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THE SUCCESFUL DELIVERY OF MEGAPROJECTS: A NOVEL RESEARCH METHOD

ABSTRACT

Megaprojects are often associated with poor delivery performance and poor benefits realization. This paper provides a method of identifying in a quantitative and rigorous manner the megaprojects’ characteristics related to project management success in Megaprojects. It provides an investigation of how stakeholders involved in Megaprojects can use this knowledge to ensure the more effective design and delivery of megaprojects. The research is grounded in 44 megaprojects and a systematic, empirically based methodology that employs the Fisher Exact Test and Machine Learning techniques to identify the correlation between the megaprojects’ characteristics and performance, paving the way to the understanding their causation.

Keywords: Megaprojects, Case studies, Statistical analysis, Budget, Schedule

Introduction

Megaprojects are temporary endeavors (i.e. projects) characterized by: large investment commitment, vast complexity (especially in organizational terms), and long-lasting impact on the economy, the environment, and society (Brookes and Locatelli, 2015). Megaprojects include power plants, oil and gas extraction plants, airports and processing projects, railways, motorways, dams and even cultural events (Van Wee, 2007). What megaprojects have in common is their requirement for the co-ordination and control of a vast and complex array of financial, social and technical resources to turn them into reality (Hu et al., 2013; Locatelli, Mancini, et al., 2014). Megaprojects have significant implications for society, and they have a pivotal role in the implementation of both energy and transport policies (Locatelli, Invernizzi, et al., 2017; Locatelli, Mariani, et al., 2017; Sovacool, Nugent, et al., 2014). Megaprojects represent the largest proportion of governmental and European commission expenditure on infrastructure and their successful design and delivery have major implications for public finances (Flyvbjerg et al., 2016). Despite their criticality, megaprojects are associated with extremely poor delivery performance and an extremely poor long-term benefits realization (Flyvbjerg et al., 2003; Kardes et al., 2013; van Marrewijk et al., 2008; Merrow, 2011).

The successful transfer of learning across projects and megaprojects has been a long-held desire by those involved in their design and delivery. The difficulties in learning are created by the very nature of projects themselves, i.e. their separation from a "permanent" organization and their uniqueness (Jacobsson et al., 2015; Kujala et al., 2010; Wikström et al., 2010). Moreover the size and complexity of megaprojects make it very difficult to discern which actors and element of its myriad configurations have actually influenced the success in their delivery (Chang et al., 2013; Chapman, 2016; van Marrewijk et al., 2008).

In the last decades, project management literature has vastly investigated the "success factors" that impact on the success of the projects, measured through the so-called "success indicators" (or criteria). A "success factors" can be a detailed Front-End-Engineering-and-Design (FEED) (Merrow, 2011) or the early engagement of external and internal stakeholders (Brookes and Locatelli, 2015). Project "success indicators" are defined as the measures by which the successful outcome of a project is assessed, while "success factors" are the elements of a project that can be influenced to increase the likelihood of success (Müller and Turner, 2007). Traditional "success indicators" in project management refers to the so-called iron triangle, i.e. cost, time and quality. However this short-term, contract-based view has been challenged by researches considering multiple perspectives of different stakeholders in different timeframes (Davis, 2014; Dimitriou et al., 2013; Turner and Zolin, 2012). Recently Williams (2016) has emphasized that it is increasingly recognized that the nature of project success is multidimensional, with different criteria, only some clearly measurable and that there is still limited understanding in the causal chains through which success emerges. Zavadskas et al. (2013) also analyse common construction performance, focusing on what they call project management "problems" against the "success factors", illustrating how to assess the projects' efficiency using aggregated indicators. Gunathilaka et al. (2013) reviewing papers about the relationship between project success factors and project success indicators highlight the scarce empirical evidence that support the actual correlation between them. Bassam (2013) does not limit his research to the construction filed, and employs statistical analysis to examine the correlations between the risk factors that are common to success indicators, to conclude that there are some factors in the initiation phase that could lead to the occurrence of additional risk factors in the implementation and evaluation phases. A detailed example of this latter case related to EXPO 2015 is presented in (Locatelli and Mancini, 2010).

This paper aims to provide a method to identify in a quantitative and rigorous manner the (mega) project characteristics (i.e. the aforementioned "success factors") correlated to project management success indicators. It also aims to provide a model for Megaproject cost and time performance prediction.

As clarified in the literature review section, a key novelty of the research presented in this paper is the transparent leveraging of project characteristics and case studies rather than, for instance, survey or proprietary database. Specifically the paper addresses 46 project characteristics (e.g. *"there is planned a long-term stability in usage and value"* or *"the project receive financial Support from the European Union".* See the full list in the appendix, table 4 to table 10) and their correlation with 3 project management success indicators *("The project had a cost overrun", "delayed in the planning phase"* and *"delayed in the construction phase"*).

Literature review

The majority of the existing literature about project management success indicators can be clustered into three groups:

1. Statistical analysis of large databases;
2. Survey with project managers and stakeholders;
3. Case studies analysis;

Statistical analysis of large database. Prominent research has been undertaken in the statistical analysis of large databases of megaprojects (Ansar et al., 2014; Cantarelli et al., 2012; Flyvbjerg, 2006; Merrow, 2011). For example, by analyzing a large database Flyvbjerg (2006) investigates why projects are late or over-budget and, once delivered, provide less benefit than planned. Optimism bias and strategic misrepresentation are significant contributory factors for overestimation of benefits and underestimation of costs of megaproject design and delivery. According to Merrow (2011) the main reasons for a project failure are poor Front-End Loading (FEL), FEED and misaligned incentives. Such statistical analyses provide invaluable insights into megaproject design and delivery but, the lack of availability of the base data used to create these findings is inimical to further investigations.

A particular subset of statistical researchers have are focused on a particular type of megaprojects. Koch (2014) investigated seven Danish and Swedish offshore wind farms; Ansar et al. (2014) analyzed a large database of dams. Locatelli et al (2014) were focused on power plants, Sovacool et al (2014a, 2014b) conducted empirical studies relying on extensive database composed of 401 electricity infrastructure projects. Despite their large statistical significance, the sectoral construction of these investigation’s datasets make it difficult to extend findings to other megaproject sectors.

Surveys of project participants. Several researchers follow this path, by asking directly to Project Managers about the success factors in projects (e.g. (Kog and Loh, 2012; Pinto and Mantel, 1990; Pinto and Slevin, 1987)), or the "*factors that were regarded as critical to that project's outcome"* (White and Fortune, 2002 p. 1) or the *"project success factors for design and build projects and the relative importance of these factors on project outcome"* (Chan et al., 2001, p. 93). These papers provide a very interesting contribution, but the methodological choice followed by these investigations means that their results can only really be considered as normative studies of what scholars and practitioners involved in the surveys think. Often their responses are extremely constrained by the survey instruments utilized in the investigations.

Case studies Analysis. Case study methodology is a research methodology extensively used to describe and understand the behavior of a projects (Yin, 2013). It can be considered as a very effective methodology for the theory building (Eisenhardt, 1989). Case studies do provide a useful approach to investigating megaprojects (Brookes, N.J.; Hickey, R.; Littau, P.; Locatelli, G.; Oliomogbe, 2015). For example Locatelli and Mancini (2012) analyzed the case studies of the nuclear reactors "Olkiluoto 3" and "Flamanville 3. Greiman (2013) starts with a deep analysis of a single megaproject (Central Artery/Tunnel Project in Boston, known unofficially as the Big Dig) to generalize a set of lessons and guidelines. The main limitation of the case study approach is with its emphasis on theory building rather than theory testing.

Despite the substantial amount of work already undertaken to understand megaproject behavior, a limited number of attempts to quantitatively express the relationships between project characteristics and success indicators. It is particularly unclear on how to use this understanding to build a performance prediction model for megaprojects that would be of particular use to megaproject design and delivery professionals.

Method

Key Challenges

Given the limitations of existing work in this area, the authors sought further approaches that relate megaprojects characteristics to their success indicators. The main challenges in the process of identifying such relationships originate from the complexity of megaprojects and the size, availability and representation of the data describing them.

The complexity of megaprojects: due to their investment size, long duration, technological complexity, political and social environment (including a large network of internal and external stakeholders) megaprojects are an extremely complex phenomenon. In order to use statistics to analyze megaprojects, it is necessary to cope with this complexity, specifically in terms of the number of characteristics that are being included. The reductionism is dangerous as it can move investigators away from identifying complex holistic phenomena, but it is necessary if statistical significance is sought with the preference for model simplicity (Easterby-Smith et al., 2012).

The nature of megaproject data: comparing to the other types of projects across different sectors, the number of megaprojects is very limited. Moreover, information sensitivity issues can also highly affect availability and quality of specific megaproject data.

Data representation suitable for statistical analysis: when converting the real-life complexity of megaprojects to a dataset amenable to statistical analysis, it is necessary to identify the way of measuring and describing characteristics, i.e. "independent variables". Frequently, the conversion process adopted by researchers relays on integer likert-type scales to rank qualitative variables. The application of likert-type scales could potentially be differently interpreted by researchers and wider practitioner audience (ranking the complexity of a megaproject on a scale of 1-7, for example, seemed a subjective exercise). In addition, given the small size of available megaprojects dataset, high dimensionality of project characteristics could lead to inadequate statistical models, unable to capture the relationship between project characteristics and the project performance ("curse of dimensionality") (Indyk and Motwani, 1998). Considering the previously defined challenges, when identifying significant relationships between project characteristics and performance, the authors applied a data-driven approach using the database presented in (Brookes, 2013), and a list of project characteristics presented in the appendix. The method is based on two macro-phases:

1 – Data collection and preparation

2 – Data analysis using the Fisher Exact Test (FET) and Machine Learning (ML)

Data collection and preparation

Data collection and preparation consist of cases collection & brainstorming, systematization & definition of possible project characteristics. The authors identified 46 independent variables (i.e. project characteristics) for 44 megaprojects cases.

Step 1 – *Case collection*

Each case study is a megaproject delivered in the EU. The authors collected information about the specific case study, and gained a preliminary qualitative knowledge of the factors influencing successful project delivery[1].

The final sample consists of 44 cases clustered as following:

- 30 transport: 6 motorways, 15 rail projects, 5 urban transport projects (4 metro lines and 1 tram), 2 bridges (road bridges), 1 tunnel (for road and rail traffic), 1 airport
- 12 energy (5 nuclear, 3 thermal, 2 windfarms, 1 solar and 1 NLG extracting platform)
- 2 hydro-technical megaprojects (Mose in Venice and Raciborz reservoirs in Poland).

The qualitative data describing these case studies is available in (Brookes, 2013; UCL, 2015).

[1] The authors acknowledge the contribution of scholars and practitioners involved in the “Megaproject cost action”. A full list of the people involved and the portfolio of projects analysed is available from http://www.mega-project.eu/

Step 2 – *Identification of project characteristics as possible determinants of project management success*

After the collection of cases, the authors identified a large range of megaproject characteristics that might be correlated with the success indicators. The list of project characteristics are therefore based on the knowledge acquired during the case studies elaboration, the researchers' previous knowledge and the literature summarized in the Appendix.

Step 3 – *Systematization*

Following the identification process, the authors gathered to systematize the data. This "cleaning-up" led to the final definition of 46 project characteristics (e.g. First Of A Kind - FOAK, turnkey contract between Client and EPC Contractor, etc.) clustered in 5 groups (see table 4 to table 10 in the Appendix). The groups of characteristics are: Project Stakeholders (subgroups Internal and External), Project Environment (Legal, Socio-Economic and Political), Project Management, Technology and Other.

Step 4 – *Data representation*

In order to deal with data complexity and the curse of dimensionality project characteristics and success indicators were coded as binary values. For each project characteristic, the researchers derived definitions to assign unambiguously the value 0 (not present), 1 (present) or N/A for not available / not applicable (see Appendix). The same applied to the three success indicators: *cost overrun*, *delay during the construction phase*, and *delay during the planning phase* as detailed in Table 1.

Steps 2, 3 and 4 were iterative and, while new project characteristics were included, other dropped out, and the definitions improved. Using these definitions and the data from the case studies templates the researchers derived a dataset with the 44 projects cases described by 46 project characteristics and 3 success indicators.

PLEASE INSERT TABLE 1 HERE

Applied methods for data analysis

To perform the analysis on this dataset, there is a limited number of suitable statistical tests: in particular, the chi-squared test, the FET and different ML techniques. A common test when dealing with large samples described by categorical data (coal power plant / Nuclear Power plant / solar power plant etc.) is the chi-squared test (Leach, 1979). However, the chi-squared test provides only an approximation of the significance value, which is a major limitation for relatively small datasets, like in the case considered. Therefore, since the data is limited in size and it is binary in its nature, the authors applied the FET to investigate potential relationships between the previously defined independent and dependent megaproject variables. The other approach which recently gains in popularity in project management literature uses different ML techniques to establish predictive models for behavior and outcomes of projects described by its characteristics (Cheng et al., 2010; Le et al., 2009; Son et al., 2012; Wang and Gibson, 2010; Williams and Gong, 2014)

ML techniques enable rigorous "pattern spotting" analysis of the existing (andrelatively small) dataset that did not allow the application of multivariate statistical analysis. After conducting the FET, three different ML classifiers and two feature selection techniques were applied. These techniques were adopted for small data sets to build models for prediction of megaproject management success.

Fisher Exact Test

The purpose of the FET is to ascertain whether or not an independent variable is correlated with the presence (or absence) of a dependent variable (Leach, 1979). With respect to this research the FET has two key features (Sheskin, 2011). Firstly the FET makes no assumption about distributions. The FET is a non-parametrical statistical significance test. It is not necessary to make "a priori" assumptions on the data distribution and therefore this type of test can have a wide application. Secondly the FET uses categorical data in the form of a contingency table. The test is used for categorical binary data. The probability of a relationship existing between the variables can be calculated exactly and not estimated as in other statistical techniques. Further information about the FET and the steps to apply it in this kind of research are detailed in (Brookes and Locatelli, 2015).

Machine Learning

ML belong to a continuum of data analysis techniques which learn from underlying data to describe structural patterns, explain the trends and make predictions (Kohavi and Provost, 1998; Witten et al., 2011). In this research the authors formulated the problem of project management success assessing correlations between project characteristics and performance where a set of classified examples (megaproject cases) is given as the input to a ML technique. Based on this classification, ML techniques map the relationships between project characteristics and success indicators classes. Examples are represented as binary vectors (i.e. the 46 project characteristics, see Appendix) and a class label (success indicators, see Appendix, Table 1) according to which the examples were classified. The output may also include an actual description of a structure that can be used to classify unknown examples. Descriptions can become fairly complex and are typically expressed as sets of rules. Since there are three success indicators adopted for investigation in this research (Table 1), the authors built a separate classification model for each of them. The framework for building and evaluating the proposed models is described in the following sections.

Testing protocol

In order to assess the quality of the analysis on the available megaprojects data, which ends with the selection of the most informative characteristics for the specific success indicator, the authors proposed different classification models and estimated their performance based on the selected characteristics, with the reasonable assumption that more important project characteristics lead to better prediction accuracy. Models were evaluated on test data using the *leave one out* procedure that minimizes the negative effects of small sample size (Reich and Barai, 1999). The procedure iteratively divides the dataset with n examples (megaproject cases) into training (n-1 examples) and test part (one example). In each iteration the test part rotates throughout the dataset enabling the model to be both trained and tested on all available data (Reich and Barai, 1999). An aggregated confusion matrix, which accumulates classification results from each iteration, is maintained and further used to calculate standard model performance measures, i.e. precision, recall (for each class and overall), accuracy and F-measure (Williams and Gong, 2014; Witten et al., 2011). The precision of the classification model for "class C" represents the percentage of examples classified as C, which actually belongs to C. The recall for C is the percentage of all examples from C in the test set that is predicted as C.

When comparing different models, it is convenient to use a single measure, such as accuracy (percentage of accurately classified examples in the test set) or weighted F-measure .The F-measure has been widely used in the field of Data Mining and Information Retrieval (He et al. 2012, Japkowicz & Shah 2011). It integrates recall and precision in a single indicator. Weighted F-measure is the weighted sum of harmonic means between class precision and recall. There is no unified standard for a threshold to be used for judging whether results of a project management success prediction is acceptable. In past studies, both accuracy and F-measure equal or above 0.7 are often considered reasonably good (He et al., 2012; Thung et al., 2012; Zhang et al., 2013).

Selection of the most informative project characteristics

Correlation-Based Feature Subset Selection (CFS) and selection of project characteristic based on Information Gain (IG) were applied to find the most informative subsets of project characteristic for predicting each of the three class labels (i.e. the project management success). CFS is based on the hypothesis that good feature sets contain features that are highly correlated with the class, yet uncorrelated with each other (Hall, 1999). The algorithm couples evaluation formula with an appropriate correlation measure and a heuristic search strategy in order to find the best subset of available features. Opposite to CFS, IG calculates the score of each feature independently of other features and selects the top n features from the sorted score list. The score is calculated based on IG, which is the expected reduction in entropy caused by partitioning the examples according to a given project characteristic (Quinlan, 1986). The entropy characterizes the (im)purity of an arbitrary collection of examples with respect to their class. While in the case of CFS the number of selected project characteristics is determined by the produced most informative subset, in this research top 10 most informative project characteristics by IG were selected.

Applied learning methods

Three different learning methods (Decision tree (DT), Naive Bayes (NB) and Logistic Regression (LR)) were trained on the available project characteristics. DT is a non-parametric learning method used for classification and regression (Mitchel, 1997). The goal is to build a tree from available data where, in each node, an example is tested against the value of the project characteristic associated with the node. Depending on the test result, the example is forwarded down the tree until it reaches the leaf node with the appropriate class label. The selection of the characteristics associated with the nodes is conducted using IG by placing the most informative characteristics at the root node. The procedure is recursively repeated until all nodes are inserted into the tree. When built, DT is interpretable by human experts since it provides rules for classification in the form of a sequence of if/then clauses (each branch from root to a leaf node is a conjunction of characteristics tests).

NB is a probabilistic classifier which assumes the mutual independence between the characteristics given a class of an example (Yun and Caldas, 2009). It selects the class with the maximum posterior probability given an example represented with its characteristics by using the Bayes theorem. The classifier is easy to implement but it is dependent on class prior probabilities – tends to classify towards classes that occur more frequently in training data. LR is a type of probabilistic statistical classification model, used to predict the class based on one or more characteristics which are usually but not necessarily continuous. It measures the relationship between the class and the independent characteristics by using probability scores of the predicted values of the class (Hair et al., 2009).

Results

For ML the quality of the prediction models is presented through "accuracy" and "F-measure" for three success indicators. For each success indicators the authors used three learning techniques (DT, NB, LR) and three characteristics selection techniques (all characteristics, CFS and IG). The results obtained from ML tools application are given in Table 2. As previously stated, both accuracy and F-measure value equal or above 0.7 are considered reasonably good.

PLEASE INSERT TABLE 2 HERE

The best performing models are:

- For cost overrun – LR with IG (Accuracy 0.718, F-measure 0.720; slightly higher F-measure than LR with CFS);
- For delay in construction – LR with CFS (Accuracy 0.732, F-measure 0.730):
- For delay in planning – DT with CFS (Accuracy 0.718, F-measure 0.720).

Results show that the best performing models are LR and DT which allow identification of the most informative project characteristics due to their expressive power. The prediction performance of the majority of models improves when the techniques for the selection of characteristics are applied, indicating that many megaproject characteristics taken into account with the available data are not sufficiently informative. Table 3 shows the most informative subsets of project characteristics correlated to cost overrun, delays in construction and delays in the planning phase of megaprojects within the existing dataset.

The most informative project characteristics for ML have an "X" indication (irrespectively of having a positive or negative influence on megaproject outcome). Regarding the FET results, Table 3 presents the p-value and the type of correlation. Plus (+) are project characteristics that, if existing, are supportive, i.e. influence positively the project outcome. Minus (-) are project characteristics that, if existing, are antagonist, i.e. negatively influence the project outcome. The results therefore represent the correlation between the individual project characteristics and the success indicators.

Regarding ML, for each success indicator there is a small subset of characteristics identified as the most informative for the prediction of megaprojects' success. For cost overrun, these mostly come from the categories: Project Environment (Legal and Socio-Economic) and Technological Aspects of the Project. Half of the most informative characteristics for both Delay in Construction and Planning also fall in the category Technological Aspects. These are firstly related to the complexity of megaprojects, since they are often first of a kind in a country (characteristic T4) and challenging due to the sector specific requirements, such as nuclear projects (characteristic T7) or location, such as offshore projects (characteristics T8). For instance, according to ML, modularity when designing and building Megaprojects (characteristic T1) helps to prevent delays in the Megaproject planning phase. However, the dependency of modules results to be correlated to delays in construction (characteristic T2).

In the results of FET, project characteristics from the category Stakeholders have the lowest p-value, i.e. the stronger correlation with success indicators. The "litigation between client and EPC" and "the presence of an SPE" (Special Purpose Entity) are the project characteristics correlated with all three success indicators.

In summary out of 46 project characteristics only 10 have been recognized as correlated with the megaproject management success by both ML and FET. Regarding the cost overrun, there are three project characteristics identified both by ML and FET: "Environmental groups have been engaged ex ante, not ex-post"; "The project has a strong regulation system" and "The project is nuclear reactor". These prove that the role of external stakeholders is extremely relevant: indeed, actions from environmental groups, the regulation system (and agencies), and national government are strongly correlated with the cost overrun performance. The "physical characteristics” are not correlated, unless the project is a nuclear reactor: all the nuclear reactors under construction in Europe are cost overrun and late.

Regarding the delay in construction, the most correlated characteristics (identified by both ML and FET) are: “The project has national public acceptability”; “There is planned a long-term stability in usage and value”; “There was a formal litigation procedure during the contract between Client and EPC”; “Offshore project” and “The project has an SPE”. They are, again, mostly related to the project stakeholders: public acceptability, the contractual relation between Client and a Contractor and the existence of an SPE. Interestingly, “The project has an SPE” is among the most relevant variables both for Delay in Construction and Delay in Planning. SPE are fenced organization having limited pre-defined purposes and a legal existence (Sainati et al., 2017). They require a long due diligence process (often delaying the beginning of the project), but then help to keep the project on schedule.

Regarding the delay in planning, four project characteristics are identified as correlated by both MLT and FET: “The project has a strong regulation system”; “FOAK weak – country level” and “The project has an SPE”. The key results show that the regulatory system and the regulations have the strongest correlation with the delay in the planning phase of a megaproject. Also the FOAK in a technological sense and the usage of an SPE is correlated with this outcome. Only one out of 7 project characteristics from the Project Management category (table 9), has been identified as important by either ML or FET (“There was a formal litigation procedure during the contract between Client and EPC”). However the small sample of data about these characteristics might hide existing correlations.

Table 3 presents the overall results.

PLEASE INSERT TABLE 3 HERE

Limitations and challenges in practical application

In this research, the following limitations of both FET and ML methods were identified:

(1) FET and ML models require a representative data sample hard to collect in the context of Megaprojects. In this research, special attention has been made to the processes of collecting relevant project cases and their preparation (see the four steps in the section "Data collection and preparation").

(2) Projects characteristics were represented in the form of binary (YES/NO) attributes leading to the loss of information. The proposed representation was needed due to the nature of the FET. Concerning the applied ML techniques and the effects of the curse of dimensionality, The characteristics could be modeled with multi-valued attributes, once the number of project cases in the available database increases.

Specific limitations regarding FET are:

(1) Due to the availability of a small sample size, possible correlations between project success indicators and characteristics could be considered not significant because the p-value is not lower than a certain threshold. Therefore, these correlations are disregarded leading to a type II error. A Type II error is committed when we fail to believe a truth (Leach, 1979).

(2) The test only considers the correlations between a single project characteristic and a project management success (i.e. characteristic C correlated with performance P). This does not allow to unveil correlations due to multiple project characteristics (i.e. simultaneous occurrence of C1 and C2 correlated with P).

Opposite to FET, ML can be used to assess if a group of project characteristics is correlated with the success criteria (project characteristics used to train more performant prediction models are likely to be more correlated with project management success). However, ML cannot be generalized well from small data sets. Therefore, the applied protocols for model building and validation were adapted to minimize the effects of the low number of available data.

When comparing the possible application of ML to FET in an EPC company, ML requires substantially more expert effort and knowledge. The results of both methods require expert interpretation and validation. However, our findings show that best performing ML methods (LR, DT) are interpretable by human inspection, as opposed to other ML black-box methods (such as Neural Networks).

The FET can be implemented in a regular excel spreadsheet or even executed from several free websites. The execution of ML is more challenging. The proposed ML experiments were conducted using open source Weka package issued under the GNU General Public License (MLGATUOW, 2017). Weka is a collection of ML algorithms for data mining tasks. In order to conduct training and testing protocols suitable for small data sets, we needed to adapt Weka accordingly.

Conclusions

Megaprojects are large, unique and complex projects. Their uniqueness and complexity are due to their physical elements and the dynamic network of the stakeholders involved. Consequently, it is challenging to set up a "lessons learned system". Nevertheless, there are project characteristics (e.g. types of contracts, financing schemes, technological choices) that are quite standard. By investigating these characteristics, it is possible to discover common patterns behind successful and unsuccessful projects.

This paper provides a method to identify in a quantitative and rigorous manner how megaproject characteristics relate to success indicators. Firstly, it provides an initial understanding of how stakeholders in megaprojects can use this knowledge to ensure the more effective design and delivery of megaprojects. Secondly, the analysis of the empirical data using statistical techniques such as the FET and ML investigates the correlations between project characteristics and success indicators.

The results show that stakeholder characteristics are strongly correlated with success indicators (respecting time and cost overrun). This finding supports existing understanding in the project management research community and provides invaluable reinforcement for the further researches of these factors. The project environment, especially legal and socio-economical characteristics have also been identified as having an important relationship with megaproject success. Of particular importance, and previously has received scant attention, is the influence of SPE in megaproject management success.

The investigation outlined in this paper indicates that, if the successful delivery of megaprojects is to be secured, projects need to:

- Engage better with external stakeholders of the megaproject (and especially environmental groups) the affected population and regulators;
- Understand how to make the best use of SPEs in the governance of megaprojects.

What is really relevant for practitioners and policy makers is that, with the contribution provided by this analysis, they will have an insight into the project characteristics correlated with project outcomes even before starting the project. By being aware of the characteristics in Table 3 the stakeholders involved in megaproject design and delivery can use the characteristic of their megaproject to identify potential problems and make their projects more resilient.

This investigation provides a starting point for future research. The success indicators (for schedule and cost overrun performance) only give a partial understanding or megaproject management success. A first logical extension is to add other indicators to assess addressing a 'quality' dimension. Similarly, further project characteristics can be added. If more cases are collected, it will be possible to use a chi-squared test, and the key advantage would be the possibility to use more complex contingency tables allowing the testing of other, more elaborated, hypothesis. In addition, an initial effort in proposing a Megaproject success indicators prediction model presented in this paper could be continued when data from more cases becomes available.

More in general, the method and variables presented in this papers can be applied to the specific types of megaprojects and sectors. For instance, the application to the nuclear decommissioning sector can include project characteristics related to the different strategies and project management about the environment. An EPC company might want to apply it to its portfolio of Oil&Gas projects with the specific form of contracts as project characteristics and the average production in the first two years as project management success.

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Appendix

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Tables

Table 1 Project Management performance definitions. Adapted from (Brookes and Locatelli, 2015)

Dependent Variable Construct	Operationalization
The project had a cost overrun	The project was judged to have a cost overrun if the final cost of the project was greater than the 110% of the original estimate (adjusted for inflation). The estimated cost was taken to be a publically available figure obtained either through direct interview with the project client or through public review at the time as close as possible to the point at which the first formal activity (as, for instance, the first stage in the acquisition of any land rights required for the project) was entered into. The final cost was taken to be a publically available figure obtained either through direct interview with the project client or through public review at the point at which the project entered operation. The final cost and initial estimate were assumed to have been made on the same basis.
The project was delayed in the planning phase	The project was judged to be delayed in the planning if the actual commencement of physical construction was more than 12 months later than the planned date for the commencement of construction. The planned date for the commencement of construction was taken to be a publically available figure obtained either through direct interview with the project client or through public review at the time as close as possible to the point at which the first formal activity (such as the first stage in the acquisition of any land rights required for the project) was entered into. The actual date for the commencement of construction was taken at the point at which any physical construction activity related directly to key functionality of the project was undertaken as reported through direct interview with the project client or through public review.
The project was delayed in the construction phase	The project was judged to be delayed in the construction phase if it exceeded the planned date for entry into service by 12 months (compared to the date set at the point of entry into construction). The planned date for the entry into service was taken to be a publically available figure obtained either through direct interview with the project client or through public review at the time as close as possible to the commencement of construction work. The actual date for the entry into service was taken at the point at which the output from the project was first provided to its intended beneficiaries as reported through direct interview with the project client or through public review.

Table 2: Quality of megaproject prediction - Accuracy and F-measure for different classification models

Project outcome		Y1 Cost Overrun			Y2 Delay in Construction			Y3 Delay in Planning		
ML technique		DT	NB	LR	DT	NB	LR	DT	NB	LR
Accuracy	All project characteristics	0.400	0.513	0.436	0.546	0.634	0.610	0.665	0.650	0.450
	CFS	0.556	0.692	0.718	0.634	0.707	0.732	0.727	0.575	0.575
	IG	0.515	0.513	0.718	0.534	0.659	0.634	0.705	0.550	0.475
F-measure	All project characteristics	0.389	0.515	0.440	0.529	0.632	0.614	0.527	0.609	0.468
	CFS	0.553	0.694	0.715	0.626	0.710	0.730	0.724	0.555	0.555
	IG	0.511	0.515	0.720	0.527	0.663	0.638	0.691	0.537	0.489

Table 3 General results – the most informative Megaproject characteristics

Project characteristics / Performance indicators		Machine learning			Fisher Exact Test		
		Cost Overrun	Delay in construction	Delay in planning	Cost Overrun	Delay in construction	Delay in planning
SI1	The EPC has a clear goal			x			
SI2	The project is mono cultural (weak definition)				15% (-)		
SE1	International environmental groups have been raised concern against the project					3% (-)	
SE2	The project has national public acceptability	X	X			2% (+)	
SE3	The project has local public acceptability					14% (+)	
SE4	Environmental groups have been engaged ex-ante, not ex post	X			1% (+)		
EL2	The project has a strong regulation system: authority gave fine	X			6% (-)	5% (-)	
EL3	The project has a strong regulation system. Actions from the authority postponed the completion	X		X			2% (-)
EL4	The project fits in the long term plan of the country's government	X					
ES1	There is planned a long term stability in usage and value	X	X			14% (+)	
ES3	Financial Support from national government	X					
ES5	The majority of the national population trust the national authority			X			
EP2	Support of the local government (no national)					9% (-)	
PM5	There was a formal litigation procedure during the contract between Client and EPC		X		14% (-)	10% (-)	9% (-)
T1	The megaproject is composed of more than 1 identical independent unit			X			
T2	The project is modular - dependent modules		X				
T4	FOAK weak – country level			X			11% (-)
T7	The project is nuclear reactor	X	X		11% (-)		
T8	Offshore project	X	X	X		8% (+)	
T9	Project physically connects two countries	X					
O2	The project has an SPE		X	X	4% (+)	4% (+)	9% (-)

Table 4 Project stakeholders – Internal (SI)

	Independent Variable	Operationalization		Justification
		NO (0)	YES (1)	
SI1	Project has a foreign Engineering Procurement and Construction (EPC) / main contractor company	The EPC has his main headquarter in the county hosting the project	The EPC has his main headquarter in a foreign country	Foreign EPC / main contractors could be unfamiliar with the project environment (Ruuska et al., 2009)
SI2	The Client is also the EPC or main contractor	The EPC is delivering the infrastructure for a certain customer	The EPC will own the infrastructure	In some projects (e.g. Flamanville 3) the EPC will also be the owner of the infrastructure (Locatelli and Mancini, 2012)
SI3	The EPC has a clear goal	There aren't any documents to backup this characteristic	There are documents to backup this characteristic	It is a key factor in (Pinto and Slevin, 1987)(Pinto and Mantel, 1990)
SI4	The project is mono cultural (weak definition)	Client and EPC have different nationality (main headquarters in different countries)	Client and EPC have the same nationality (main headquarters in the same country)	The impact of multiculturalism in project is stressed in the literature as a key aspect of project governance (Ofori and Toor, 2009; Rees-Caldwell and Pinnington, 2013; Ruuska et al., 2011; Swart and Harvey, 2011)
SI5	The project is mono cultural (strong definition)	Client, EPC and all the important first tier contractors have different nationalities (main headquarters in different countries)	Client and EPC and all the important first tier contractors have different nationalities (main headquarters in the same country)	
SI6	More than 50% share of the client is under the state control	The national state owns directly or indirectly less than 50% of the share in the project	The national state owns directly or indirectly more than 50% of the share in the project	When the customer is the government, the project is managed differently and the risk pattern changes (Aritua et al., 2011)

Table 5 Project Stakeholders – External (SE)

	Independent Variable	Operationalization		Justification
		NO (0)	YES (1)	
SE1	International environmental groups have been raised concern against the project	No evidence of actions from environmental groups	The project has been openly censured by international environmental groups such as Greenpeace	Concerns from environmental groups can trigger scopes change or even stop the project (Ross and Staw, 1993). The real effectiveness is assessed with this variable
SE2	The project has national public acceptability	There are relevant protests or referendums against the project at national level	The population living in that nation was supportive (or not objected) about the project	Public acceptability is often advocated as a precondition for project success (Brunsting et al., 2013; Kaldellis et al., 2013)
SE3	The project has local public acceptability	There are relevant protests or referendums against the project at local level	The local population was supportive (or not objected) about the project	
SE4	Environmental groups have been engaged ex-ante, not ex post	External stakeholders have been involved after the construction started	External stakeholders have been involved before the construction started, particularly in the planning process	In large construction projects, the early involvement of external stakeholders such as "environmental groups" has been suggested as a best practice to avoid issues as the NIMBY syndrome (Alexander and Robertson, 2004)
SE5	Local level protests occurred during construction or commissioning, not during planning	The definition does not apply to the project	The definition applies to the project	Public participation is a key fact and the support toward a certain infrastructure can evolve over time (Drazkiewicz et al., 2015)

Table 6 Project Environment – Legal (EL)

	Independent Variable	Operationalization		Justification
		NO (0)	YES (1)	
EL1	The project has a strong regulation system as evidenced by a) The safety authority stopping the project or very similar projects in the same country	The definition does not apply to the project	The definition applies to the project	A strong regulatory system, in case of not compliance, can foster the EPC and its contractor to expensive scope changes (Locatelli et al., 2011; Ross and Staw, 1993).
EL2	b) The authority giving a fine to the EPC or one of the internal stakeholders in the project			
EL3	c) Action from the authority postponing the final completion of the project			
EL4	The project fits in the long term plan of the country's government	There are no evidences to support how the project fits in the long term plan of the country's government	There is at least an official document presenting how this project fits in the long term strategy of the country	Long term view is often advocated as a key aspect of project delivery (Ahola et al., 2008; Park, 2009)

Table 7 Project Environment – Socio-Economic (ES)

	Independent Variable	Operationalization		Justification
		NO (0)	YES (1)	
ES1	There is planned a long term stability in usage and value	There is no evidence of long term value/stability planned	There is evidence of instruments like a price floor for electricity to support the long term stability of the project	Long term view is often advocated as a key aspect of project delivery. (Ahola et al., 2008; Park, 2009)
ES2	Financial Support from the European Union (EU)	The definition does not apply to the project	The definition applies to the project	Infrastructural projects partially financed by the European Union are supposed to go through an independent cost-benefit analysis and third-part appraisal. (CBA Guide Team, 2008; Kelly et al., 2015)
ES3	Financial Support from the national government			
ES4	Unemployment in the area is above the national average	Unemployment in the area is below the national average	Unemployment in the area is above the national average	The deployment of megaprojects in areas with high unemployment creates job positions useful to reduce the NIMBY problem (Invernizzi et al., 2017; Martinát et al., 2014)
ES5	The majority of the national population trusts the national authority	There are documents (e.g. pools) showing the trust of the national population toward the national authority	There are documents (e.g. pools) showing that the national population do not trust the national authority	The trust on the national authority is linked to public acceptability is positive (He et al., 2013). However, a "trustful national authority" might impose very restricting measures to the project increasing the risks
ES6	The compensation to the local community is above 0.1 of the total budget	The definition does not apply to the project	The definition applies to the project	The compensation to the local community is a way to increase the local public acceptability of the project (NEI, 2003), (Meacham, 2012)
ES7	The density of the population of the province is below the national average	The definition does not apply to the project	The definition applies to the project	Some projects, particularly the controversial ones, might be delivered in areas scarcely populated to reduce the risk of local protest (Barrett and Lawlor, 1997) (Lindén et al., 2015)

Table 8 Project Environment – Political (EP)

<table>
<tr><th rowspan="2"></th><th rowspan="2">Independent Variable</th><th colspan="2">Operationalization</th><th rowspan="2">Justification</th></tr>
<tr><th>NO (0)</th><th>YES (1)</th></tr>
<tr><td>EP1</td><td>Support of the national government (no local)</td><td>The national government has not supported the plant through direct financial subsidies, loan guarantee and tax exception.</td><td>The national government has supported the plant. This includes direct financial subsidies, loan guarantee and tax exception.</td><td rowspan="4">The government is a key player in the megaprojects. It can have several roles and influences directly and indirectly the performances. For instance, several megaprojects are delivered as Public-Private-Partnerships PPP (Evers and de Vries, 2013; Greco et al., 2017; Liu et al., 2016; Locatelli and Mancini, 2014)</td></tr>
<tr><td>EP2</td><td>Support of the local government (no national)</td><td>There are no official documents or incentives or subsides from the local government to support the project</td><td>There are official documents or incentives or subsides from the local government to support the project</td></tr>
<tr><td>EP3</td><td>Support of both national and local government</td><td rowspan="2">The definition does not apply to the project</td><td rowspan="2">The definition applies to the project</td></tr>
<tr><td>EP4</td><td>Not supported by either national and local government</td></tr>
</table>

Table 9 Project Management (PM)

	Independent Variable	Operationalization		Justification
		NO (0)	YES (1)	
PM1	The project uses planning by milestones	There is no evidence that the Project Manager (PM) used a "planning by milestone" approach	There is evidence that the PM used a "planning by milestone" approach	These three variables test the impact of well-known project management tools and techniques. (Golini et al., 2015) (Mir and Pinnington, 2014)
PM2	The project uses formal project management tools and techniques	There is no evidence that the PM heavily used formal project management tools and techniques. At least: Gantt chart, PERT (or simulation), Risk analysis, Earned Value, Cost schedule control System.	There is evidence that the PM heavily used formal project management tools and techniques. At least: Gantt chart, PERT (or simulation), Risk analysis, Earned Value, Cost schedule control System.	
PM3	Usage of performance metrics	There is no evidence that the PM used performance metrics	There is evidence that the PM used performance metrics	
PM4	Turnkey contract between Client and EPC/main contractor	The definition does not apply to the project	The definition applies to the project	The type of contract influences project management success (Suprapto et al., 2016) and turnkeys are blamed for poor risk allocation and therefore performance (Ruuska et al., 2009)
PM5	There was a formal litigation procedure (e.g. international chamber of commerce) during the contract between Client and EPC	The definition does not apply to the project	The definition applies to the project	The alignment of goals between the stakeholders is key for the project delivery. Litigation is an indicator of misalignment between stakeholders
PM6	Project has a well-developed FEED (Front End Engineering Design)	Frequent design amendments and elaborations	There are no change of the FEED during the construction & the FEED was finished before the construction started	A well-developed FEED is often considered a key success factor for the delivery of the project (Merrow, 2011)
PM7	An experienced project director is present	The definition does not apply to the project	The definition applies to the project	Key factors suggested in (Pinto and Slevin, 1987)

Table 10 Technological aspects (T) & other (O)

	Independent Variable	Operationalization		Justification
		NO (0)	YES (1)	
T1	The megaproject is composed of more than 1 identical independent unit	The definition does not apply to the project	The definition applies to the project	Modularisation is often advocated as a strategy to make project more manageable and delivery them on time and on budget (Locatelli, Bingham, et al., 2014). Modularisation can be intended in two ways: 1 – as the decomposition of a large structure in dependent prefabricated modules or 2 – as the construction of several small units with a total capacity comparable to a large plant
T2	a) The project is modular - dependent modules			
T3	b) The project is modular - independent modules			
T4	FOAK weak – country level	At least a similar project was delivered somewhere in the country	The plant is absolutely the first in the country or the design has radical modification respect to existing ones	FOAK project (in particular megaproject) have several unknown unknowns (Ramasesh and Browning, 2014) jeopardizing the planning and delivery. Often FOAK projects are late and has a cost overrun (Merrow, 2011)
T5	FOAK strong – global level	At least a similar project was delivered somewhere in the world	The plant is the absolutely the first in the world or the design has radical modification respect to existing ones	
T6	Industrial sector (Energy, Transport, Miscellaneous)	The definition does not apply to the project	The definition applies to the project	This variable assess the correlation of sector with the performance and support the Machine Learning (ML) algorithm
T7	The project is a nuclear reactor	The project is not about a nuclear reactor	The project is the construction or major refurbishment of a nuclear reactor	Nuclear power plants projects are usually have cost overrun and late even more frequently and then other megaproject (Sovacool, Nugent, et al., 2014)
T8	Offshore project	The definition does not apply to the project	The definition applies to the project	(Merrow, 2011) reports offshore projects as particularly problematic and affected by poor performance in the delivery
T9	The project physically connects two countries	The definition does not apply to the project	The definition applies to the project	Projects connecting two countries (as the well-known channel tunnel) represent a challenge from several perspective, including technology, governance and stakeholders management (Genus, 1997)(Anguera, 2006)
O1	Previous similar project was on time and budget (N/A for FOAK)	The definition does not apply to the project	The definition applies to the project	The deployment of similar facilities might benefit from the industrial learning effect leading to better cost estimation and project delivery performances (David and Rothwell, 1996) (Locatelli, Bingham, et al., 2014) (Choi et al., 2009)
O2	The project has a Special Purpose Entity (SPE)	No SPE is involved in the delivery of the project	One or more SPE are involved in the delivery of the project as Client and/or EPC	Special Purpose Entity are temporary organisations often involved in the project planning and delivery. They might reconcile the interest of several stakeholder toward the common goals of the project (Sainati et al., 2017)