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# Assessment of Complexity for Megaprojects in the Energy Sector

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## Abstract:

Megaprojects are characterised by their large-scale capital costs, long duration and extraordinary levels of technical and process complexity. Empirical data demonstrate that these projects experience alarming rates of failure. One of the main causes of such project failure is the high level of complexity and the absence of effective tools to assess and manage it. This study develops a new project complexity assessment method, which is specifically aimed at megaprojects in the energy sector. The assessment method contains a taxonomy of 51 complexity indicators and their consolidated weights, which are established through a novel Delphi-AHP Group Decision Making method. Numerical Scoring criteria for all indicators are defined on the basis of synthesis of existing knowledge of megaprojects to facilitate the application of the new method. It is reviewed and evaluated by experts and tested through a case study energy megaproject.

## 29 Introduction

30 Megaprojects, are commonly defined as projects with a capital investment of at least one billion U.S.  
31 dollars (Flyvbjerg 2014; Merrow 2011). Beside the scale of their price tag, megaprojects are also  
32 typically characterised as being risky, complex, with high uncertainty and significant social impact, as  
33 well as engaging many stakeholders (Kardes et al. 2013; Peng et al. 2012). With growing demands for  
34 energy, more and more energy infrastructure megaprojects are being carried out worldwide  
35 (Merrow 2011; Sovacool and Cooper 2013). Examples include the UK's Round Three offshore wind  
36 farms, the Trans-ASEAN gas pipeline network, Flamanville 3 Nuclear Power Plant, and the Tsangpo-  
37 Brahmaputra hydroelectric project dam. Unfortunately, megaprojects have experienced alarming  
38 rates of failure in meeting their business goals, their capital budgets and/or schedules (Cantarelli et  
39 al. 2012; Fiori and Kovaka 2005; Flyvbjerg et al. 2003; Merrow 2011; Hu et al. 2016). Studies of global  
40 energy and national oil companies suggest that one of the biggest risks to project delivery is the  
41 incapacity of the project team to adequately understand and manage the complexity of these  
42 projects (Merrow 2012).

43 Project complexity is one of the main factors to be taken into account when planning and managing  
44 projects (Shenhar 1998; Shenhar and Dvir 1996). A project team needs to carry out reliable  
45 assessment of project complexity before adopting effective management and control strategies  
46 (Augustine et al. 2005; Austin et al. 2002; Thomas and Mengel 2008). In recent years, research has  
47 mainly focused on exploring the concept of project complexity and determining the characteristics  
48 of complex projects by defining the factors and indicators of complexity in a project (Geraldi et al.  
49 2011). Although various researchers have recognised the importance of objective and quantitative  
50 evaluation of complexity (Little et al. 1998; Williams 2002), existing studies are mostly devoted to  
51 the theoretical aspects of project complexity (Kardes et al. 2013; Maylor et al. 2008). Yet, what  
52 industry needs is practice-oriented complexity assessment methods that entail explicit objective  
53 measures (Remington and Pollack 2007). Unfortunately, there is a lack of research into this aspect,  
54 particularly in the context of megaprojects. While megaprojects are not unique to the energy sector,

55 they are more common in this sector. In addition to the common characteristics with all  
56 megaprojects, energy megaprojects often have some distinctive features. (1) The level of technical  
57 challenge is usually very high in energy projects. For example, new drilling techniques become  
58 essential for many oil and gas exploration projects; a nuclear power plant requires more complex  
59 technologies than a large road project. (2) Most energy megaprojects involve trans-national and  
60 multi-national collaboration. (3) In response to the global climate change agenda, many countries  
61 adopt new laws and regulations on energy use and energy supply. These create uncertainties for  
62 investment decisions in energy projects and increase their complexity. With these considerations,  
63 this study chooses to focus on the energy sector. However, the investigation approach can be  
64 applied in other sectors and the research outcomes can also be the basis for adaptation for other  
65 types of megaprojects.

66 This research aims to fill this gap by developing a Project Complexity Assessment (PCA) method. The  
67 method enhances theoretical literature by establishing a comprehensive structure of project  
68 complexity indicators, i.e. a taxonomy of project complexity. Using a Group Decision Making (GDM)  
69 approach involving industry experts, the paper also defines numerical weights for all indicators.  
70 Finally, and quite uniquely in contrast with existing literature, the paper establishes scoring criteria  
71 for all indicators, which enables effective practical use of the method for the objective assessment of  
72 project complexity of megaprojects in the energy sector.

## 73 **Literature Review**

74 Megaprojects are highly complex (Remington and Pollack 2007; Williams 2013); their execution  
75 often requires organisations to develop capacities of dynamism, experience and technology (Fiori  
76 and Kovaka 2005; Gransberg et al. 2013; Puddicombe 2012). Megaprojects are usually characterized  
77 by their high internal complexity, such as task complexity (Brockmann and Girmscheid 2007), and  
78 structural and directional complexity (Remington and Pollack 2007). Previous megaproject research  
79 is mostly devoted to these internal complexity aspects. External complexity, or 'contextual

80 uncertainty', has received less attention by comparison (Hu et al. 2013). Economic instabilities,  
81 market fluctuations, and social and cultural transitions (the latter one emerging mostly in developing  
82 countries) transform megaproject environments into uncertain situations (Shehu and Akintoye  
83 2010). To understand and conceptualise the complexity of megaprojects comprehensively, both  
84 internal and external factors need to be investigated.

85 Despite the growing recognition of the importance of project complexity, there is still a lack of  
86 consensus on its definition and on a way to quantify it (Hu et al. 2013; Sinha et al. 2001). Baccarini  
87 (1996) offered one of the early attempts to define project complexity as a number of interrelated  
88 parts of a project (differentiation) and the relationships between the different parts  
89 (interdependency). These two perspectives are based on two key aspects of projects, resulting in  
90 two different types of project complexity – organisational complexity and technological complexity.  
91 The former refers to the composition and structure of the project team and the latter refers to the  
92 process, tools and product. In many business sectors, the ever increasing demands from the multiple  
93 facets of project success, such as speed of implementation, cost and quality controls, health and  
94 safety requirements, environmental issues, together with technological advances, economic  
95 liberalisation and globalisation, have resulted in a rapid increase in project complexity (Gidado  
96 1996). Williams (1999) termed Baccarini's definition as 'structural complexity' and added another  
97 element to it – uncertainty. Uncertainty here refers to the fact that, in a typical project, both the  
98 project's goal and the methods needed to achieve this goal are not always certain. This uncertainty,  
99 together with the inherent structural complexity, produce the overall difficulty and messiness  
100 experienced in such projects (Williams, 1999). Geraldi and Adlbrecht (2008) characterised project  
101 complexity into three forms: faith, fact and interaction. Bosch-Rekvelde et al. (2011) determined  
102 technical, organisational, and environmental elements for the complexity of large engineering  
103 projects. Vidal et al. (2011) emphasised the difficulty of understanding, predicting, and controlling  
104 project complexity, but underlined the significance of project complexity assessment to enrich  
105 support to decisions making. The ability of an organisations to foresee, recognise and pilot

106 complexity is a key criterion of project success or failure (Office of Government Commerce 2009). All  
107 the above authors consider project complexity as an intrinsic property of a project, which can be  
108 both described and measured. This approach is known as 'descriptive complexity', which emphasises  
109 the objective existence of complexity. There is another approach, 'perceived complexity' which  
110 considers complexity as subjective and may vary depending on the perception of different observers  
111 (Schlindwein and Ison 2004). In practice, project managers always deal with perceived complexity  
112 because their perception of complexity of a project, and solutions to it, will depend on their personal  
113 knowledge and competence as well as the descriptive complexity of the project (Vidal and Marle  
114 2008). Descriptive complexity and perceived complexity are two ends of the complexity perception  
115 spectrum. The former focuses on the objective nature of complexity; while the latter looks at  
116 complexity from a particular perspective of an individual party, taking into account the individual's  
117 ability to handle the concept of complexity. In reality, however, there is no hard boundary between  
118 these two. This study concentrates on the complexity measurement, not complexity management.  
119 This emphasis is on the objectivity of complexity measurement. The aim for the new assessment  
120 method is to produce the same result regardless who does the assessment. However, it is  
121 recognised that it may not be possible to eliminate the impact of assessor's subjectivity completely.

122 To gain a deeper understanding of project complexity, many studies tried to unpack the concept of  
123 project complexity and identify a list of elements or indicators of complexity, especially in the  
124 context of large engineering projects (Bosch-Rekvelde et al. 2011; Lessard et al. 2014; Liu et al. 2015)  
125 and megaprojects (He et al. 2015). Most of these studies were influenced by Baccarini (1996), first  
126 exploring organisational and technological aspects of the project or projects. Following a study of six  
127 large projects, Bosch-Rekvelde et al. (2011) identified five organisational complexity elements (size,  
128 resources, project team, trust and risk) and five technical complexity elements (goals, scope, tasks,  
129 experience and risk). They also introduced another 'environment' category and identified four  
130 elements within it (stakeholders, location, market conditions, and risk). Each of these elements is  
131 further divided into multiple elements at another lower level; altogether these form a Technology-

132 Organisation-Environment (TOE) framework with 50 elements in total. The hierarchical  
133 decomposition principle of this framework offers an effective way of organising the large number of  
134 complexity elements. However, the inclusion and definitions of some of the elements are debatable.  
135 For instance, 'risk' is more like an outcome of complexity instead of part of project complexity; some  
136 members of 'stakeholders' are part of the 'project team'. The coverage of external elements in the  
137 TOE framework is very limited and is not sufficient to reflect the important, even critical, impact of  
138 external factors in large projects. Lu et al. (2015) also presented a TO hierarchy of project  
139 complexity, which divides all influencing factors into two broad groups: task complexity factors and  
140 organisation complexity factors. Technological factors are considered part of task complexity factors,  
141 together with environmental (external) factors and others. In addition to the number and complexity  
142 of tasks, this study also distinguished the types of interdependency between tasks as pooled,  
143 sequential or reciprocal interdependencies. Lessard et al. (2014) proposed a 'House of Project  
144 Complexity', which combines inherent features of a project and performance aspects or outcomes.  
145 The inherent features refer to technical and organisational complexities that similar to those defined  
146 in the studies above (Baccarini, 1996; Bosch-Rekvelde et al. 2011; Lu et al. 2015). The desired project  
147 outcomes are defined as emergent properties such as quality, flexibility, maintainability, etc. An  
148 intermediate layer is introduced between inherent features and outcomes, which specifies project  
149 governance structure and execution process (architectural features). Lessard et al.'s study tries to  
150 establish the link between the inherent complexities of a project, the project team's response to  
151 them and the final outcome of the project. In doing so, it defines a scaling system to determine  
152 complexity and performance scores, although but that system mainly relies on subjective  
153 assessment.

154 The need to quantitatively measure project complexity has been the focus of a growing number of  
155 recent studies (He et al. 2015; Sinha et al. 2006; Vidal et al. 2011; Xia and Chan 2012). The research  
156 challenges include: the identification of a list of indicators against which measurement is to be  
157 carried out; the determination of the significance (weight) of each indicator; and specification of

158 scoring scales for these indicators. Sinha et al. (2006) proposed a project complexity measurement  
159 framework that breaks a project down into activities and subtasks at different stages. It goes on to  
160 define a way of measuring complexity at the subtask level by taking into account work, time,  
161 motivational and social factors. A complexity index can then be calculated for the whole project by  
162 aggregating that of all the subtasks. A framework is provided in (Global Alliance for Project  
163 Performance Standards 2007) to classify projects based on their management complexity, by using a  
164 tool known as CIFTER developed by Aitken and Crawford (2007). The tool analyses complexity  
165 through seven project management complexity factors: stability, number of distinct disciplines,  
166 magnitude of implication, expected financial impact, strategic importance, stakeholder cohesion,  
167 and number of interfaces for complexity of project in a four-point scale. Vidal et al. (2011) developed  
168 a comparative complexity measurement method, which is aimed at comparing different alternatives.  
169 It identifies 18 complexity drivers (indicators) and proposes a method to calculate their weights  
170 using an Analytic Hierarchy Process (AHP). Instead of measuring against objective scales, different  
171 alternatives are measured against each other. The aim of such an assessment is to establish a  
172 complexity ranking order of several alternatives. Xia and Chan (2011) put forward a relatively simple  
173 complexity measurement method to apply to building projects. It only contains six indicators and  
174 weights are calculated from the importance index using a 5-point Likert scale. The interesting aspect  
175 of this study is its use of the Delphi method when surveying a panel of experts in order to establish  
176 the importance of indices. In another study, He et al. (2015) developed a complexity measurement  
177 model comprising of 28 indicators in six categories, including technological, organisational, goal,  
178 environmental, cultural and information complexities. The method uses the fuzzy analytic network  
179 process (FANP) and Delphi method to obtain individual weights for these indicators, in the context of  
180 one construction megaproject. Their general research approach is broadly relevant to this study.  
181 However, as our focus is on megaprojects in the energy sector, the composition of the complexity  
182 indicators and their weights will be different in our study from theirs. Furthermore, their model does  
183 not define scoring criteria for the indicators, which are essential for quantifying the complexity of a



184 new project. Recently, Dao et al. (2016) propose a Project Complexity Assessment and Management  
185 (PCAM) tool that includes 37 complexity indicators and objective scoring methods for these  
186 indicators. It was implemented as a simple spreadsheet tool, allowing the user to assess the  
187 complexity level of project at different stages during the project life cycle. The proposal to  
188 implement different strategies according complexity level of project is another element of this  
189 method; however, effectiveness of proposed strategies must be further investigated by applying in  
190 different projects and evaluation of performance.

191 The literature review findings have revealed the magnitude of the challenge of studying project  
192 complexity. Given the diversity of projects, it is unlikely that one measurement system is suitable for  
193 all projects. Complexity indicators and their importance rankings and weights depend on the nature  
194 of the specific projects. Megaprojects in the energy sector have not been the main focus of any of  
195 the existing studies. This study intends to fill this gap. Lessons were learned from the literature  
196 review, which helped with the choice of research methods in this study.

197 While existing studies contributed in improving the collective understanding of project complexity  
198 and proposed various assessment methods for general projects, there is still a lack of dedicated  
199 project complexity assessment methods for megaprojects in the energy sector. A number of  
200 knowledge gaps are particularly identified that need to be addressed before such a method can be  
201 developed:

- 202 1. A raft of complexity indicators are proposed by different authors (Bosch-Rekvelde et al.  
203 2011; Geraldi et al. 2011; He et al. 2015; Vidal et al. 2011). There is a need to evaluate these  
204 indicators, synthesize them and establish their relevance from the particular perspective of  
205 megaprojects.
- 206 2. There is limited research on the relative importance of different indicators when assessing  
207 project complexity of megaprojects.

208 3. Another clear shortcoming is the lack of any objective criteria for quantitatively measuring  
209 the impact of project complexity indicators – this is true in general not just in the energy  
210 sector.

211 These observations underlie both the main rationale and the detailed conduct of our study. The aim  
212 of this study is to develop a project complexity assessment (PCA) method that defines: (1) the  
213 indicators that are relevant to energy megaprojects; (2) the weights of each indicator when  
214 assessing the overall complexity of the whole project; and (3) the scoring criteria for all the identified  
215 complexity indicators. Finally, the study must (4) evaluate the developed PCA method. This study  
216 seeks to build on existing studies with new contribution from academic and professional experts  
217 who have relevant practical knowledge of energy megaprojects.

## 218 **Research methods**

219 This research is carried out in four main phases as is depicted in Fig. 1:

220 < Fig. 1. Research phases and methods >

221 1. Compiling a list of Project Complexity Indicators (PCIs) is achieved through a comprehensive  
222 literature review and synthesis. Firstly a systematic review of project complexity is adopted  
223 based on the approach suggested by Geraldi et al. (2011). The Web of Science (WoS), Scopus  
224 and American Society of Civil Engineers (ASCE) databases are searched (these databases  
225 include papers from all these prominent journals). To ensure the quality and relevance of  
226 publications, only journal articles, books and published proceedings are considered. In total  
227 41 relevant papers and 5 books are identified, including studies on megaprojects as well as  
228 general projects. Secondly complexity indicators are identified in all those publications and  
229 recorded with a brief definition. Altogether 121 relevant indicators were identified. The  
230 next task is to consolidate these indicators into a taxonomy of PCIs. This is carried out in two  
231 steps: (1) the identified indicators are compared and merged when similar. This step reduces  
232 the number of indicators from 121 to 51; (2) the remaining 51 indicators are categorised into

233 semantic groups to develop a logical hierarchical structure. The outcome is a taxonomy of  
234 PCIs for megaprojects, which are not specific to the energy sector at this stage.

235 2. The second phase seeks to evaluate the appropriateness of the identified PCIs and to  
236 establish their relative importance when assessing megaprojects. This requires inputs from a  
237 group of domain experts. In recent years, some studies have proposed Group Decision  
238 Making (GDM) techniques to obtain consistent knowledge and opinions from groups of  
239 experts, instead of from separate individuals (Herrera-Viedma et al. 2007; Hwang and Lin  
240 1987; Moreno-Jiménez et al. 2007; Saaty 1989). The GDM method is defined as a process to  
241 find a plural answer to a decision problem, where a group of experts offer their judgments  
242 about multiple alternatives (Zhang et al. 2014). This study aims at establishing the relative  
243 importance of the indicators, based on input from a group of domain experts. A range of  
244 methods was adopted by other researchers (Locatelli and Mancini 2012; Nguyen et al. 2015;  
245 Vidal et al. 2011) for such a task. Based on a review of these methods, this study decides to  
246 use an integrated Delphi- AHP method. It involves two intertwining processes: a prioritising  
247 process of the indicators using AHP by individual expert and a consensus process using  
248 Delphi between all experts. 20 international experts with high familiarity and knowledge of  
249 the energy sector and megaprojects are selected and divided into two panels, with 10  
250 academics and 10 industry practitioners. Therefore, the results are specifically applicable to  
251 the energy sector. Adoption to other sectors can be achieved following the same method,  
252 but with contribution from domain experts in other sectors. More details of the application  
253 of this method are provided in the following sections.

254 3. Scoring criteria are essential to the practical quantification of project complexity, yet this  
255 aspect is frequently neglected in existing research. To fill this gap, numerical scoring criteria  
256 for all identified indicators are defined for the comprehensive literature synthesis.

257 4. The outcomes from the first three phases define the principle and algorithms of the new  
258 PCA method. The final phase is to implement the PCA method as a tool with a user interface

259 for data input and presentation of the output. It is then evaluated by expert review and  
260 tested through a case study project.

## 261 Taxonomy of project complexity indicators

262 A taxonomy is a semantic classification which organises a large number of related concepts into a  
263 logical hierarchy (Krishnaswamy and Sivakumar 2009; Marradi 1990). The taxonomy of PCIs for  
264 megaprojects is established to provide a clear, simple and effective structure to understand the  
265 factors influencing project complexity. It is also essential for the next step of the PCA development  
266 process which involves establishing a weight for each indicator using the AHP method (Kian Manesh  
267 Rad and Sun 2014). Indeed, it is not feasible to conduct pairwise comparisons between tens of  
268 indicators; nor is it meaningful to compare unrelated indicators. The development of the taxonomy  
269 allows comparisons to be conducted between fewer indicators within sub-categories, and between  
270 the sub-categories.

271 At the first step, a comprehensive list of PCIs is obtained through a comprehensive literature review  
272 (Kian Manesh Rad and Sun 2014).

273 The process of constructing the taxonomy consists of two interactive and iterative procedures: top-  
274 down and bottom-up. The top-down process helps to determine the higher levels groupings of the  
275 taxonomy hierarchy, e.g. Levels 1 and 2 categories for both internal and external PCIs as well as  
276 Level 3 of internal PCIs . The bottom-up process analyses the list of PCIs to identify logical groups of  
277 related indicators and links the groups to the higher level categories. This process leads to the  
278 development of the final PCI taxonomy (Tables 1 and 2).

279 <Table 1. Taxonomy of PCIs - external factors >

280 <Table 2. Taxonomy of PCIs - internal factors >

281 At Level 1, there are two distinct categories which distinguish indicators within the project (internal)  
282 from those imposed from outside (external). External indicators are those outside the direct control

283 of the project delivery organisation and relate to external stakeholders, such as governments or  
284 market forces. In contrast, internal indicators are those actually within the control of the project  
285 management team.

286 The external category contains 10 PCIs divided into five sub-categories (Level 2) including  
287 environmental, political, legal and regulatory, economic and social aspects.

288 There are 41 internal indicators grouped into three sub-categories (Level 2) defined as  
289 corresponding to the questions 'What' 'Who' and 'How' respectively (Office of Government  
290 Commerce 2009). This grouping reflects the principle of the PRINCE2 project management standard  
291 provided by the Office of Government Commerce (2009).

292 1. 'What' refers to "Project characteristics" that are further divided into two sub-  
293 categories (Level 3): technical characteristics and project objectives.

294 2. 'Who' refers to "Project delivery organisation/team" and includes four sub-  
295 categories (Level 3): people, disciplines, capital and physical resources.

296 3. 'How' is associated with "Process of delivery" of the project and includes four sub-  
297 categories (Level 3) of tasks, information, tools and methods, and time.

298 Table 2 and Table 3 present the detailed taxonomy of external and internal indicators respectively.  
299 For easier reference, a code is allocated to each indicator based on the level and category it belongs  
300 to.

### 301 **Establishing the weights of indicators**

302 When assessing project complexity, all indicators may not exhibit the same levels of importance (He  
303 et al. 2015). Therefore, different weights should be attributed to the indicators to ensure reliable  
304 assessment. In this research, this weighting is achieved through a Delphi-AHP method that elicits the  
305 collective knowledge and judgement of 20 international experts. Two challenges during this process  
306 are to ensure (i) *consistency* of judgement of individual experts; and (ii) *consensus* amongst experts

307 (Dyer and Forman 1992; Saaty 1989). Several studies have proposed methods for achieving  
308 consistency and consensus (Herrera-Viedma et al. 2002, 2014). Zhang et al. (2014) reviewed the  
309 advantages and drawbacks of these methods and concluded that the method developed by Chiclana  
310 et al. (2008) is one of the most effective. This method employs transitivity properties of criteria in a  
311 mathematical procedure to retain original values of judgments at an optimal level, whilst obtaining  
312 acceptable levels of consistency and consensus. Therefore, this study adopted an integrated  
313 consistency-checking consensus-building method based on that of Chiclana et al. (2008), with some  
314 additions to it. Fig. 2 summarises the steps of the integrated Delphi-AHP method, including the  
315 process for consistency checking and consensus building:

316 < Fig. 2. Integrated Delphi-AHP consistency checking and consensus building method >

- 317 1. Selecting experts: Identify, nominate and select the most appropriate experts for the panel.
- 318 2. Delphi-AHP round 1: To elicit the weights of PCIs, by asking the selected experts to complete  
319 a series of pairwise judgements matrices. Responses from each expert are checked for  
320 consistency and corrections are applied automatically when required, following the method  
321 suggested by Chiclana et al. (2008).
- 322 3. Delphi-AHP round 2 (consensus building): Builds the required level of consensus through  
323 sets of feedback matrices.
- 324 4. Calculating weights for PCIs: Compute weights of indicators using the geometric mean  
325 method.

326 Each step of this process is detailed in the following.

327 **Selecting experts:** This study adopted a multi-stage process to identify experts to participate in the  
328 Delphi-AHP process, as suggested by Delbecq et al. (1975). In the first stage, a Knowledge Resource  
329 Nomination Worksheet (KRNW) was developed, which defines the key qualifications required for  
330 these experts. It was then used to record individual names identified from related publications in  
331 journals and books, professional social media (LinkedIn), websites of some large energy

332 organisations and professional bodies such as governments and the European Cooperation in  
333 Science and Technology (COST). Using the KRNW helped ensure that there are no gaps in the skills of  
334 the expert panel. At the end of this stage, 78 potential experts were identified. At the second stage,  
335 all the identified experts were contacted and provided with information about this study. They were  
336 invited to participate in the Delphi-AHP process, with explanations about their roles and expected  
337 contributions. Twenty experts agreed to participate; 10 of them are academics and 10 are  
338 professionals working in the energy industry. Table 4 shows background information on the experts.

339 <Table 3. Information of experts>

340 **Delphi-AHP Round 1:** In the first round of the Delphi-AHP process, the experts were asked to  
341 complete a questionnaire, which contains pairwise comparisons matrices of complexity indicators,  
342 using a 1-9 Saati scale (Saaty 1977). Twelve matrices were provided based on the taxonomy,  
343 comprising of: one matrix of external indicators at level 3, one matrix of internal indicators at level 3  
344 and ten matrices of internal indicators at level 4, one for each category (Table 5). The experts were  
345 asked to conduct the comparisons based on their cumulative knowledge/expertise rather than any  
346 specific project. Table 6 shows a judgement matrix corresponding to the internal category of People  
347 (Level 4).

348 <Table 4. Matrices used in the Delphi-AHP process>

349 <Table 5. Sample of AHP pairwise comparison matrix in round 1 Delphi-AHP, category of people>

350 In GDM problems, consensus of judgments of multiple experts is usually reached on the basis of  
351 rationality principles that each expert exhibits. The requirement of rationality demands consistency  
352 of judgement from each individual expert. Therefore, given the experts' responses in round 1, the  
353 first task is to evaluate the degree of consistency of each expert, and improve it to an acceptable  
354 level (threshold) if required. To do this, inconsistent judgments are first identified from the Delphi-  
355 AHP round 1 results. Chiclana et al. (2008) devised an iterative process requesting experts to amend

356 their initial judgments based on the advised values until an acceptable consistency level was  
357 reached. Whereas consistency of all individual judgements is mandatory for the basis of AHP  
358 method, the feedback process to experts seems unnecessary here. One of the dangers of using the  
359 Delphi method is that an increasing number of rounds may lead experts to lose interest and not  
360 returning the questionnaires, which would threaten the validity of the results. Therefore, in this  
361 research, the inconsistent judgments are amended with advised values automatically generated by  
362 a software tool based on the method proposed by Chiclana et al. (2008). This process is iterated until  
363 the experts' responses for all matrices satisfy the consistency threshold. Saaty (1977) defined 10% as  
364 an acceptable level of inconsistency in each matrix, so a consistency threshold value  $\beta = 0.9$  is used  
365 and each expert judgment is assessed against it. Firstly, for each set of judgments by an expert  $l$   
366 related to alternatives (i.e. indicators)  $(i, j)$ , if one or more pairwise comparisons have a consistency  
367 degree  $cd_{ij}^l \leq \beta$ , then an automatic consistency checking process is applied. Although individual  
368 consistency is essential, it should be noted that the initial independence of each expert's judgment  
369 should not be violated. To ensure this, a threshold  $\delta = 35\%$  is defined and each judgment matrix  
370 with more than  $\delta$  of its values requiring update in the initial judgement values is omitted from  
371 further computations. Afterwards, a scenario analysis process is carried out to determine the  
372 optimal number of necessary updates for the inconsistent judgments. Our software tool not only  
373 implements the algorithm put forward by Chiclana et al. (2008) but also builds and performs a  
374 procedure of automatic maximum consistency checking. Using this method, new adjusted values  
375 and consistency levels for each matrix are computed.

376 Table 7 shows the results of the application of the automated consistency checking process. 2.1% of  
377 judgment matrices exceeded  $\delta$ , which is small and thus indicates a good initial consistency for the  
378 majority of experts. The process then updated on average 10.2% of the initial expert judgments to  
379 achieve individual consistency for all experts.

380 < Table 6. Results of consistency building process >



381 **Delphi-AHP Round 2:** Consensus should be sought among all the experts for all PCIs, although a full  
382 consensus is not always necessary in practice. A consensus threshold  $\gamma \in [0,1]$  is defined; and at  
383 each stage of the process the level of consensus is measured and compared against it. If the  
384 consensus level is not satisfactory, the most diverse judgment values from combined experts'  
385 judgments are identified and those experts are asked in the Delphi-AHP round 2 to review their  
386 initial judgment to reach a higher consensus level. This is an iterative process that continues until an  
387 acceptable level of consensus is reached, and only then are the consolidated and global weights of  
388 indicators computed. It should be noted that in this research, all levels of consistency and consensus  
389 were reached after only one iteration (i.e. at the end of round 2).

390 Depending on the type of problem, experts' backgrounds, or specific project situations, different  
391 levels of consensus may be required. For this reason, three ranges  $\gamma_1$ ,  $\gamma_2$  and  $\gamma_3$  for consensus are  
392 defined to highlight the consensus rate ( $cr$ ), as showed in Fig. 3. The thresholds gauge local  
393 consensus (each category) and total consensus, and identify if the obtained consensus is acceptable  
394 or if the process should progress into another round. In this research, a medium level i.e.  $0.8 \leq cr \leq$   
395  $0.9$  is considered satisfactory for the total consensus because of the complex character of the  
396 problem. The consensus rates are acceptable if they are within any of the ranges defined by  $\gamma_1$ ,  $\gamma_2$   
397 and  $\gamma_3$ .

398 < Fig. 3. Defined ranges of acceptable consensus >

399 The consensus building process firstly identifies those experts and judgment values that should be  
400 reviewed. These normally are the furthest individual values from the combined panel's judgement.  
401 Secondly, these experts are provided with advised values obtained by combining all judgment values  
402 of the panel, using the arithmetic mean method. A questionnaire is sent to these experts comprising  
403 their round 1 judgements alongside the advised values, and they are asked to reconsider their  
404 judgement. All experts responded to round 2 questionnaires; however some of them have chosen to  
405 keep their initial judgments and did not update them as suggested. Once all responses were  
406 received, the level of consensus based on the modified judgement values was re-evaluated.

407 As shown in Table 8, initially  $cr = 0.75$  is in the low consensus range. After one iteration of the  
408 consensus building process, the overall  $cr = 0.81$  suggests the effectiveness of the proposed  
409 Delphi-AHP GDM process to achieve consensus. The highest local consensus is found for the  
410 “Information” category with 86% while “Physical Resources” and “Tools and Methods” showed the  
411 lowest consensus levels with 72% and 71% respectively, although both still satisfy the (low)  
412 consensus threshold. Since the overall medium consensus level desired in this study is reached,  
413 there is no need for any further round of Delphi.

414 < Table 7. Results of Consensus reaching and advice system

415  
416 **Calculating weights of indicators:** The subject of priorities derivation (here weights of indicators) in  
417 AHP has been discussed by Ishizaka and Lusti (2006) in order to establish the best method. A review  
418 of their study and other literature found that weight calculation methods can be classified in two  
419 categories: the eigenvalue vector (EV) and geometric mean (GM) vector methods (Johnson et al.  
420 1979; Saaty 1977). The EV method obtains a scale of the importance of each element of a collection,  
421 relative to the others, while GM yields priority of elements using the geometric mean distance  
422 metric. Crawford & Williams (1985) conducted an extensive comparison of these two categories of  
423 methods using statistical and simulation analysis and demonstrated a better performance of the  
424 geometric mean method over the eigenvalue methods. Thus, this method has been applied in this  
425 research. Given  $p_{ij}$  a preference relation between indicator  $i$  and  $j$  in a  $n \times n$  judgment matrix,  $i \neq j$ ,  
426 the consolidated weight of indicator  $i$ ,  $w_i$ , is obtained with the geometric mean formula as follows:

$$w_i = \prod_{j=1}^n p_{ij}^{1/n}$$

427  
428 While consolidated weights represent the relative importance of indicators within the given  
429 category, it is also useful to obtain the global weight of each indicator so that all indicators can be  
430 compared against one another, regardless of the category they belong to. One method to do this is  
431 to multiply the weight of the category with the weight of the indicator. However, a main weakness

432 of this method is that weights of indicators decline when the number of them in each category  
433 increases. Ramanathan (1997) proposed a solution to this problem by calculating the global weight  
434  $gw_i$  of indicator  $i$  using its relative weight within the category. The proposed formula is:

$$435 \quad gw_i = \left( \frac{w_i}{w^*} \right) \times A$$

436 where  $w^*$  is the highest value in the category,  $A$  is the category's weight and  $w_i$  is the weight of  
437 indicator  $i$ .

438 The consolidated and global weights of each indicator and category in level 2, 3 and 4 of the  
439 taxonomy have been calculated and are presented in Table 9 and Table 10.

440 < Table 8. Consolidated and global weights of external complexity indicators >

441 < Table 1. Consolidated and global weights of internal complexity indicators >

## 442 **Defining scoring criteria for complexity indicators**

443 Establishing scoring criteria is a key phase in the process of project complexity assessment. However,  
444 this phase is very often neglected in the existing studies and methods for project complexity  
445 evaluation. In contrast, this study established comprehensive scoring criteria for all identified PCIs  
446 based on an extensive literature review and synthesis. Both a content analysis and interpretive  
447 synthesis have been carried out to couple the indicators and criteria, and form the scoring metrics.  
448 As an example of the approach followed in this research, Locatelli & Littau (2013) and Locatelli et al.  
449 (2014) identified performance variables of energy megaprojects based on an analysis of eleven  
450 European case studies. In addition, Brooks (2013) extracted thematic influencing criteria from the  
451 analysis of a European megaprojects portfolio. These provided a set of objective criteria for the  
452 "Significance on public agenda" indicator (Table 11). While each project entails a level of complexity  
453 and megaprojects register higher levels of such, each numerical scale of complexity should be able  
454 to capture this variability. Therefore a 1-5 Likert scale (see "Scores" column in example shown in  
455 Table 11) is used to determine the numerical score for each indicator, based on the identified

456 scoring criteria, where “1” indicates the least and “5” the highest complexity level. The scoring  
457 criteria are defined as objectively as possible, so that they can be understood and agreed by  
458 decision-makers.

459 < Table 10. Scoring criteria defined for the “Significance on public agenda” indicator >

460 Scaling the numerical indicators is also a critical stage in defining the measure. For example,  
461 “Number of activities” frequently appears in the existing PCA literature (Bosch-Rekvelde et al. 2011;  
462 He et al. 2015; Nguyen et al. 2015; Vidal et al. 2011). However, no viable measure or method has  
463 been proposed to quantitatively measure this indicator. It is problematic to determine absolute  
464 numerical thresholds for different levels of complexity, based on the number of activities, due to  
465 inaccessibility of reliable data. In addition, the absolute value may well vary for different companies  
466 based on their experience and capabilities: a project may be extremely complex in terms of activities  
467 for company A, but very simple for company B. In other words, using absolute numerical thresholds,  
468 based on the number of activities, would revert to assessing perceived complexity which this  
469 research aims to avoid. To tackle this problem and reach the most reliable numerical criteria, this  
470 research borrows the concept of a “*competitiveness*” criterion, initially defined by Merrow (2011) to  
471 reflect relative cost overrun and schedule slip of megaprojects compared to similar projects in the  
472 company, and develops it to broader definitions. For instance, applying this relative complexity  
473 definition,

474 Table 12 shows the scoring criteria defined for the “Number of activities” indicator. To ensure  
475 validity of the developed scoring criteria, an expert review is adopted. The results of this review also  
476 helped to refine the obtained scoring criteria.

477 < Table 11. Defined scoring criteria for “Number of activities”>

478 With all the components of the PCA method defined (indicators, global weights and scoring criteria),  
479 a Complexity Index (*CI*) can now be computed for any project using the formula:

$$480 \quad CI = \sum_{i=1}^m gw_i \times s_i$$

481 Where  $gw_i$  is the global weight of indicator  $i$ ,  $m$  is the total number of indicators and  $s_i$  is the  
482 awarded score to the indicator. The *CI* value should be between 1 and 5; is calculated separately for  
483 external and internal indicators. The complexity levels of each category of the taxonomy are also  
484 calculated using this method.

## 485 Evaluation of PCA method

486 The developed PCA method is evaluated to gauge its validity and tested for application in practice.  
487 An expert review is conducted in two stages with both academics and professionals for the purpose  
488 of assessing the validity of the developed PCA method. Because the PCI taxonomy and the PCI  
489 weights were produced based on experts input, there is no need for additional evaluation of their  
490 validity. Therefore, expert review at this stage is focused on validating the scoring criteria for all the  
491 PCI indicators. To test the application of the PCA method, a case study is carried out using a real  
492 energy megaproject.

493 Nine experts participated in the expert review including three academics and six professionals with a  
494 high level of familiarity and knowledge about the energy sector and megaprojects. The background  
495 information of the experts is summarised in Table 13.

496 < Table 12. Background information of participants in expert review of scoring criteria>

497 A questionnaire is designed in the form of a spreadsheet. Assessment of each scoring criterion  
498 included two questions: a closed-ended yes/no questions to capture agreement or disagreement  
499 with the proposed scoring criteria for the given PCI, and an open-ended question to enable the user  
500 to state underlying reasons (particularly in the case of disagreement).

501 The questionnaire was sent to the nine experts and the responses analysed for refining the criteria.  
502 Overall, the feedbacks showed that the experts strongly supported the numeric scoring criteria. Few  
503 but useful refinements of the criteria were nonetheless suggested, as summarised in Table 14.

504 < Table 13. Summary of expert's feedbacks and analysis >

## 505 Case study

506 To evaluate the application of the proposed PCA method further, a case study is carried out with an  
507 offshore gas field reservoir development programme. It is one of the world's largest reservoirs of  
508 natural gas condensates. Development of the field is planned in multiple phases; each phase is  
509 appraised to have an average capital cost of more than US\$1 billion, and is executed by international  
510 oil & gas contractors working in partnership with local companies. This case study is conducted on  
511 the development of two phases, referred to as A and B, which are at the tendering stage. The field  
512 development programme has been delayed and interrupted due to different technical, contractual,  
513 financial and political issues. The two phases are typical examples of energy megaprojects. Assessing  
514 their complexity shall provide valuable information to help the project management team adopt  
515 appropriate complexity management strategies. The weighted indicators produced by the proposed  
516 PCA method are provided in a spreadsheet tool for the project management teams of phases A and  
517 B. Also, in order to produce a reference, levels of complexity are computed for a set of completed  
518 phases currently in operation (OPT). The level of complexity of each phase is assessed by the project  
519 manager of each phase with high levels of knowledge about the project.

520 Fig. 4 depicts and compares weighted aspects of project complexity and a computed final  
521 Complexity Index (CI) for each project. Phase A shows a higher degree of complexity than the

522 operational phases and phase B ( $CI(A) > CI(OPT) > CI(B)$ ). Furthermore, the values of  
523 complexity in each category enable decision makers to better understand the degrees of complexity  
524 in all aspects of the project, and therefore implement more effective mitigation strategies.

525 By computing the level of complexity for each phase, the project team decided to implement specific  
526 strategies to cope with complexities in each aspect. For instance, phase A and B are significantly  
527 more complex than OPT in capital resources complexity, therefore the project team established a  
528 dedicated capital management system within the overall project management organisation to  
529 manage the financial resources. Another example is the political complexity of phase A that is far  
530 higher than Phase B and OPT. From this, it is decided that a separate team be put together during  
531 the project tendering and operation stages to manage political issues and communication with the  
532 main stakeholders.

533 < Fig. 4. Level of complexity in aspects of internal and external complexity and values of CIs >

## 534 Discussions and Conclusions

535 The complexity assessment method developed in this study adds to the growing body of knowledge  
536 concerned with the issue of project complexity, from a particular perspective of megaprojects in the  
537 energy sector. Comparing with existing research, this study makes three significant contributions.

- 538 • The taxonomy of project complexity indicators provides a more comprehensive framework  
539 to assess energy megaprojects. The groupings of internal complexity indicators reflect  
540 common project management principles and make them easily understandable to  
541 professionals (Office of Government Commerce, 2009). In recognition of the fact that  
542 external influencing factors, such as government policies and environment concerns, often  
543 play a crucial role in the success of energy megaprojects, the taxonomy also puts more  
544 emphasis on external complexity indicators compared with previous studies (Baccarini,  
545 1996; Bosch-Rekvelde et al. 2011).

- 546       • The PCA method developed in this research is tailorable and can be applied in other similar  
547 megaprojects to objectively measure various aspects of project complexity for improving the  
548 decision making process and enhancing the success of megaproject delivery. The weights for  
549 all complexity indicators used to calculate complexity indices were established based on  
550 inputs from 20 international experts obtained through an integrated Delphi-AHP process. It  
551 is acknowledged that a different group of experts may produce different indicator weights.  
552 Indeed, different interpretations of expert inputs, e.g. giving weights to different experts  
553 depending on their backgrounds and competencies, can lead to different results.  
554 Nonetheless, the breadth of expertise sought in this research suggests that the weights  
555 produced by this study offer an appropriate benchmark for assessing similar future projects.  
556 But, if a new project team wants to achieve more accurate measurement, it can follow the  
557 Delphi-AHP method of phase 3 of this study to establish indicator weights that are specific to  
558 its (type of) project.
- 559       • The definitions of scoring criteria for all complexity indicators constitute a significant  
560 contribution of this study. These are specified as explicitly and objectively as possible to  
561 reduce the influence of subjectivity by the assessor(s). The defined criteria have been  
562 reviewed by highly knowledgeable experts and refined based on their feedback.

563 The complexity assessment method has been implemented as a simple spreadsheet tool. When  
564 using it, a practitioner only needs to score the complexity indicators by applying the scoring criteria.  
565 The tool then calculates two separate complexity indices – one for internal complexity and the other  
566 for external complexity. These indices provide an indication of the overall level of complexity of a  
567 project. The tool also provides detailed breakdowns of complexity in the different categories of  
568 indicators. This allows the project team to identify particular areas where high levels of complexity  
569 exist, so that due attention can be paid to managing them. The method and tool have been  
570 evaluated by the experts involved in the study and tested in one case study. Results suggest that it is  
571 a useful tool for managing megaprojects in the energy sector.



572 This study has only developed a PCA method, and did not propose ways for managing various levels  
573 of project complexity in different categories. Future work could explore this subject and establish  
574 managerial strategies that could be suggested to the management team for each complexity degree.

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## 578 Supplementary Data

579 Tables S14-S17 are available online in the ASCE Library ([ascelibrary.com](http://ascelibrary.com))

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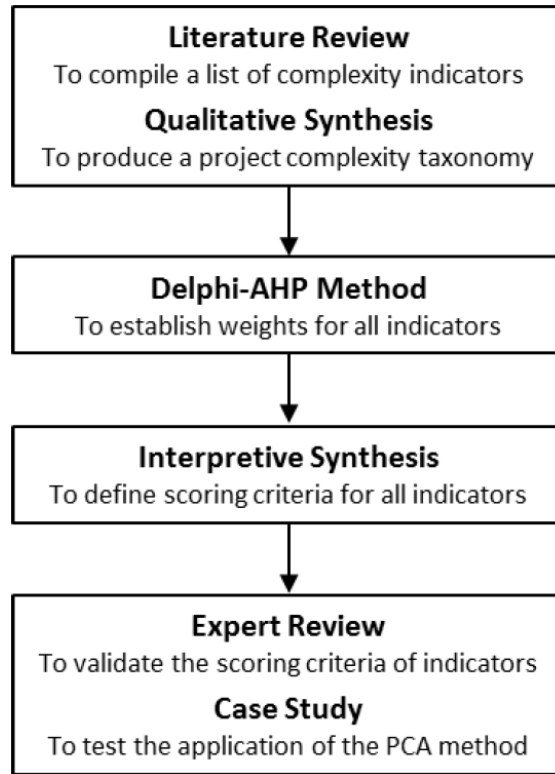
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739 **Figures**

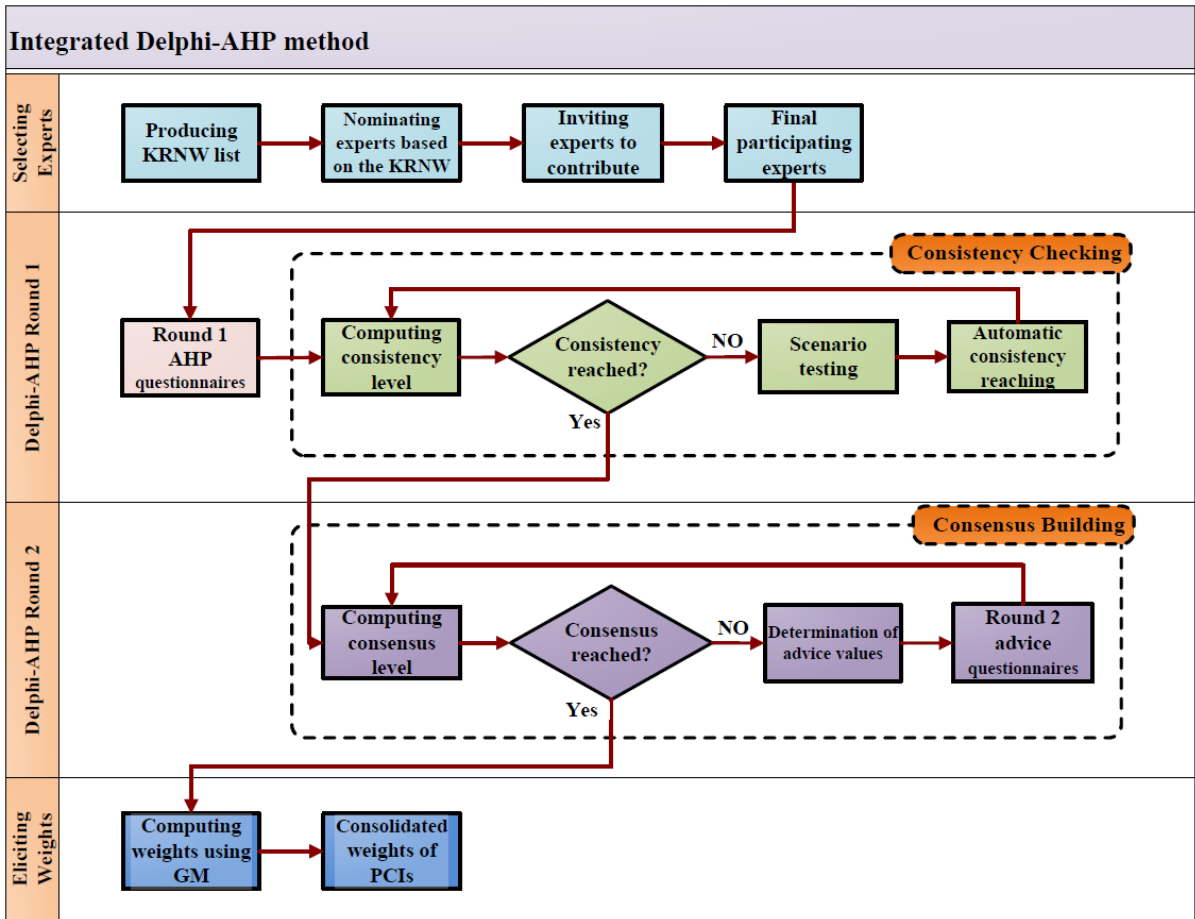


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Fig. 1. Research phases and methods

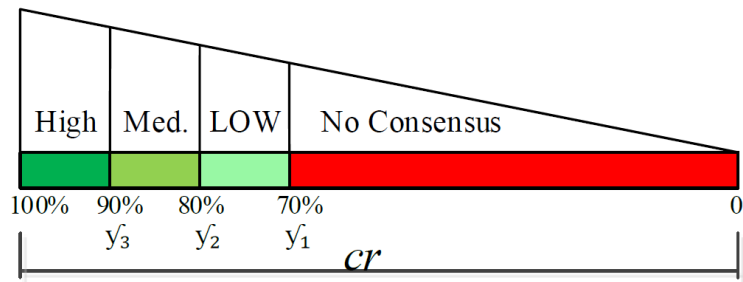


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Fig. 2. Integrated Delphi-AHP method



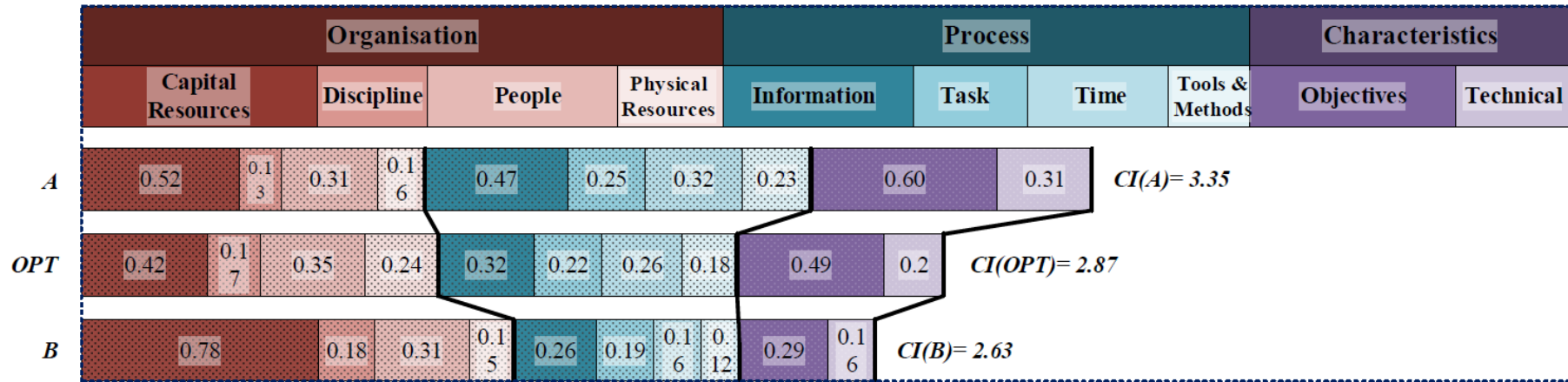
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Fig. 3. Defined ranges of acceptable consensus

### Internal Complexity



Weighted Score of project in aspect of complexity

### External Complexity

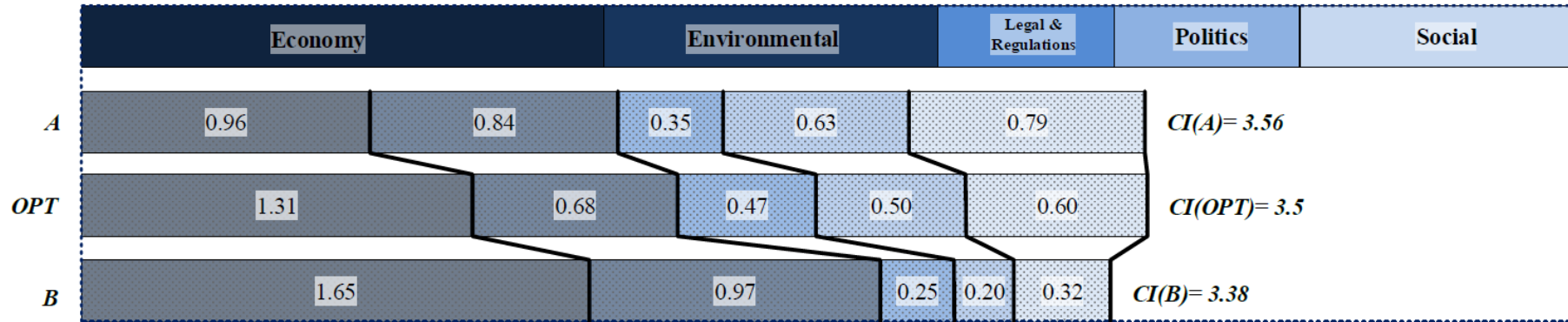


Fig. 4. Calculated level of complexity for case study



752 **Tables**

753 Table 2. Taxonomy of PCIs - external factors (indicators are compiled from number of sources such as Gerald  
754 et al. 2011; Flyvbjerg, 2014; Merrow, 2011)

Level2		Level3
Economy (EC)	EEC1	Changing economy
	EEC2	Market competition
	EEC3	Market unpredictability and uncertainty
Environmental (EN)	EEN1	Stability of project environment
	EEN2	Interaction between the technology system and external environment
Legal & regulations (LE)	ELE1	Local laws and regulations
Politics (PO)	EPO1	Political influence
	ESO1	Cultural configuration and variety
Social (SO)	ESO2	Cultural differences
	ESO3	Significance on public agenda

755

756 Table 3. Taxonomy of PCIs - internal factors (indicators are compiled from number of sources such as Bosch-  
 757 Rekveldt et al. 2011; Vidal et al. 2011; He et al. 2015)

Level2	Level3	Level4
Organisation / Team of Delivery (OR)	Capital resources (CA)	IORCA1 Size of capital investment
		IORCA2 Variety of investors and financial resources
		IORDI1 Contract types
	Disciplines (DI)	IORDI2 Variety of institutional configuration
		IORDI3 Support from permanent organisations
		IORDI4 Team cooperation and communication
		IORPE1 Availability of human resources
	People (PE)	IORPE2 Level of trust ( inter/intra teams)
		IORPE3 Diversity of participants
		IORPE4 Dynamic and evolving team structure
		IORPE5 Experience and capabilities within teams
		IORPE6 Interest and perspectives among stakeholders
		IORPH1 Resource and raw material interdependencies
	Physical resources (PH)	IORPH2 Variety of resources
IORPH3 Availability of physical resources		
IPRIN1 Availability of information		
IPRIN2 Reliability of information platforms		
Information (IN)	IPRIN3 Interdependence of information systems	
	IPRIN4 Level of processing and transferring information	
	IPRTA1 Diversity of sites and locations	
	IPRTA2 Process interdependencies	
Process of Delivery (PR)	Tasks (TA)	IPRTA3 Dependencies between tasks
		IPRTA4 Number of activities
		IPRTA5 Unpredictability of tasks
		IPRTA6 Diversity of activities elements
		IPRTI1 Duration of project
		IPRTI2 Dependencies between schedules
	Time (TI)	IPRTI3 Intensity of project schedule
		IPRTO1 Applicability of project management methods and tools
	Tools & methods (TO)	IPRTO2 Variety of project management methods and tools
		IPCOB1 Variety of goals and objectives
Objectives (OB)	IPCOB2 Interdependence of objectives	
	IPCOB3 Transparency of objectives	
	IPCOB4 Scope changing	
	IPCTE1 Level of innovation	
Project Characteristics (PC)	IPCTE2 Technological experience and capabilities	
	IPCTE3 Repetitiveness of process	
	IPCTE4 Specifications interdependencies	
	IPCTE5 Technological varieties	
	IPCTE6 Variety of system components	
	IPCTE7 Changing technology	

758

759 Table 4. Information of experts

a) Experience in energy sector					
Years	6-10	11-15	16-20	>20	
Academia	2	3	3	2	
Professional	2	1	3	4	
b) Sub-Sector of professionals					
Sector	Oil&Gas	Renewable	Utility	Consultancy	Construction
Professional	3	2	1	1	3
c) Level of experience in megaprojects					
Level	Familiar	Knowledgeable	Advanced	Expert	
Academia	0%	50%	30%	20%	
Professional	0%	20%	30%	50%	

760

761 Table 5. Matrices used in the Delphi-AHP process

Name of matrix	Size of matrix
External indicators - Level 3	10
Internal indicators - Level 3	10
Capital resources - Level 4 of internal	2
Disciplines - Level 4 of internal	4
People - Level 4 of internal	6
Physical resources - Level 4 of internal	3
Information - Level 4 of internal	4
Tasks - Level 4 of internal	6
Time - Level 4 of internal	3
Tools & Methods - Level 4 of internal	2
Objectives - Level 4 of internal	4
Technical - Level 4 of internal	7

762

763 Table 6. Sample of AHP pairwise comparison matrix in round 1 Delphi-AHP, category of people

	A	B	C	D	E	F
Availability of human resources (A)		5	7	3	1	1
Level of trust ( inter/intra teams) (B)			3	1	1/3	1
Diversity of participants (C)				1/3	1/3	1/3
Dynamic and evolving team structure (D)					1/5	1
Experience and capabilities within teams (E)						5
Interest and perspectives among stakeholders (F)						

764

765 Table 7. Results of consistency building process

Panel	Expert	Avg initial individual consistency (cd)	Number of inconsistent matrices	%Avg updated for inconsistent matrices	Avg built individual consistency (cd)
Academic	P1	0.91	5	13.3%	0.94
	P2	0.93	2	1.0%	0.94
	P3	0.87	5	22.6%	0.92
	P4	0.88	4	11.4%	0.92
	P5	0.95	3	4.0%	0.95
	P6	0.90	5	11.0%	0.94
	P7	0.91	4	8.7%	0.93
	P8	0.89	5	18.0%	0.93
	P9	0.93	1	3.8%	0.94
	P10	0.91	5	10.9%	0.92
Professional	P11	0.92	1	5.0%	0.93
	P12	0.90	6	13.8%	0.93
	P13	0.90	4	17.8%	0.93
	P14	0.92	2	4.9%	0.92
	P15	0.92	3	2.9%	0.93
	P16	0.92	4	11.7%	0.94
	P17	0.89	8	20.6%	0.92
	P18	0.92	1	1.7%	0.93
	P19	0.91	2	7.7%	0.93
	P20	0.92	4	12.8%	0.94

766

767 Table 8. Results of Consensus reaching and advice system

Category	Initial <i>cr</i>	% of judgments asked to modify	% of judgments accepted to modify	Combined final <i>cr</i>
External	0.76	16%	13%	0.81
Internal	0.79	16%	10%	0.81
Capital Resources	0.73	30%	23%	0.81
Disciplines	0.72	18%	14%	0.84
People	0.82	15%	9%	0.84
Physical Resources	0.64	40%	33%	0.72
Information	0.83	8%	6%	0.86
Tasks	0.74	36%	21%	0.79
Time	0.75	29%	21%	0.81
Tools & Methods	0.62	45%	33%	0.71
Objectives	0.77	30%	25%	0.84
Technical	0.80	28%	21%	0.84
Average	0.75	26%	19%	0.81

768

769 Table 9. Consolidated and global weights of external complexity indicators

Level2	category weight	Level3 indicators	$w_i$	$gw_i$
Economy	34.84%	EEC1	13.00%	20.50%
		EEC2	9.10%	14.35%
		EEC3	12.74%	20.10%
Environmental	22.52%	EEN1	14.50%	10.48%
		EEN2	8.02%	5.80%
Legal & regulations	11.63%	ELE1	11.63%	5.23%
Politics	12.52%	EPO1	12.52%	5.85%
		ESO1	4.72%	4.52%
Social	18.47%	ESO2	4.32%	4.14%
		ESO3	9.43%	9.03%

770



771 Table 10. Consolidated and global weights of internal complexity indicators

Level2	Level3	category weight	Level4 indicators	$w_i$	$gw_i$
Organisation / Team of Delivery	Capital resources	15.78%	IORCA1	67.02%	5.43%
			IORCA2	32.98%	2.67%
			IORDI1	33.54%	2.51%
	Disciplines	7.29%	IORDI2	24.08%	1.80%
			IORDI3	22.62%	1.69%
			IORDI4	19.76%	1.48%
			IORPE1	16.33%	3.14%
			IORPE2	22.80%	4.38%
	People	12.73%	IORPE3	9.77%	1.88%
			IORPE4	15.06%	2.89%
			IORPE5	21.73%	4.17%
			IORPE6	14.32%	2.75%
Physical resources	7.09%	IORPH1	40.07%	2.44%	
		IORPH2	29.34%	1.79%	
		IORPH3	30.59%	1.86%	
Process of Delivery	Information	12.71%	IPRIN1	36.12%	3.97%
			IPRIN2	39.73%	4.37%
			IPRIN3	11.55%	1.27%
			IPRIN4	12.60%	1.39%
			IPRTA1	18.97%	2.30%
			IPRTA2	15.90%	1.93%
	Tasks	7.68%	IPRTA3	21.78%	2.64%
			IPRTA4	11.54%	1.40%
			IPRTA5	20.33%	2.47%
			IPRTA6	11.48%	1.39%
	Time	9.88%	IPRTI1	36.85%	3.40%
			IPRTI2	27.69%	2.56%
			IPRTI3	35.47%	3.27%
Tools & methods	5.40%	IPRTO1	64.46%	1.86%	
		IPRTO2	35.54%	1.02%	
Project Characteristics	Objectives	13.83%	IPCOB1	11.99%	1.38%
			IPCOB2	14.51%	1.66%
			IPCOB3	41.47%	4.76%
			IPCOB4	32.03%	3.67%
			IPCTE1	19.12%	2.37%
			IPCTE2	21.09%	2.62%
			IPCTE3	9.92%	1.23%
	Technical	7.61%	IPCTE4	17.45%	2.17%
			IPCTE5	11.17%	1.39%
			IPCTE6	10.35%	1.29%
			IPCTE7	10.90%	1.35%

772

773 Table 11. Scoring criteria defined for the “Significance on public agenda” indicator

Indicator	Criteria	Scores
Significance on public agenda	Regarding significance of project in public, how many of the following criteria are (will be) met?	1: If 4 or 5 criteria are met.
	a. Green Peace or other international environmental activists have been involved in the project	3: If 2 or 3 criteria are met.
	b. The project has national public acceptability (no protest at national level)	5: If 0 or 1 criterion is met.
	c. The project has local public acceptability (no protest at local levels)	
	d. Previous similar national/local project were successful	
	e. Local residents are involved in the project	

774

775 Table 12. Defined scoring criteria for “Number of activities”

Indicator	Criteria	Scores
Number of activities	Relative to other projects in your organisation, what is the level of project task competitiveness, considering elements or deliverables in the work breakdown structure?	1: In bottom 25% 3: Between 25% and 50% 5: In top 50%

776

777 Table 13. Background information of participants in expert review of scoring criteria

a) Experience in energy sector					
Years	6-10	11-15	16-20	>20	
Academia	0	2	1	0	
Professional	0	1	3	3	
b) Sub-Sector of professionals					
Sector	Oil&Gas	Renewable	Utility	Consultancy	Construction
Professional	2	2	1	1	0
c) Level of experience in megaprojects					
Level	Familiar	Knowledgeable	Advanced	Expert	
Academia	0	1	1	1	
Professional	0	0	3	3	

778

779 Table 14. Summary of expert’s feedbacks and analysis

Indicator	Comments from experts on criteria	Results
Market competition	“None of the operators/modes (competitors) leaving the market” criterion is repeating the first two criteria	The criterion redefined into “None of the operators/modes (competitors) leaving the market (or extremely reduce their operation) during the operation phase”
Local laws and regulations	An expert was not certain about the credibility of “The project is considered in the long term plan of the country’s government” criterion	The rest of experts agreed with the criterion, so no change has been made
Cultural differences	The majority of experts suggested that more criteria are needed	The sources of criteria were reviewed, and as a result the criterion was split into two different ‘cultures’, business and national-geographical culture criteria.
Contract types	Two experts argued that more criteria were needed.	A new criterion is defined as “The organisation obtaining the contract will subcontract to other companies”.
Support from permanent organisation	Five experts disagreed with “Project manager has a position in the company’s board” criterion.	This criterion was removed.
Interdependence of information systems	Four experts suggested the question is not clear.	The question was re-written in a more explicit way.
Level of processing and transferring information	Three experts criticised the clarity of the question.	The question was rewritten and expanded.
Intensity of project schedule	Two experts proposed more criteria were needed and offered a related publication.	The review of the publication led to the selection of a new criterion: “Harsh physical or environmental conditions”.
Applicability of project management methods and tools	An expert declared uncertainty about the “Existence of sensitivity analysis” and “Appointment of a dedicated project manager in the team”	The rest of experts agreed with the criterion, so no change has been made
Variety of goals and objectives	Two experts were unsure about the importance of “Environmental activist have opinion and voice about the project”.	The importance of criterion is supported by the rest of experts, then no change has been made

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