Complexity for Megaprojects in the Energy Sector

Assessment of Complexity for Megaprojects in the Energy Sector

Ehsan Kian M. R.[1], Ming Sun[2], Frédéric Bosché[3]

[1] *Ph.D, Business Improvement Lead, Petrofac, 1 N Esplanade W, Aberdeen, AB11 5QF, UK (Corresponding auther). E-mail: e.kianmaneshrad@gmail.com*

[2] *Ph.D, Professor in Construction Management and Innovation, School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University, Edinburgh, EH14 4AS, UK. E-mail: m.sun@hw.ac.uk*

[3] *Ph.D, Associate Professor, School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University, Edinburgh, EH14 4AS, UK. E-mail: f.n.bosche@hw.ac.uk*

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.

Introduction

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

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

2

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.

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-Rekveldt 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

4

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-Rekveldt 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-Rekveldt 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-Rekveldt 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-Rekveldt 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.

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

10

259   for data input and presentation of the output. It is then evaluated by expert review and

260   tested through a case study project.

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.

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

13

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 δ 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 δ, 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 γ_1, γ_2 and γ_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 γ_1, γ_2

397   and γ_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.

16

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 ≠ j*,

426   the consolidated weight of indicator *i, w_i,* is obtained with the geometric mean formula as follows:

427
$$w_i = \prod_{j=1}^{n} p_{ij}^{1/n}$$

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

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>

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

18

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-Rekveldt 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
$$CI = \sum_{i=1}^{m} gw_i \times s_i$$

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>

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-Rekveldt 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.

Acknowledgement

Supplementary Data

579   Tables S14-S17 are available online in the ASCE Library (ascelibrary.com)

References

581   Aitken, A., and Crawford, L. (2007). "A study of project categorisation based on project management
582   complexity." *IRNOP VIII*.

583   Augustine, S., Payne, B., Sencindiver, F., and Woodcock, S. (2005). "Agile project management."
584   *Communications of the ACM*, ACM, 48(12), 85–89.

585   Austin, S., Newton, A., Steele, J., and Waskett, P. (2002). "Modelling and managing project complexity."
586   *International Journal of Project Management*, 20(3), 191–198.

587   Baccarini, D. (1996). "The concept of project complexity—a review." *International Journal of Project
588   Management*, 14(4), 201–204.

589   Bosch-Rekveldt, M., Jongkind, Y., Mooi, H., Bakker, H., and Verbraeck, A. (2011). "Grasping project complexity
590   in large engineering projects: The TOE (Technical, Organizational and Environmental) framework."
591   *International Journal of Project Management*, 29(6), 728–739.

592   Brockmann, C., and Girmscheid, G. (2007). "Complexity of Megaprojects." *CIB World Building Congress*.

593   Brooks, N. (2013). *Emergent Cross-Case and Cross-Sectoral Themes from the Megaproject Portfolio*.

594   Cantarelli, C. C., Flyvbjerg, B., and Buhl, S. L. (2012). "Geographical variation in project cost performance: the
595   Netherlands versus worldwide." *Journal of Transport Geography*, 24, 324–331.

596   Chiclana, F., Mata, F., Martinez, L., Herrera-Viedma, E., and Alonso, S. (2008). "Integration of a Consistency
597   Control Modile Within a Consensus Model." *International Journal of Uncertainty, Fuzziness and
598   Knowledge-Based Systems*, World Scientific Publishing Company, 16(1), 35–53.

599   Crawford, G., and Williams, C. (1985). "A note on the analysis of subjective judgment matrices." *Journal of
600   Mathematical Psychology*, 29(4), 387–405.

601   Dao, B., Kermanshachi, S., Shane, J., and Anderson, S. (2016). "Project Complexity Assessment and
602   Management Tool." *Procedia Engineering*, 145, 491–496.

603   Delbecq, A. L., de Ven, A. H., Gustafson, D. H., Ven, A. H. Van de, and Gustafson, D. H. (1975). *Group techniques
604   for program planning: a guide to nominal group and Delphi processes*. Management applications series,
605   book, Scott, Foresman.

606   Dyer, R. F., and Forman, E. H. (1992). "Group decision support with the Analytic Hierarchy Process." *Decision
607   Support Systems*, 8(2), 99–124.

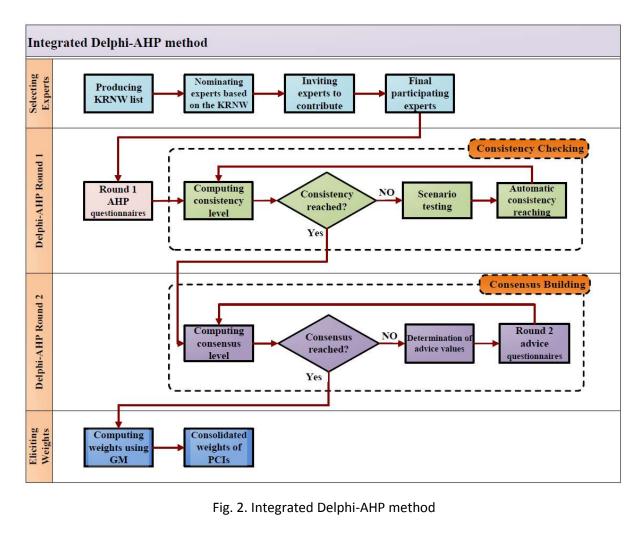608   European Cooperation in Science and Technology (COST). (2012). "European Cooperation in Science and
609   Technology (COST) Megaprojects Action TU1003."
610   <http://www.cost.eu/COST_Actions/tud/Actions/TU1003>.

611   Fiori, C., and Kovaka, M. (2005). "Defining megaprojects: Learning from construction at the edge of
612   experience." *Proceedings of Research Congress, ASCE*, (480).

613   Flyvbjerg, B. (2014). *Megaproject planning and management: essential readings*. Edward Elgar Publishing.

614   Flyvbjerg, B., Bruzelius, N., and Rothengatter, W. (2003). *Megaprojects and Risk: An Anatomy of Ambition*.
615   Megaprojects and Risk: An Anatomy of Ambition, book, Cambridge University Press.

616   Geraldi, J., and Adlbrecht, G. (2007). "On faith, fact and interaction in projects." *Project Management Journal*,
617   38(1), 32–43.

618   Geraldi, J., Maylor, H., and Williams, T. (2011). "Now, let's make it really complex (complicated)." *International
619   Journal of Operations & Production Management*, Emerald Group Publishing Limited, 31(9), 966–990.

620   Gidado, K. I. (1996). "Project complexity: The focal point of construction production planning." *Construction
621   Management and Economics*, 14(3), 213–225.

622   Global Alliance for Project Performance Standards. (2007). *A Framework for Performance Based Competency
623   Standards for Global Level 1 and 2 Project Managers*.

624   Gransberg, D., Shane, J., Strong, K., and del Puerto, C. (2013). "Project Complexity Mapping in Five Dimensions
625   for Complex Transportation Projects." *Journal of Management in Engineering*, American Society of Civil
626   Engineers, 29(4), 316–326.

627   He, Q., Luo, L., Hu, Y., and Chan, A. P. C. (2015). "Measuring the complexity of mega construction projects in
628   China—A fuzzy analytic network process analysis." *International Journal of Project Management*, 33(3),
629   549–563.

630   Herrera-Viedma, E., Cabrerizo, F. J., Kacprzyk, J., and Pedrycz, W. (2014). "A review of soft consensus models in
631   a fuzzy environment." *Information Fusion*, 17, 4–13.

632   Herrera-Viedma, E., Chiclana, F., Herrera, F., and Alonso, S. (2007). "Group Decision-Making Model With
633   Incomplete Fuzzy Preference Relations Based on Additive Consistency." *IEEE Transactions on Systems,
634   Man and Cybernetics, Part B (Cybernetics)*, 37(1), 176–189.

635   Herrera-Viedma, E., Herrera, F., and Chiclana, F. (2002). "A consensus model for multiperson decision making
636   with different preference structures." *IEEE Transactions on Systems, Man, and Cybernetics - Part A:
637   Systems and Humans*, 32(3), 394–402.

638   Hu, Y., Chan, A. P. C., Le, Y., and Jin, R. (2013). "From Construction Megaproject Management to Complex
639   Project Management: Bibliographic Analysis." *Journal of Management in Engineering*, American Society
640   of Civil Engineers, 4014052.

641   Hu, Y., Chan, A. P. C., Le, Y., Yelin, X. and Shan, M. (2016). "Developing a Program Organization Performance
642   Index for Delivering Construction Megaprojects in China: Fuzzy Synthetic Evaluation Analysis." *Journal of
643   Management in Engineering*, American Society of Civil Engineers, 05016007.

644   Hwang, C.-L., and Lin, M.-J. (1987). *Group Decision Making under Multiple Criteria*. Springer.

645   Ishizaka, A., and Lusti, M. (2006). "How to derive priorities in AHP: a comparative study." *Central European
646   Journal of Operations Research*, 14(4), 387–400.

647   Johnson, C. R., Beine, W. B., and Wang, T. J. (1979). "Right-left asymmetry in an eigenvector ranking
648   procedure." *Journal of Mathematical Psychology*, 19(1), 61–64.

649   Kardes, I., Ozturk, A., Cavusgil, S. T., and Cavusgil, E. (2013). "Managing global megaprojects: Complexity and
650   risk management." *International Business Review*, 22(6), 905–917.

651   Kian Manesh Rad, E., and Sun, M. (2014). "Taxonomy of Poject Complexity Indicators in Energy Megaprojects."
652   *People, Buildings and Environment an international scientific conference, Czech Republic*.

653 Krishnaswamy, K. N., and Sivakumar, A. I. (2009). *Management Research Methodology: Integration of Methods*
654   *and Techniques*. book, Pearson Education.

655 Lessard, D., Sakhrani, V., and Miller, R. (2014). "House of Project Complexity—understanding complexity in
656   large infrastructure projects." *Engineering Project Organization Journal*, Taylor & Francis, 4(4), 170–192.

657 Little, G., Tuttle, R., Clark, D. E. R., and Corney, J. (1998). "A feature complexity index." *Proceedings of the*
658   *Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* , JOUR, 212(5),
659   405–412.

660 Liu, B., Shen, Y., Chen, Y., Chen, X., and Wang, Y. (2015). "A two-layer weight determination method for
661   complex multi-attribute large-group decision-making experts in a linguistic environment." *Information*
662   *Fusion*, 23, 156–165.

663 Locatelli, G., and Littau, P. (2013). *Closing Report on the Research Activities of the Energy Working Group*.

664 Locatelli, G., Littau, P., Brookes, N. J., and Mancini, M. (2014). "Project Characteristics Enabling the Success of
665   Megaprojects: An Empirical Investigation in the Energy Sector." *Procedia - Social and Behavioral*
666   *Sciences*, Elsevier B.V., 119, 625–634.

667 Locatelli, G., and Mancini, M. (2012). "A FRAMEWORK FOR THE SELECTION OF THE RIGHT NUCLEAR POWER
668   PLANT." *International Journal of Production Research*, 50(17), 4753–4766.

669 Marradi, A. (1990). "Classification, Typology, Taxonomy." *Quality & Quantity*, 24, 129–157.

670 Maylor, H., Vidgen, R., and Carver, S. (2008). "Managerial complexity in project-based operations: A grounded
671   model and its implications for practice." *Project Management Journal*, 39(S1), S15–S26.

672 Merrow, E. (2012). "Oil and Gas Industry Megaprojects: Our Recent Track Record." *Oil and Gas Facilities*,
673   (September 2011), 38–42.

674 Merrow, E. W. (2011). *Industrial Megaprojects: Concepts, Strategies, and Practices for Success*. book, Wiley.

675 Moreno-Jiménez, J. M., Aguarón, J., and Escobar, M. T. (2007). "The Core of Consistency in AHP-Group
676   Decision Making." *Group Decision and Negotiation*, 17(3), 249–265.

677 Nguyen, A. T., Nguyen, L. D., Le-Hoai, L., and Dang, C. N. (2015). "Quantifying the complexity of transportation
678   projects using the fuzzy analytic hierarchy process." *International Journal of Project Management*, 33(6),
679   1364–1376.

680 Office of Government Commerce. (2009). *Managing Successful Projects with PRINCE2*. Stationery Office Books.

681 Peng, X., Che, W., and Shou, Y. (2012). "A bibliometric description and content analysis of mega-project
682   characteristics." *2012 IEEE International Conference on Industrial Engineering and Engineering*
683   *Management*, Ieee, 2331–2336.

684 Puddicombe, M. S. (2012). "Novelty and Technical Complexity: Critical Constructs in Capital Projects." *Journal*
685   *of Management in Engineering*, American Society of Civil Engineers, 138 (5) (2012), pp. 613–620.

686 Ramanathan, R. (1997). "A note on the use of goal programming for the multiplicative AHP." *Journal of Multi-*
687   *Criteria Decision Analysis*, 6(5), 296–307.

688 Remington, K., and Pollack, J. (2007). *Tools for Complex Projects*. book, Gower.

689 Remington, K., Zolin, R., and Turner, R. (2009). "A model of project complexity : distinguishing dimensions of
690   complexity from severity." *Proceedings of the 9th International Research Network of Project*
691   *Management Conference*, IRNOP.

692 Saaty, T. L. (1977). "A scaling method for priorities in hierarchical structures." *Journal of Mathematical*
693   *Psychology*, 15(3), 234–281.

694 Saaty, T. L. (1989). "Group Decision Making and the AHP." *The Analytic Hierarchy Process*, 59–67.

695 Schlindwein, S. L., and Ison, R. (2004). "Human knowing and perceived complexity: implications for systems
696   practice." *Emergence: Complexity and Organization*, 6(3), 27–32.

697 Shehu, Z., and Akintoye, A. (2010). "Major challenges to the successful implementation and practice of
698   programme management in the construction environment: A critical analysis." *International Journal of*
699   *Project Management*, 28(1), 26–39.

700 Shenhar, A. J. (1998). "From Theory to Practice: Toward a Typology of Project-Management Styles." *IEEE*
701   *Transactions on Engineering Management*, 45(1), 33–48.

702 Shenhar, A. J., and Dvir, D. (1996). "Toward a typological theory of project management." *Research Policy*,
703   25(4), 607–632.

704 Sinha, S., Kumar, B., and Thomson, A. (2006). "Measuring project complexity: A project manager's tool."
705   *Architectural Engineering and Design Management*, 2, 187–202.

706 Sinha, S., Thomson, A. I., and Kumar, B. (2001). "A complexity index for the design process." *WDK Publications*,
707   157–163.

708 Sovacool, B. K., and Cooper, C. J. (2013). *The Governance of Energy Megaprojects: Politics, Hubris and Energy*
709   *Security*. book, Edward Elgar Publishing, Incorporated.

710 Thomas, J., and Mengel, T. (2008). "Preparing project managers to deal with complexity – Advanced project
711   management education." *International Journal of Project Management*, 26(3), 304–315.

712 Vidal, L.-A., and Marle, F. (2008). "Understanding project complexity: implications on project management."
713   *Kybernetes*, 37(8), 1094–1110.

714 Vidal, L.-A., Marle, F., and Bocquet, J.-C. (2011). "Measuring project complexity using the Analytic Hierarchy
715   Process." *International Journal of Project Management*, 29(6), 718–727.

716 Williams, T. (2002). *Modelling Complex Projects*. *Wiley*.

717 Williams, T. (2013). *MEGAPROJECTS: Shaping the Research Agenda Symposium Record*.

718 Williams, T. . (1999). "The need for new paradigms for complex projects." *International Journal of Project*
719   *Management*, 17(5), 269–273.

720 Xia, B., and Chan, A. P. C. (2012). "Measuring complexity for building projects: a Delphi study." *Engineering,*
721   *Construction and Architectural Management*, 19(1), 7–24.

722 Zhang, H., Dong, Y., and Xu, Y. (2014). "An Analysis of Several Novel Frameworks and Models in the Consensus
723   Reaching Process." *Procedia Computer Science*, 31, 245–254.

724

725

726

727

728

729

730

731

732

733

734

735

736

737

738

739   Figures

Literature Review
To compile a list of complexity indicators
Qualitative Synthesis
To produce a project complexity taxonomy

↓

Delphi-AHP Method
To establish weights for all indicators

↓

Interpretive Synthesis
To define scoring criteria for all indicators

↓

Expert Review
To validate the scoring criteria of indicators
Case Study
To test the application of the PCA method

740

741   Fig. 1. Research phases and methods

742

743

Fig. 2. Integrated Delphi-AHP method

744

745

Fig. 3. Defined ranges of acceptable consensus

746

747

748

749

Internal Complexity

	Organisation				Process				Characteristics	
	Capital Resources	Discipline	People	Physical Resources	Information	Task	Time	Tools & Methods	Objectives	Technical
A	0.52 0.13	0.31 0.16	0.47 0.25	0.32 0.23	0.60		0.31		CI(A)= 3.35	
OPT	0.42 0.17	0.35 0.24	0.32 0.22	0.26 0.18	0.49		0.2		CI(OPT)= 2.87	
B	0.78	0.18 0.31 0.15	0.26 0.19 0.16 0.12	0.29 0.16					CI(B)= 2.63	

⬚ Weighted Score of project in aspect of complexity

Exteral Complexity

	Economy		Environmental		Legal & Regulations	Politics	Social
A	0.96	0.84	0.35	0.63	0.79		
OPT	1.31	0.68	0.47	0.50	0.60		
B	1.65		0.97	0.25	0.20 0.32		

CI(A)= 3.56
CI(OPT)= 3.5
CI(B)= 3.38

750

751   Fig. 4. Calculated level of complexity for case study

31

Tables

Table 2. Taxonomy of PCIs - external factors (indicators are compiled from number of sources such as Geraldi 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
Social (SO)	ESO1	Cultural configuration and variety
	ESO2	Cultural differences
	ESO3	Significance on public agenda

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
	Disciplines (DI)	IORDI1	Contract types
		IORDI2	Variety of institutional configuration
		IORDI3	Support from permanent organisations
		IORDI4	Team cooperation and communication
	People (PE)	IORPE1	Availability of human resources
		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
	Physical resources (PH)	IORPH1	Resource and raw material interdependencies
		IORPH2	Variety of resources
		IORPH3	Availability of physical resources
Process of Delivery (PR)	Information (IN)	IPRIN1	Availability of information
		IPRIN2	Reliability of information platforms
		IPRIN3	Interdependence of information systems
		IPRIN4	Level of processing and transferring information
	Tasks (TA)	IPRTA1	Diversity of sites and locations
		IPRTA2	Process interdependencies
		IPRTA3	Dependencies between tasks
		IPRTA4	Number of activities
		IPRTA5	Unpredictability of tasks
		IPRTA6	Diversity of activities elements
	Time (TI)	IPRTI1	Duration of project
		IPRTI2	Dependencies between schedules
		IPRTI3	Intensity of project schedule
	Tools & methods (TO)	IPRTO1	Applicability of project management methods and tools
		IPRTO2	Variety of project management methods and tools
Project Characteristics (PC)	Objectives (OB)	IPCOB1	Variety of goals and objectives
		IPCOB2	Interdependence of objectives
		IPCOB3	Transparency of objectives
		IPCOB4	Scope changing
	Technical (TE)	IPCTE1	Level of innovation
		IPCTE2	Technological experience and capabilities
		IPCTE3	Repetitiveness of process
		IPCTE4	Specifications interdependencies
		IPCTE5	Technological varieties
		IPCTE6	Variety of system components
		IPCTE7	Changing technology

758

33

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 cr	% of judgments asked to modify	% of judgments accepted to modify	Combined final cr
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%
Social	18.47%	ESO1	4.72%	4.52%
		ESO2	4.32%	4.14%
		ESO3	9.43%	9.03%

770

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%
	Disciplines	7.29%	IORDI1	33.54%	2.51%
			IORDI2	24.08%	1.80%
			IORDI3	22.62%	1.69%
			IORDI4	19.76%	1.48%
	People	12.73%	IORPE1	16.33%	3.14%
			IORPE2	22.80%	4.38%
			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%
	Tasks	7.68%	IPRTA1	18.97%	2.30%
			IPRTA2	15.90%	1.93%
			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%
	Technical	7.61%	IPCTE1	19.12%	2.37%
			IPCTE2	21.09%	2.62%
			IPCTE3	9.92%	1.23%
			IPCTE4	17.45%	2.17%
			IPCTE5	11.17%	1.39%
			IPCTE6	10.35%	1.29%
			IPCTE7	10.90%	1.35%

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? a. Green Peace or other international environmental activists have been involved in the project b. The project has national public acceptability (no protest at national level) 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	1: If 4 or 5 criteria are met. 3: If 2 or 3 criteria are met. 5: If 0 or 1 criterion is met.

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

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

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

780