable energy selection etc.,
 739 to further validate its effectiveness.

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912

913 **Author Contributions:**

914 The individual contribution and responsibilities of the authors were as follows:

- 915 - Kajal Chatterjee -- designed the research, methodology, performed the development of the paper,
- 916 - Krishnendu Adhikary- collected and analyzed the data and the obtained results,
- 917 - Edmundas Kazimieras Zavadskas- provided extensive advice throughout the study,
- 918 - Jolanta Tamošaitienė- regarding the research design, revised the manuscript.
- 919 - Samarjit Kar- methodology, findings.

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921 All the authors have read and approved the final manuscript.

922

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