Complexity for Megaprojects in the Energy Sector

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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.

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

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

Literature Review

Megaprojects are highly complex (Remington and Pollack 2007; Williams 2013); their execution often requires organisations to develop capacities of dynamism, experience and technology (Fiori and Kovaka 2005; Gransberg et al. 2013; Puddicombe 2012). Megaprojects are usually characterized by their high internal complexity, such as task complexity (Brockmann and Girmscheid 2007), and structural and directional complexity (Remington and Pollack 2007). Previous megaproject research is mostly devoted to these internal complexity aspects. External complexity, or ‘contextual uncertainty', has received less attention by comparison (Hu et al. 2013). Economic instabilities, market fluctuations, and social and cultural transitions (the latter one emerging mostly in developing countries) transform megaproject environments into uncertain situations (Shehu and Akintoye 2010). To understand and conceptualise the complexity of megaprojects comprehensively, both internal and external factors need to be investigated.

Despite the growing recognition of the importance of project complexity, there is still a lack of consensus on its definition and on a way to quantify it (Hu et al. 2013; Sinha et al. 2001). Baccarini (1996) offered one of the early attempts to define project complexity as a number of interrelated parts of a project (differentiation) and the relationships between the different parts (interdependency). These two perspectives are based on two key aspects of projects, resulting in two different types of project complexity – organisational complexity and technological complexity. The former refers to the composition and structure of the project team and the latter refers to the process, tools and product. In many business sectors, the ever increasing demands from the multiple facets of project success, such as speed of implementation, cost and quality controls, health and safety requirements, environmental issues, together with technological advances, economic liberalisation and globalisation, have resulted in a rapid increase in project complexity (Gidado 1996). Williams (1999) termed Baccarini's definition as 'structural complexity' and added another element to it – uncertainty. Uncertainty here refers to the fact that, in a typical project, both the project's goal and the methods needed to achieve this goal are not always certain. This uncertainty, together with the inherent structural complexity, produce the overall difficulty and messiness experienced in such projects (Williams, 1999). Geraldi and Adlbrecht (2008) characterised project complexity into three forms: faith, fact and interaction. Bosch-Rekveldt et al. (2011) determined technical, organisational, and environmental elements for the complexity of large engineering projects. Vidal et al. (2011) emphasised the difficulty of understanding, predicting, and controlling project complexity, but underlined the significance of project complexity assessment to enrich support to decisions making. The ability of an organisations to foresee, recognise and pilot complexity is a key criterion of project success or failure (Office of Government Commerce 2009). All the above authors consider project complexity as an intrinsic property of a project, which can be both described and measured. This approach is known as ‘descriptive complexity’, which emphasises the objective existence of complexity. There is another approach, ‘perceived complexity’ which considers complexity as subjective and may vary depending on the perception of different observers (Schlindwein and Ison 2004). In practice, project managers always deal with perceived complexity because their perception of complexity of a project, and solutions to it, will depend on their personal knowledge and competence as well as the descriptive complexity of the project (Vidal and Marle 2008). Descriptive complexity and perceived complexity are two ends of the complexity perception spectrum. The former focuses on the objective nature of complexity; while the latter looks at complexity from a particular perspective of an individual party, taking into account the individual’s ability to handle the concept of complexity. In reality, however, there is no hard boundary between these two. This study concentrates on the complexity measurement, not complexity management. This emphasis is on the objectivity of complexity measurement. The aim for the new assessment method is to produce the same result regardless who does the assessment. However, it is recognised that it may not be possible to eliminate the impact of assessor’s subjectivity completely.

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

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

The need to quantitatively measure project complexity has been the focus of a growing number of recent studies (He et al. 2015; Sinha et al. 2006; Vidal et al. 2011; Xia and Chan 2012). The research challenges include: the identification of a list of indicators against which measurement is to be carried out; the determination of the significance (weight) of each indicator; and specification of scoring scales for these indicators. Sinha et al. (2006) proposed a project complexity measurement framework that breaks a project down into activities and subtasks at different stages. It goes on to define a way of measuring complexity at the subtask level by taking into account work, time, motivational and social factors. A complexity index can then be calculated for the whole project by aggregating that of all the subtasks. A framework is provided in (Global Alliance for Project Performance Standards 2007) to classify projects based on their management complexity, by using a tool known as CIFTER developed by Aitken and Crawford (2007). The tool analyses complexity through seven project management complexity factors: stability, number of distinct disciplines, magnitude of implication, expected financial impact, strategic importance, stakeholder cohesion, and number of interfaces for complexity of project in a four-point scale. Vidal et al. (2011) developed a comparative complexity measurement method, which is aimed at comparing different alternatives. It identifies 18 complexity drivers (indicators) and proposes a method to calculate their weights using an Analytic Hierarchy Process (AHP). Instead of measuring against objective scales, different alternatives are measured against each other. The aim of such an assessment is to establish a complexity ranking order of several alternatives. Xia and Chan (2011) put forward a relatively simple complexity measurement method to apply to building projects. It only contains six indicators and weights are calculated from the importance index using a 5-point Likert scale. The interesting aspect of this study is its use of the Delphi method when surveying a panel of experts in order to establish the importance of indices. In another study, He et al. (2015) developed a complexity measurement model comprising of 28 indicators in six categories, including technological, organisational, goal, environmental, cultural and information complexities. The method uses the fuzzy analytic network process (FANP) and Delphi method to obtain individual weights for these indicators, in the context of one construction megaproject. Their general research approach is broadly relevant to this study. However, as our focus is on megaprojects in the energy sector, the composition of the complexity indicators and their weights will be different in our study from theirs. Furthermore, their model does not define scoring criteria for the indicators, which are essential for quantifying the complexity of a new project. Recently, Dao et al. (2016) propose a Project Complexity Assessment and Management (PCAM) tool that includes 37 complexity indicators and objective scoring methods for these indicators. It was implemented as a simple spreadsheet tool, allowing the user to assess the complexity level of project at different stages during the project life cycle. The proposal to implement different strategies according complexity level of project is another element of this method; however, effectiveness of proposed strategies must be further investigated by applying in different projects and evaluation of performance.

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

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

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

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

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

Research methods

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

< Fig. 1. Research phases and methods>

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

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

2. The second phase seeks to evaluate the appropriateness of the identified PCIs and to establish their relative importance when assessing megaprojects. This requires inputs from a group of domain experts. In recent years, some studies have proposed Group Decision Making (GDM) techniques to obtain consistent knowledge and opinions from groups of experts, instead of from separate individuals (Herrera-Viedma et al. 2007; Hwang and Lin 1987; Moreno-Jiménez et al. 2007; Saaty 1989). The GDM method is defined as a process to find a plural answer to a decision problem, where a group of experts offer their judgments about multiple alternatives (Zhang et al. 2014). This study aims at establishing the relative importance of the indicators, based on input from a group of domain experts. A range of methods was adopted by other researchers (Locatelli and Mancini 2012; Nguyen et al. 2015; Vidal et al. 2011) for such a task. Based on a review of these methods, this study decides to use an integrated Delphi- AHP method. It involves two intertwining processes: a prioritising process of the indicators using AHP by individual expert and a consensus process using Delphi between all experts. 20 international experts with high familiarity and knowledge of the energy sector and megaprojects are selected and divided into two panels, with 10 academics and 10 industry practitioners. Therefore, the results are specifically applicable to the energy sector. Adoption to other sectors can be achieved following the same method, but with contribution from domain experts in other sectors. More details of the application of this method are provided in the following sections.
3. Scoring criteria are essential to the practical quantification of project complexity, yet this aspect is frequently neglected in existing research. To fill this gap, numerical scoring criteria for all identified indicators are defined for the comprehensive literature synthesis.
4. The outcomes from the first three phases define the principle and algorithms of the new PCA method. The final phase is to implement the PCA method as a tool with a user interface

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

Taxonomy of project complexity indicators

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

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

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

<Table 1. Taxonomy of PCIs - external factors >

<Table 2. Taxonomy of PCIs - internal factors >

At Level 1, there are two distinct categories which distinguish indicators within the project (internal) from those imposed from outside (external). External indicators are those outside the direct control of the project delivery organisation and relate to external stakeholders, such as governments or market forces. In contrast, internal indicators are those actually within the control of the project management team.

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

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

1. ‘What’ refers to “Project characteristics” that are further divided into two sub-categories (Level 3): technical characteristics and project objectives.
2. ‘Who’ refers to “Project delivery organisation/team” and includes four sub-categories (Level 3): people, disciplines, capital and physical resources.
3. ‘How’ is associated with “Process of delivery” of the project and includes four sub-categories (Level 3) of tasks, information, tools and methods, and time.

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

Establishing the weights of indicators

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

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

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

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

Each step of this process is detailed in the following.

Selecting experts: This study adopted a multi-stage process to identify experts to participate in the Delphi-AHP process, as suggested by Delbecq et al. (1975). In the first stage, a Knowledge Resource Nomination Worksheet (KRNW) was developed, which defines the key qualifications required for these experts. It was then used to record individual names identified from related publications in journals and books, professional social media (Linkedln), websites of some large energy organisations and professional bodies such as governments and the European Cooperation in Science and Technology (COST). Using the KRNW helped ensure that there are no gaps in the skills of the expert panel. At the end of this stage, 78 potential experts were identified. At the second stage, all the identified experts were contacted and provided with information about this study. They were invited to participate in the Delphi-AHP process, with explanations about their roles and expected contributions. Twenty experts agreed to participate; 10 of them are academics and 10 are professionals working in the energy industry. Table 4 shows background information on the experts.

<Table 3. Information of experts>

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

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

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

In GDM problems, consensus of judgments of multiple experts is usually reached on the basis of rationality principles that each expert exhibits. The requirement of rationality demands consistency of judgement from each individual expert. Therefore, given the experts' responses in round 1, the first task is to evaluate the degree of consistency of each expert, and improve it to an acceptable level (threshold) if required. To do this, inconsistent judgments are first identified from the Delphi-AHP round 1 results. Chiclana et al. (2008) devised an iterative process requesting experts to amend their initial judgments based on the advised values until an acceptable consistency level was reached. Whereas consistency of all individual judgements is mandatory for the basis of AHP method, the feedback process to experts seems unnecessary here. One of the dangers of using the Delphi method is that an increasing number of rounds may lead experts to lose interest and not returning the questionnaires, which would threaten the validity of the results. Therefore, in this research, the inconsistent judgments are amended with advised values automatically generated by a software tool based on the method proposed by Chiclana et al. (2008). This process is iterated until the experts' responses for all matrices satisfy the consistency threshold. Saaty (1977) defined 10% as an acceptable level of inconsistency in each matrix, so a consistency threshold value $\beta = 0.9$ is used and each expert judgment is assessed against it. Firstly, for each set of judgments by an expert l related to alternatives (i.e. indicators) (i, j), if one or more pairwise comparisons have a consistency degree $cd_{ij}^{l} \leq \beta$, then an automatic consistency checking process is applied. Although individual consistency is essential, it should be noted that the initial independence of each expert's judgment should not be violated. To ensure this, a threshold $\delta = 35\%$ is defined and each judgment matrix with more than δ of its values requiring update in the initial judgement values is omitted from further computations. Afterwards, a scenario analysis process is carried out to determine the optimal number of necessary updates for the inconsistent judgments. Our software tool not only implements the algorithm put forward by Chiclana et al. (2008) but also builds and performs a procedure of automatic maximum consistency checking. Using this method, new adjusted values and consistency levels for each matrix are computed.

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

< Table 6. Results of consistency building process>

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

Depending on the type of problem, experts' backgrounds, or specific project situations, different levels of consensus may be required. For this reason, three ranges γ_1, γ_2 and γ_3 for consensus are defined to highlight the consensus rate (cr), as showed in Fig. 3. The thresholds gauge local consensus (each category) and total consensus, and identify if the obtained consensus is acceptable or if the process should progress into another round. In this research, a medium level i.e. $0.8 \leq cr \leq 0.9$ is considered satisfactory for the total consensus because of the complex character of the problem. The consensus rates are acceptable if they are within any of the ranges defined by γ_1, γ_2 and γ_3.

< Fig. 3. Defined ranges of acceptable consensus>

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

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

< Table 7. Results of Consensus reaching and advice system

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

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

While consolidated weights represent the relative importance of indicators within the given category, it is also useful to obtain the global weight of each indicator so that all indicators can be compared against one another, regardless of the category they belong to. One method to do this is to multiply the weight of the category with the weight of the indicator. However, a main weakness of this method is that weights of indicators decline when the number of them in each category increases. Ramanathan (1997) proposed a solution to this problem by calculating the global weight gw_i of indicator *i* using its relative weight within the category. The proposed formula is:

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

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

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

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

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

Defining scoring criteria for complexity indicators

Establishing scoring criteria is a key phase in the process of project complexity assessment. However, this phase is very often neglected in the existing studies and methods for project complexity evaluation. In contrast, this study established comprehensive scoring criteria for all identified PCIs based on an extensive literature review and synthesis. Both a content analysis and interpretive synthesis have been carried out to couple the indicators and criteria, and form the scoring metrics. As an example of the approach followed in this research, Locatelli & Littau (2013) and Locatelli et al. (2014) identified performance variables of energy megaprojects based on an analysis of eleven European case studies. In addition, Brooks (2013) extracted thematic influencing criteria from the analysis of a European megaprojects portfolio. These provided a set of objective criteria for the "Significance on public agenda" indicator (Table 11). While each project entails a level of complexity and megaprojects register higher levels of such, each numerical scale of complexity should be able to capture this variability. Therefore a 1-5 Likert scale (see "Scores" column in example shown in Table 11) is used to determine the numerical score for each indicator, based on the identified scoring criteria, where “1” indicates the least and “5” the highest complexity level. The scoring criteria are defined as objectively as possible, so that they can be understood and agreed by decision-makers.

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

Scaling the numerical indicators is also a critical stage in defining the measure. For example, “Number of activities” frequently appears in the existing PCA literature (Bosch-Rekveldt et al. 2011; He et al. 2015; Nguyen et al. 2015; Vidal et al. 2011). However, no viable measure or method has been proposed to quantitatively measure this indicator. It is problematic to determine absolute numerical thresholds for different levels of complexity, based on the number of activities, due to inaccessibility of reliable data. In addition, the absolute value may well vary for different companies based on their experience and capabilities: a project may be extremely complex in terms of activities for company A, but very simple for company B. In other words, using absolute numerical thresholds, based on the number of activities, would revert to assessing perceived complexity which this research aims to avoid. To tackle this problem and reach the most reliable numerical criteria, this research borrows the concept of a “*competitiveness”* criterion, initially defined by Merrow (2011) to reflect relative cost overrun and schedule slip of megaprojects compared to similar projects in the company, and develops it to broader definitions. For instance, applying this relative complexity definition, Table *12* shows the scoring criteria defined for the "Number of activities" indicator. To ensure validity of the developed scoring criteria, an expert review is adopted. The results of this review also helped to refine the obtained scoring criteria.

< Table 11. Defined scoring criteria for "Number of activities">

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

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

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

Evaluation of PCA method

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

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

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

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

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

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

Case study

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

Fig. 4 depicts and compares weighted aspects of project complexity and a computed final Complexity Index (CI) for each project. Phase A shows a higher degree of complexity than the operational phases and phase B $(CI(A) > CI(OPT) > CI(B))$. Furthermore, the values of complexity in each category enable decision makers to better understand the degrees of complexity in all aspects of the project, and therefore implement more effective mitigation strategies.

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

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

Discussions and Conclusions

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

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

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

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

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

Acknowledgement

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Supplementary Data

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

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Figures

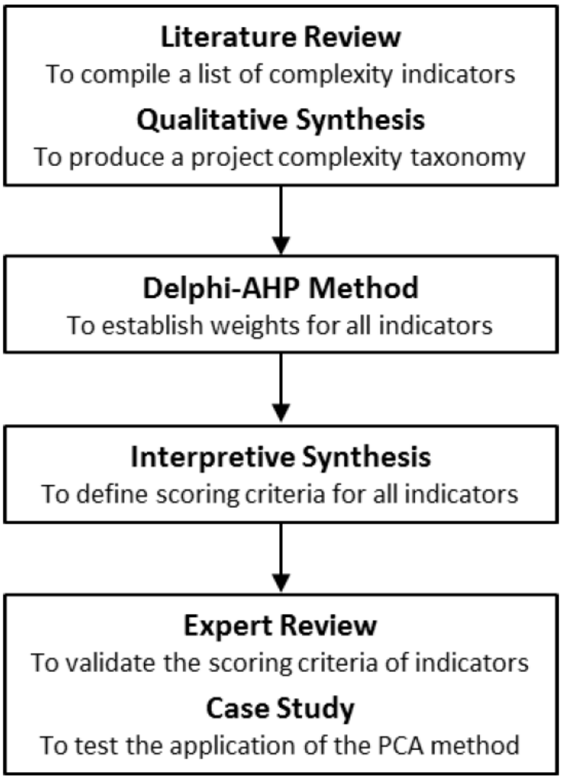

Fig. 1. Research phases and methods

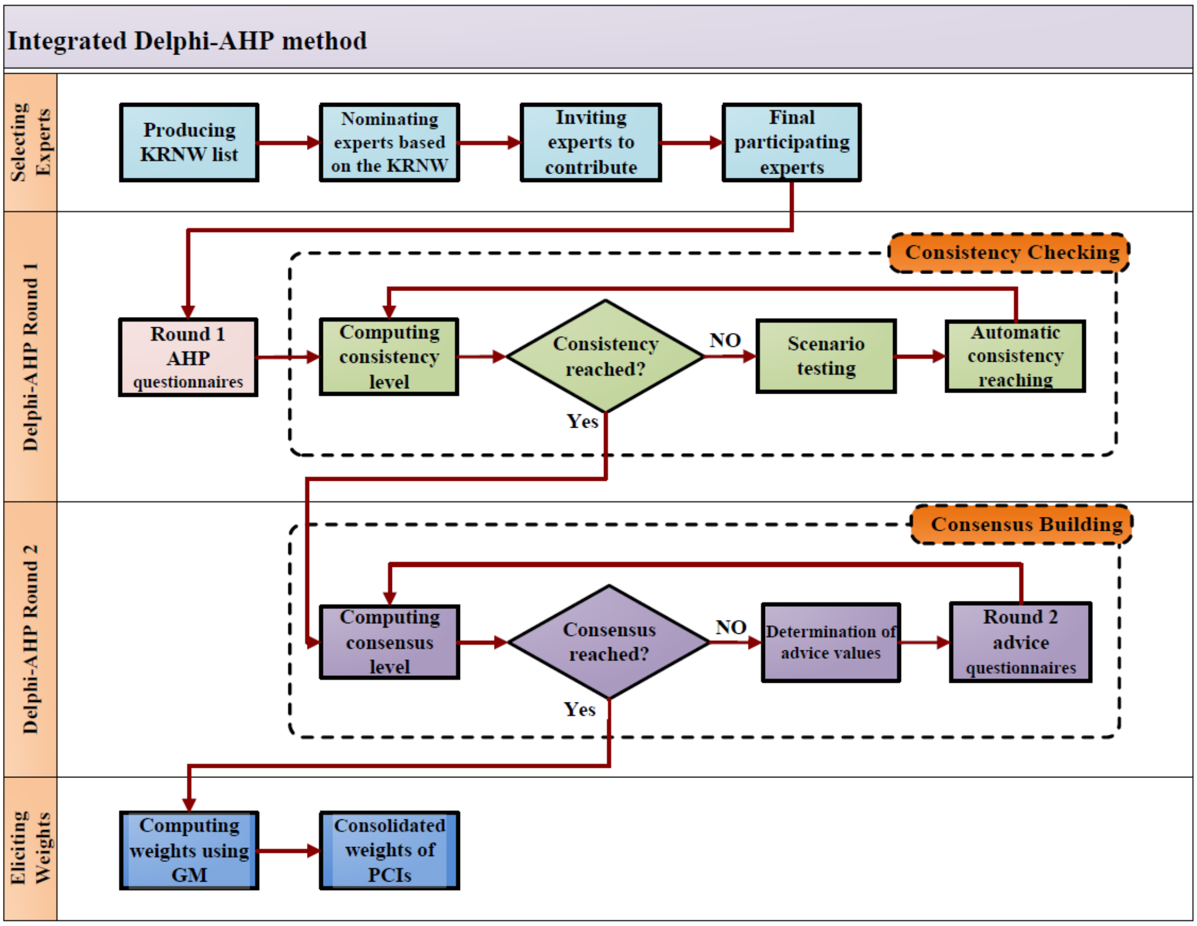

Fig. 2. Integrated Delphi-AHP method

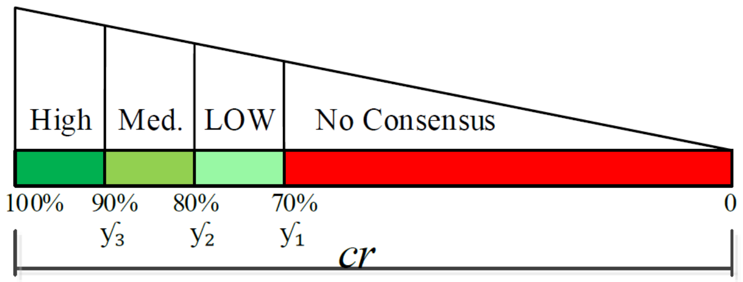

Fig. 3. Defined ranges of acceptable consensus

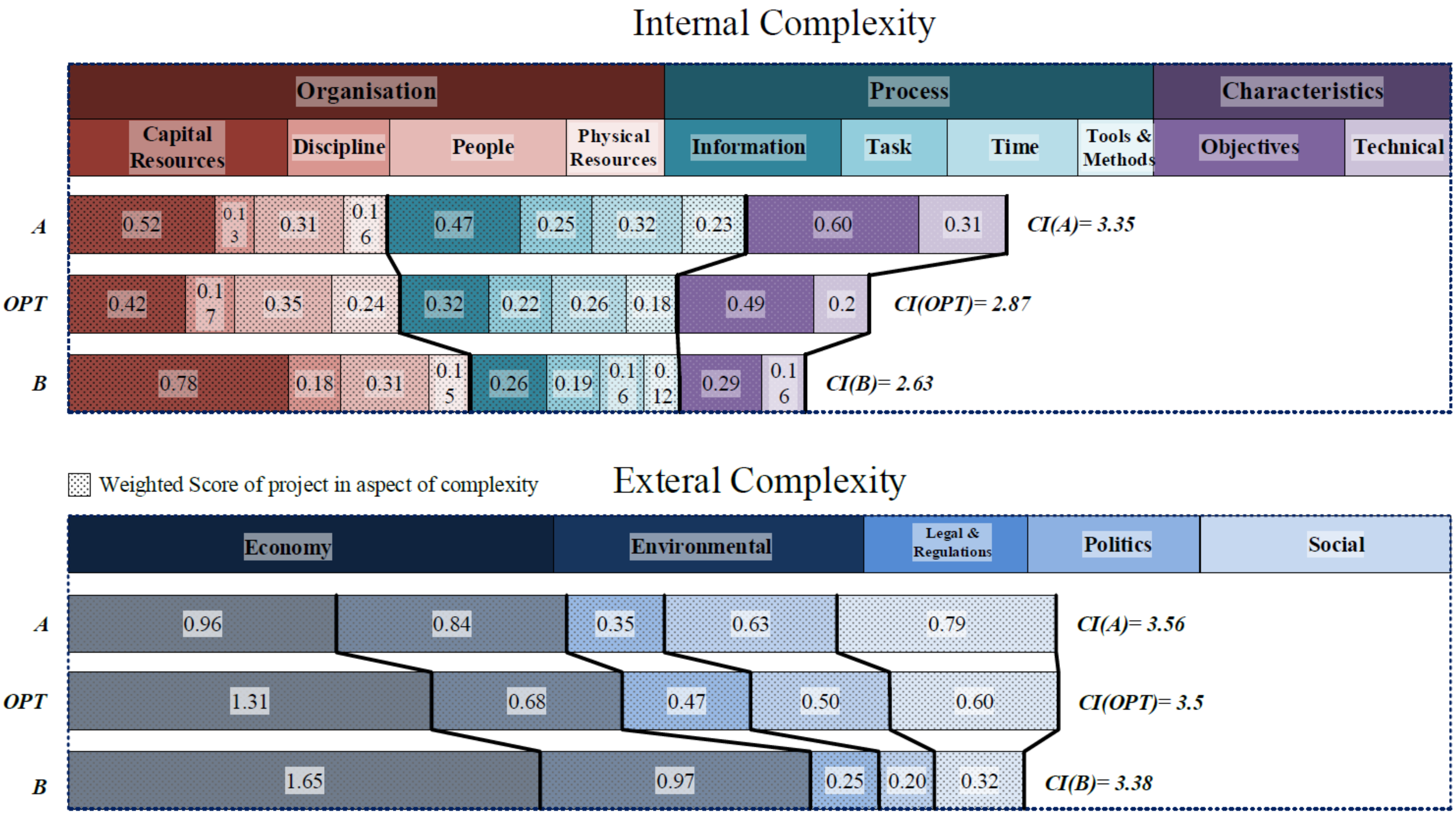

Fig. 4. Calculated level of complexity for case study

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

Table 3. Taxonomy of PCIs - internal factors (indicators are compiled from number of sources such as Bosch-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

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%	

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

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)						

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

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

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%

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%

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.

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%

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

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