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A FUZZY-BASED DECISION-SUPPORT SYSTEM

for the Analysis of Suitability of Megaproject Delivery Methods

AUTHORS

United Arab Emirates University

Moza T. Al Nahyan
Associate Professor at College of Business Administration

Yaser E. Hawas
Professor Department of Civil and Environmental Engineering

Mohammad Sherif
Research Associate

Basil Basheerudeen
Research Associate

Abstract: This article describes the Decision Support System (DSS) for identifying the best delivery methods for megaprojects, based on risk factors, opportunities for investments, and project constraints. In addition, the system accounts for the relative importance of various stakeholders' roles at different stages of a mega infrastructure project. A fuzzy-based multi-criterion decision-making technique used to develop the DSS assists the client to depict his/her best choices of contractual delivery methods. Further, the system provides the best mix of stakeholder entities that would likely provide the best environment for the project success. A two-step system calibration procedure was considered, including the expert judgment of 192 key stakeholder professionals worldwide. The fuzzy model performance was illustrated using default factor sets and sample inputs of differing weights for project risks, constraints, opportunities and the other critical categories affecting the decision-making process. Based on model results, the conventional delivery method (e.g., Design Bid Build) is least recommended if the project risk weighs more than 30%, as provided by the user. With such an intricate system, the client can investigate the specifics of various project stages and study the effects of enhancements or deficiencies of the stakeholder entities' capabilities.

Keywords: Fuzzy logic model, Project delivery methods, Megaprojects, Project risk

1 Introduction

There has been an extraordinary rise in the infrastructure development projects in the Middle East because of the upcoming mega capital events, such as Dubai Expo 2020 and Qatar FIFA World Cup 2022. The market capacity seems to be failing to keep pace with the demand, which has already negatively affected project delivery in the region. As such, the rapid infrastructure expansion and the limited period for project planning and delivery have put immense pressure on the clients to make appropriate decisions, especially about identification and selection of suitable and competent vendors for contractual delivery. It is well evident that proper selection of contractual delivery method (CDM) is a critical factor for the success of the project (Qiang et al., 2015). The selection is dependent on the client's objectives, project performance measures, and project characteristics (Touran et al., 2009). In the context of UAE construction industry, inadequate early planning and tardiness in client's decision-making process were identified amongst the key factors contributing to construction setbacks that negatively affected the project success (Faridi and El-Sayegh, 2006). The clients may have inadequate knowledge of the influential factors, risks, and constraints in the early project planning. The choice of contractual delivery was commonly based on little understanding of the possible project outcome. The mega infrastructure development is irreversible to a certain extent, which undoubtedly influences the decision-making process (Salet et al., 2013). Mega-projects are ordinarily subject to risks resulting in cost overruns and delays due to misinformation of costs, schedules, and benefits (Flyvbjerg, 2014). Practitioners' claimed that the poor performance of the mega infrastructure projects was attributed to the lack of a structured decision-making process, especially in the design and construction phase of the projects (Brookes, 2015).

Each delivery method by the client is a systematic approach of designing a comprehensive construction procedure involving other stakeholders. This includes the definition of project scope, sequencing of construction activities, and engaging public/private entities for successful completion of the construction project (Khalil, 2002; Touran et al., 2009; Chen et al., 2011). As per the Construction Country Institute (CII), there are three fundamental project delivery methods; namely, Design Bid Build (DBB), Design-Build (DB), and Construction Management at Risk (CMR). Generally, in the DBB method, the client binds with two entities like architect and contractors in separate contracts; whereas in DB, the client contracts with individual entities responsible for the project execution. However, the CMR method involves a construction manager or an agency hired by the client to work on his behalf to monitor and control the project activities. Miller et al. (2000) established additional classes of delivery methods based on the source of finance (direct or indirect) and the integration of delivery (combined or segmented).
Although many practitioners adopt the most common traditional delivery method – Design Bid Build (DBB), no universally acknowledged project delivery method suits every construction project requirement. Past researchers have often overlooked the alternate delivery methods because of lack of familiarity and their applicability in different sectors of the construction industry. The research on the development of client's advisory or management systems for large-scale infrastructure projects is limited (Brookes, 2015). The existing DSS methods fail to account for the complexity and uncertainty involved in effective management of mega infrastructure projects.
Selection of the contractual delivery method involves a multi-criterion decision-making process with due consideration of the requirements and project objectives. Till date, there is no universal agreement about the decision-making process for selection of contractual delivery methods for megaprojects. Generally, decisions are made arbitrarily to satisfy some client needs, which may vary depending on the project and the client.
The primary aim of the present study is to bridge this gap and limit the deficiency of tools, which can assist the client in making vital decisions on project execution. The study emphasizes the development of a front-end expert system to assist the client in selecting appropriate contractual delivery methods based on the evaluation of multiple criteria influencing the project outcome.

2. Contractual Delivery Method Selection

Selecting an appropriate contractual delivery method is fundamental to improving the performance of infrastructure projects. Many researchers have addressed the effectiveness of the different delivery methods, while some have also recognized the factors affecting the contractual delivery and appropriate criterion in the selecting the process. Review of literature indicates that factors influencing the contractual delivery selection are mainly grouped under project characteristics, client requirements, contractor characteristics, and project performance objectives (Alhazmi and McCaffer, 2000; Khalil, 2002; Mahdi and Alreshaid, 2005; Touran et al., 2009; Mostafavi and Karamouz, 2010; Jato-Espino et al., 2014; Yoon et al., 2017). Besides, factors like design characteristics, risks, regulatory, claims and disputes (Gordon, 1994; Love et al., 1998; Mafakheri et al., 2007; Touran et al., 2009) are also documented in the delivery selection process. However, there are no specific universal sets of influential factors; instead, there is a multitude of factors that vary for different distinct delivery alternatives. While most of the researchers till date have discussed the qualitative assessment of the factors affecting the contractual delivery in devising the selection mechanism (Love et al., 1998; Alhazmi and McCaffer, 2000; Luu et al., 2003, 2006; Qiang et al., 2016), some practitioners have focused on the historical project data related to specific project delivery method. Konchar and Sanvido (1998) proposed specific criteria (both quantitative and qualitative) to investigate the effectiveness of DB, DBB, and CMR. Furthermore, the influencing factors vary with project type, size, and cost. As an example, 34 related factors were identified in the delivery of housing projects (Mahdi and Alreshaid, 2005), while 24 factors were recognized in the large-scale transit developments (Touran et al., 2009). Lastly, the past studies reviewed the relative impact of separate factors (sensitivity analysis) in the selection of a particular contractual delivery method (Mahdi and Alreshaid, 2005).
The existing DSS system differs in their considerations on the delivery selection criterion. Noticeably, the mega project industry practitioners emphasize that the appropriate delivery selection should be based on the varying technical demands and reduced construction costs (Mahdi and Alreshaid, 2005), client interests (Khalil, 2002), the degree of stakeholder involvement specific to the contractual delivery (Touran et al., 2009), reduced risks *(Ribeiro, 2001), and average project performance (Konchar and Sanvido, 1998).*
Gordon (1994) utilized flowcharts to choose the best contracting method, which allows the client to prioritize the factors from amongst the list of significant factors provided without weight considerations. Konchar and Sanvido (1998) compared the set of fundamental delivery methods (DBB, DB, and CMR) by multivariate linear regression affecting the project performance objectives. El Sayegh (2008) investigated the effectiveness of conventional contractual methods in accordance to the UAE construction industry, based on different project objectives and client preferences, though it only highlighted the criterion set for the client to rank their preferences. Ribeiro (2001) deployed a Case-Based Reasoning (CBR) framework in the proper selection of a project delivery method. The findings derived from the past experiences of executing delivery methods can be incorporated to tailor the existing delivery methods effectively. In this regard, the Multi-Attribute Utility technique assigns weight to the decision attributes and compares the utility value of the delivery alternatives, which differs with the distinct stakeholder perception (Love et al., 1998; Ratnasabapathy and Rameezdeen, 2010; Hawas and Al-Nahyan, 2017).
To enhance the quality of decision making, Oyetunji and Anderson (2006) employed multi-attribute rating technique augmented with swing weights (SMARTS), defined as a quantitative method of estimating the relative effectiveness of the contractual delivery method for comparison. However, the CBR and the Multi-Attribute Utility technique fail to account for the vagueness in the subjective judgment of the decision attributes and the preferences on the decision attributes is purely based on the user priorities. Besides, these methods do not emphasize the relevance or irrelevance of the decision attributes considered in the selection process.
Contrary to the above methods, the fuzzy-based contractual delivery selection methods assist in handling the uncertainty and vagueness involved in mapping the subjective assessment to an exact number or ratio. Also, the fuzzy model defines different criterion sets by the user needs and preferences rather than reviewing the complete list of decision attributes in the selection process. Mostafavi and Karamouz (2010) proposed a fuzzy-based multi-attribute decision-making model (FMADM) to evaluate the utility membership functions of different contractual delivery methods in petrochemical industry, in which the delivery alternatives were ranked in the order of preference defined by the fuzzy membership function. Besides, the risk attitude of the decision maker was considered by utility membership functions. Chan (2007) proposed a fuzzy procurement model combined with the fuzzy relationships, and synthesis model to rank the contractual delivery alternatives by user needs and preferences. Again, the Analytical Hierarchy Process (AHP) is a multi-criterion decision-making mechanism applied for suitable selection of delivery method by many practitioners (Mahdi and Alreshaid, 2005; Touran et al., 2009). Alhazmi and McCaffer (2000) compared different CDM by multi-screening multi-criterion technique, which involves the integration of Parker's judging alternative technique of value engineering and AHP. A multi-tier hierarchical AHP model with relative weights to the significant factors influencing the delivery method was recognized to compare amid different contractual delivery alternatives (Khalil, 2002; Mahdi and Alreshaid, 2005; Touran et al., 2009). For incomparable alternatives, practitioners utilized the rough set technique in combination with AHP to weigh the alternatives based on a set of condition-decision rules. Pan (2008) investigated the use of fuzzy based AHP model in selecting the most suitable construction method (among three methods) taking reference from a case study of a bridge in Taiwan. However, he found that AHP required a massive dataset of indicators causing inaccuracy, which arises with the imprecise perception of experts or professionals in the industry. As such, AHP technique is sensitive and can lead to varying decisions on situations with a higher degree of uncertainty (Kordi and Brandt, 2012).
Though different selection mechanisms covering different stages of a project are available, fewer efforts are put forth to establish a toolkit that assists the client in delivery selection. The toolkit helps the user or the client to remark their particular preferences and needs in the contractual delivery selection (Kumaraswammy and Dissanayaka, 2001; Touran et al., 2009; Mostafavi and Karamouz, 2010). Kumaraswammy and Dissanayaka (2001) deployed an expert knowledge-based advisory system based on Artificial Neural Network (ANN) model to assist the decision-makers in the proper selection of the delivery method of building construction.

3. Research Approach

The selection of the contractual method is a complicated decision-making process and substantially varies with the project characteristics and client's objectives. Moreover, the uncertain nature and inherent complexities associated with the increasing size of the infrastructure projects makes the decision-making process even more difficult for the client. However, it is arduous for the client to obtain information (quantitative or qualitative) on the alternate delivery methods confining to the diverse project requirements and client needs. Moreover, the project delivery selection is governed by multiple factors constituting the project characteristics, client needs, preferences and risk factors. It is appealing to adopt the Multi-Criteria Decision Making (MCDM) approach to model the multi-dimensional and complex interface of the factors governing the selection of project delivery alternatives. Based on the predefined criteria of multiple factors, a fuzzy-based MCDM is used in this study for assessing the contractual delivery alternatives for large-scale infrastructure projects. The relative weights of the multiple criteria are estimated for the project delivery alternatives using the linguistic values represented by the fuzzy numbers. An aggregate measure of weights was evaluated for determining the suitability of delivery alternatives depending on the client preference and project goals. In order to reflect on the influence of the managerial processes of the project, the system requires the qualitative judgment of the importance of the project stakeholders at different project stages. It is feasible to adopt a human intuitive judgment process to capture the vagueness in the selection procedure, and hence, a fuzzy-based approach was adopted to characterize the factors influencing the contractual delivery in mega infrastructure projects.

Based on a thorough review of the literature, the critical factors influencing the selection process were grouped into three categories; risks, constraints, and opportunities. Indicators of the listed categories were assessed qualitatively using a questionnaire survey by the industry professionals and used to validate the developed model structure and weight factors. Based on the qualitative inputs of the system users, the indicators of the risk elements, opportunities, and constraints were used collectively to estimate a qualitative measure ( ) for each element separately. Such qualitative measures were then compared with the decision matrix to rank the alternative project delivery methods, where the highest index score refers to the best suitable method of project delivery. This paper addresses the model structure devised to aid the client in the selection of the most appropriate contractual delivery methods.Based on a thorough review of the literature, the critical factors influencing the selection process were grouped into three categories; risks, constraints, and opportunities. Indicators of the listed categories were assessed qualitatively using a questionnaire survey by the industry professionals and used to validate the developed model structure and weight factors. Based on the qualitative inputs of the system users, the indicators of the risk elements, opportunities, and constraints were used collectively to estimate a qualitative measure (L, M, H) for each element separately. Such qualitative measures were then compared with the decision matrix to rank the alternative project delivery methods, where the highest index score refers to the best suitable method of project delivery. This paper addresses the model structure devised to aid the client in the selection of the most appropriate contractual delivery methods.

4. Model Structure

The model software was developed in C#.net framework using Microsoft Visual Studio®. The system uses a database to store the input, output values, and processed information. It is compatible with Microsoft Windows Operating System and needs installation of Microsoft.Net framework 4.5 or higher to run the program. Besides, it uses FuzzyTech® generated runtime files to implement fuzzy logic.

As shown in **Figure 1**, the system evaluates elements of risks, opportunities for investments and constraints on delivery. Each category has elements defined by a set of indicators. For example, in the risk category, the economic risk was evaluated by the indicators like country's GDP, unemployment level, population size, human development index (HDI), inflation rate, and cash flow level in the market.

The developed decision support system (DSS) ensures a toolkit to assist the client in evaluating the multiple factors based on predetermined or flexible criteria to select the best suitable contractual delivery method. The DSS has three components: input interface, fuzzy rule-based processing (granular) core, and output interface. The input and output components are designed to provide the user with an interactive Graphical User Interface (GUI). Hence, it allows the users to interact easily through graphical icons and visual indicators. The input space offers flexibility to the end-users to define or prioritize the mega-project attributes, which is essential in identifying the best delivery methods.

The granular fuzzy core is designed using FuzzyTech® software, which is a runtime file used in the fuzzy calculations. The linguistic values of the indicators (as input by the user) are rated as very low, low, medium, high, and very high. Some indicators are binary and tagged as Yes or No. **Figure 2** shows a schematic representation of

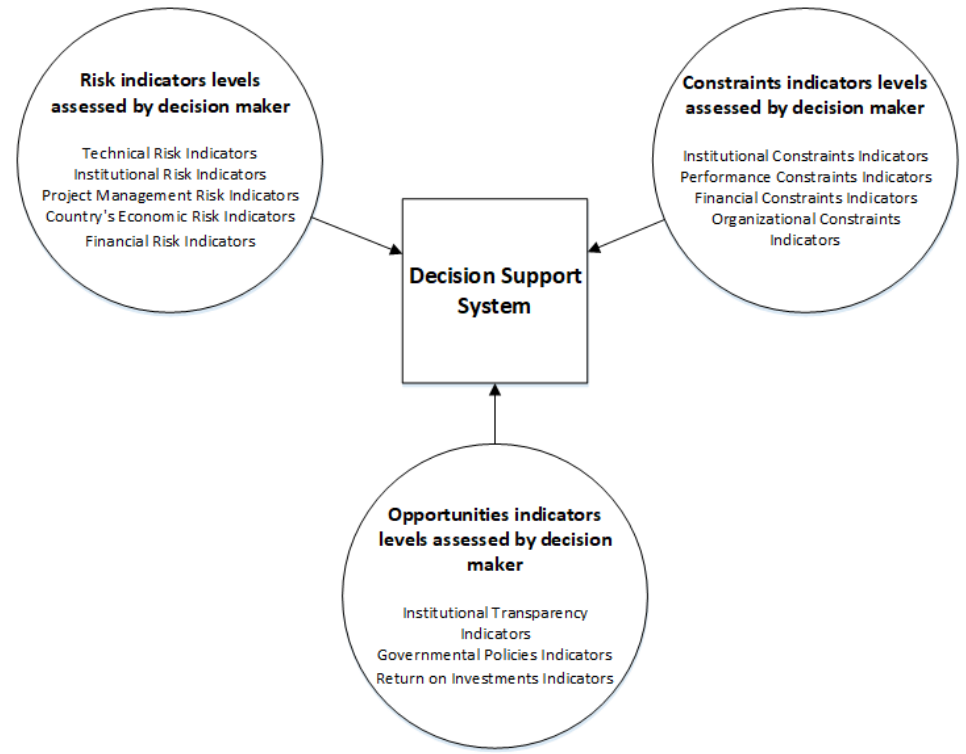


Figure 1. Elements and indicators of MCDM based DSS

the working process for the economic risk element, where the user selects the fuzzy input term from a combo box. Before passing the values on to the granular core, the fuzzy user-input terms are 'defuzzified' into numeric values by the system. The system collects the defuzzified inputs and processes them further through subsequent fuzzification process, before firing the rule base blocks. The system intermediately reports a numeric value and corresponding fuzzy term for each element (e.g., Economic Risk).

During calculations, the processing core relies on the built-in correlation values and signs (positive or negative) defined for every composition in the fuzzy rule-base. The developed DSS model structure has four stages: Configuration, Computation, Calibration, and Output and Reports. The stages are described in detail in the following sections.

4.1 *Model Configuration*

The configuration stage is defined as the point where the user inputs the essential information to the system. Once the configuration is completed through a GUI interface, the data entries are saved to a database, where they can be retrieved or re-edited whenever necessary for further calculations. **Figure 3** shows the schematic representation of the user interaction with the system at the configuration stage. As discussed earlier and as shown in **Figure 2**, the indicators' values are processed through the fuzzy system and outputs are stored in the database. The various input modules for the end user are outlined hereafter.

4.1.1 *Project Stages*

Each project has a clear set of stages with a distinct set of activities (in each stage) that executes the project right from idea conception to its implementation. The project activities in each stage are significant enough to contribute to the overall success of the project. The process of directing and controlling a typical mega-project development from start to finish is commonly divided into six stages: Planning, Scoping, Design, Scheduling, Tendering, and Construction.

4.1.2 *Project Stakeholders*

Traditionally, a stakeholder can be an individual or entire organization who can have an effect on or get affected by the project implementation or outcome of a project (Rose, 2013). It does not matter whether the project affects them negatively or positively. They can be internal or external to the organization. Based on previous reviews, the default stakeholders involved in the system development are: 1) Clients/Sponsors, 2)

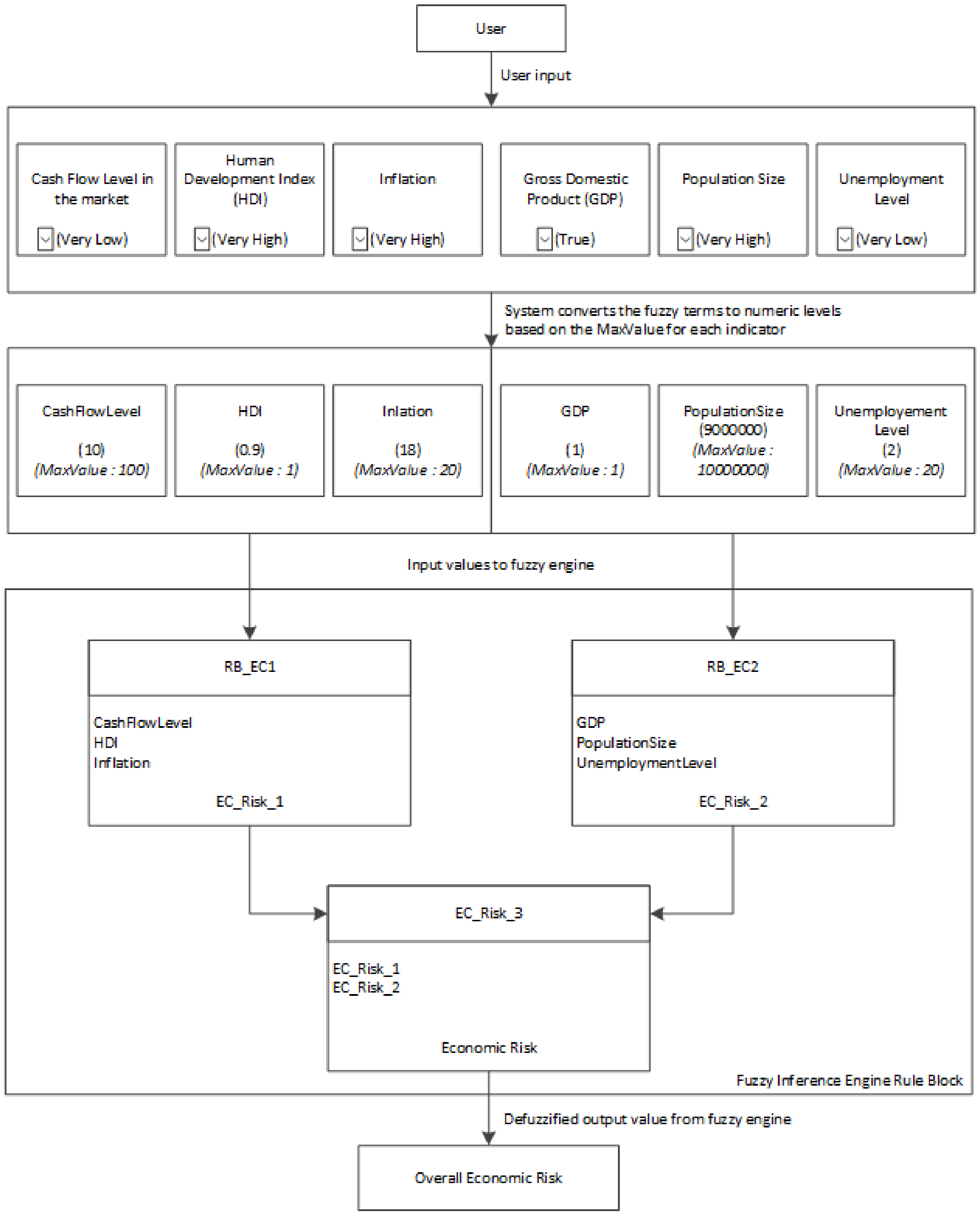


Figure 2. Estimation of economic risk from user input using fuzzy inference engine rule block

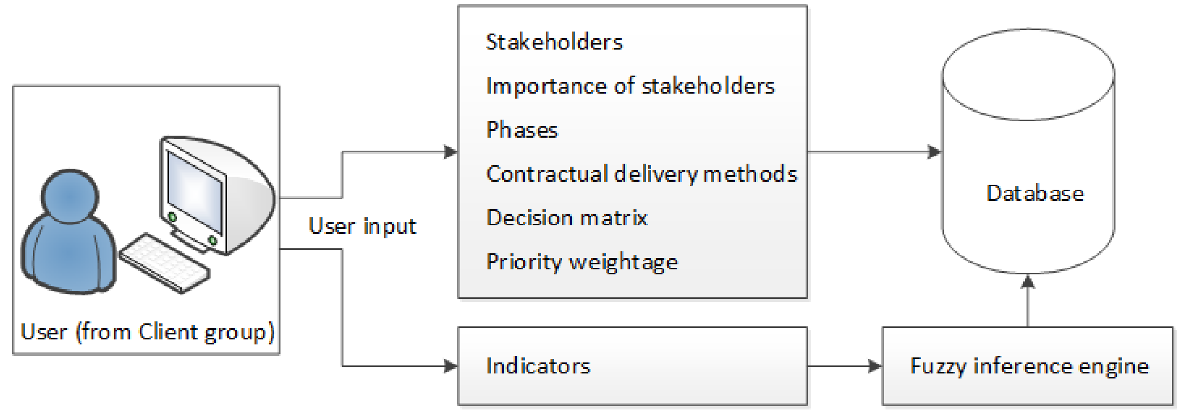


Figure 3. Configuration stage – user input and fuzzy calculation

Government Agencies, 3) Project Managers, 4) Consultants, and 5) Contractors. The system allows the user to edit various stakeholder groups by enabling the functions of add, remove, or update.

The stakeholder engagement varies amongst different stages of the project, and it is captured in the decision mechanism by estimating their importance levels as shown in Figure 4. Each stakeholder can have different levels of importance in different phases of a project. The system scales the importance value from 0 to 9, where 0 and 9 represent no importance and profoundly influential, respectively. The default values of the relative significance of specific stakeholders in different stages of a project cycle are determined using surveys of expertise in large-scale projects. The user, however, can edit and adjust these importance levels. For instance, if the importance level of the contractor is set to 6 and 3 in the tendering and design stage, respectively, it implies that the contractor's role is much more critical in the tendering stage in accordance to the user. Also, if there are multiple contractors involved, the importance rating can be varied accordingly (**Figure 4**).

4.1.3 *Contractual Delivery Methods*

The contractual delivery is a sequence or a process by which a construction project is comprehensively designed and constructed. It includes the project initiation, scope definition, organization of designers, constructors and various consultants, sequencing of design and construction operations, execution of design and construction, and closeout (Project Delivery Systems for Construction, 2004).

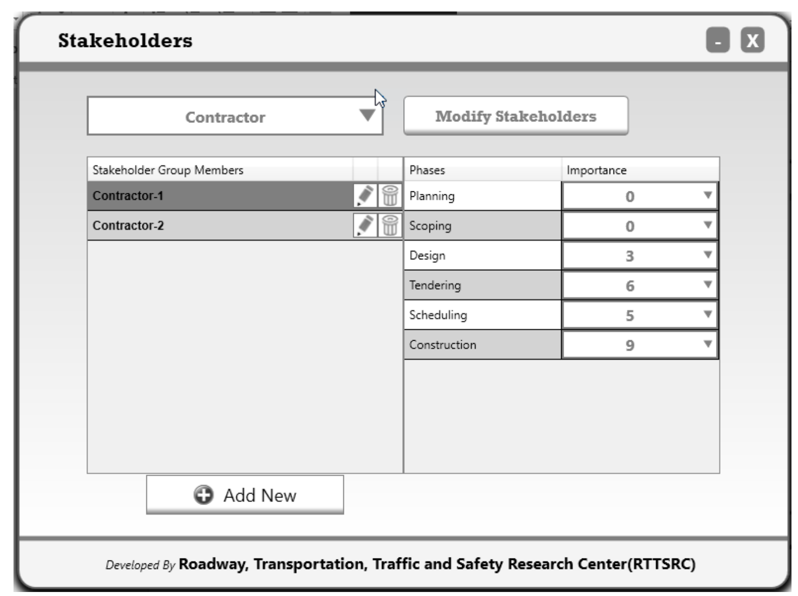


Figure 4. Configuring the stakeholders' importance levels

4.1.4 *Decision Matrix*

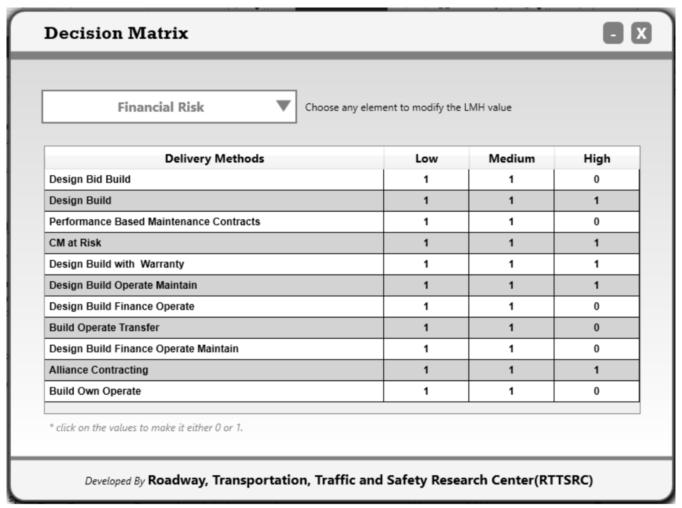
The decision matrix reflects on the inherent suitability of various contractual delivery methods against varying levels of the megaproject's attributes. The mapping of the risks, opportunities and constraints levels to the various project delivery methods was done based on the literature review and survey data. As shown in **Figure 5**, each row represents a particular delivery method. The Low, Medium and High columns represent the corresponding suitability values for each delivery method based on the chosen element from the combo box list. For instance, **Figure 5** represents the mapping values of financial risk as the chosen element. The column entries show the suitability scores for each specific delivery method. The entry of 1 indicates the suitability of the delivery method, and 0 indicates the non-suitability. Some researchers suggested that in high financial risk situations, DB is preferred over traditional DBB (Konchar & Sanvido, 1998; Gransberg et al., 2003). As can be seen in the financial risk decision matrix (Figure 5), the DB is coded as a suitable method for high financial risk, while DBB is coded unsuitable.
Also, as shown in Figure 6, for the case of low or medium Institutional Transparency Opportunity levels (e.g., when institutions lack clarity in technical and financial plans, relevant information, and communication), only the DBB and PBMC contractual methods are coded suitable.

4.1.5 *Priority Weights*

The user can set a priority weight for each element and group/category of elements (risks, opportunities, and constraints) based on his knowledge and understanding. Easy to use GUI interface facilitates the user to set the ratio for the priority. For instance, if only risks are considered (risks are weighted 100%, while constraints and opportunities are weighted 0% each). This will facilitate the selection of best project delivery methods to minimize project risks. Alternatively, if only opportunities are considered (with a relative weight of 100%), the decision on project delivery is likely to maximize the investment opportunities. Similarly, if the decision maker considers only constraints, a relative weight can be assigned, and as such, both risks and opportunities will not affect the decision making. As shown in Figure 7, the priority weight ratio for categories of risks, constraints, and opportunities are assigned as 1:2:1, whereas constraints take 50% priority, and risk and opportunities take 25% each. Owing to such an advanced mechanism, the user is empowered to alter the relative weights of different categories such as risks, constraints, and opportunities and the differential weights of the individual elements of these categories, as causative factors in multi-criteria decision making.

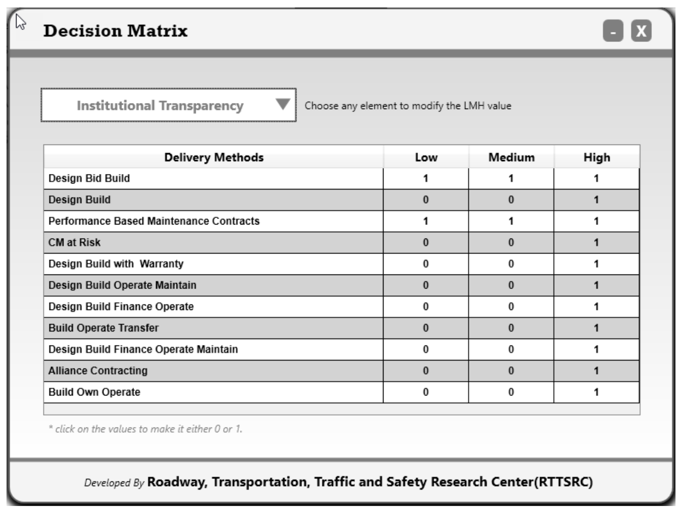
4.1.5 *Indicators*

The inputs given for indicators entail for domain knowledge of the expert or decision maker. Each element of risk has its indicators required to identify its overall risk value, which in turn becomes a part of the overall project's risk (Al Nahyan et al., 2018b). Similarly, the indicators are identified for



Delivery Methods	Low	Medium	High
Design Bid Build	1	1	0
Design Build	1	1	1
Performance Based Maintenance Contracts	1	1	0
CM at Risk	1	1	1
Design Build with Warranty	1	1	1
Design Build Operate Maintain	1	1	1
Design Build Finance Operate	1	1	0
Build Operate Transfer	1	1	0
Design Build Finance Operate Maintain	1	1	0
Alliance Contracting	1	1	1
Build Own Operate	1	1	0

Figure 5. Configuring the decision matrix for the financial risk



Delivery Methods	Low	Medium	High
Design Bid Build	1	1	1
Design Build	0	0	1
Performance Based Maintenance Contracts	1	1	1
CM at Risk	0	0	1
Design Build with Warranty	0	0	1
Design Build Operate Maintain	0	0	1
Design Build Finance Operate	0	0	1
Build Operate Transfer	0	0	1
Design Build Finance Operate Maintain	0	0	1
Alliance Contracting	0	0	1
Build Own Operate	0	0	1

Figure 6. Configuring the decision matrix for the institutional transparency opportunity

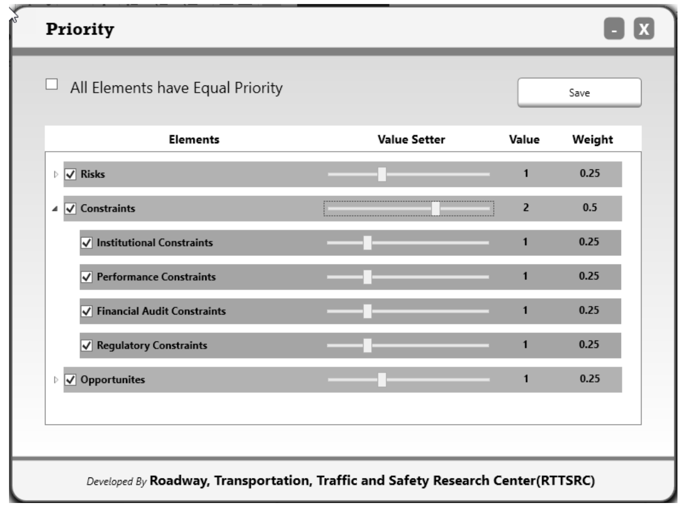


Figure 7: User-defined priority preferences for the categories and elements

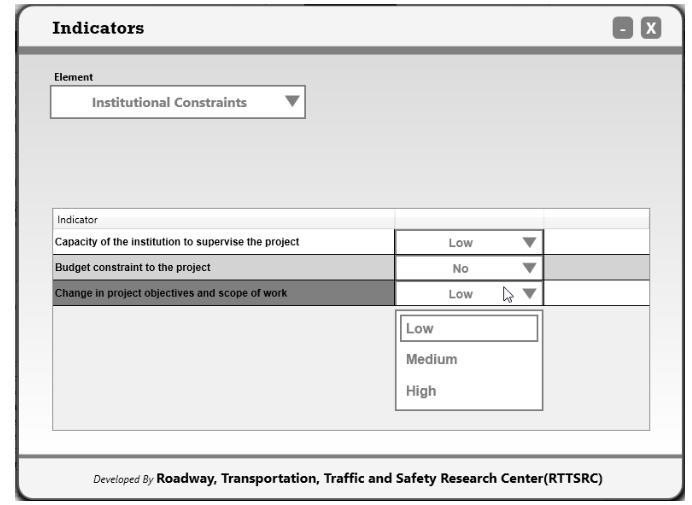


Figure 8. User's rating for the institutional constraint indicators

separate elements of categories like constraints and opportunities, which assist in estimating their respective index value. Some specific elements (e.g., communication and coordination processes) are influenced by the managerial actions of different stakeholder groups, and hence, the respective indicators of these elements are evaluated for separate stakeholders involved in the project as compared to other generic indicators.
The user-defined indicator values are then passed onto the fuzzy engine. The fuzzy rule-based inference units are used to estimate the corresponding fuzzy outputs of the element based on the input values of its indicators. The fuzzy inference block is validated using the qualitative judgment of experienced practitioners. For example, as shown in Figure 8, the change in project objectives and scope of work is identified as an indicator of institutional constraint. The required tasks agreed upon for the project may be altered due to the limited resources and hence, can affect the overall quality of the project. With frequent occurrence of changes, it is more likely to affect the project success. The users set their preferences accordingly using the linguistic terms provided in a drop-down menu.

4.2 *Model Computations*

Figure 9 shows the schematic representation of the flow of the computation process of the user-defined input data. The client/user have the flexibility to run the program considering all the delivery methods and stakeholders or evaluate by choosing a specific delivery method and stakeholder group/entities for the specific project requirements. In addition, different combinations of stakeholder entities for separate contractual delivery methods are generated according to the user selection.

Based on the user-defined indicator inputs, the fuzzy inference engine generates outputs (numeric levels) of each element of risks, constraints, and opportunities. The defuzzified numeric estimates are combined with the user-defined project stakeholder importance rating and are represented on an ordinal scale of 0 to 1. The next step is to map these numerical values to the decision matrix which accepts only the fuzzy terms. The estimates of different elements are fuzzified as Low (L), Medium (M), or High (H) and the probabilities of each category level (L, M, H) of different elements are estimated (Al Nahyan et al., 2018a).

The probability of different category levels of a particular element are denoted by $P_{X,y}(L), P_{X,y}(M)$ and $P_{X,y}(H)$, where X corresponds to different categories such as risks, constraints and opportunities, and y represents the respective elements of different categories. and For instance, we consider the financial risk element (R_f) to illustrate the fuzzification of numeric estimates, and hence, mapping onto the decision matrix to estimate the suitability index of a particular delivery method. Let say, if:

i. $\forall\ R_f \ \leq\ 0.25 \leftarrow\ R_f \in \{L\} \qquad P_{R,f}(L)\ = 1$

ii. $\forall\ R_f \ =\ 0.5 \leftarrow\ R_f \in \{M\} \qquad P_{R,f}(M)\ = 1$

iii. $\forall\ R_f \ \geq\ 0.75 \leftarrow\ R_f \in \{H\} \qquad P_{R,f}(H)\ = 1$

iv. For the case where $0.25 < R_f < 0.5$, it implies a value between the Low (L) and Medium (M) levels of financial risk. That is, a part of R_f belongs to the Low level (L) while the remaining of it belongs to the Medium level (M). If $P_{R,f}(M)$ represents the proportion of R_f categorized as Medium, and $P_{R,f}(L)$ indicates the proportion of that belongs to a Low category then:

$$P_{R,f}(M) = \left(\frac{R_f - 0.25}{0.25}\right); \quad P_{R,f}(L) = 1 - P_{R,f}(M)$$

v. In case of $(0.5 < R_f < 0.75)$ the procedure mentioned above in (iv) shall be repeated to find proportions of Medium (M) and High (H) categories as follows:

$$P_{R,f}(H) = \left(\frac{R_f - 0.5}{0.25}\right); \quad P_{R,f}(M) = 1 - P_{R,f}(H)$$

Once fuzzified, the values can be mapped to the decision matrix. For the cases of $(R_f \le 0.25)$, $(R_f = 0.5)$, and $(R_f \ge 0.75)$, the R_f value is Low (L), Medium (M), and High (H), respectively, and as such, it can be multiplied directly by the corresponding 0 or 1 under the financial risk element against every contractual delivery method (**Figure 5**). In case of $(0.25 < R_f < 0.5)$, R_f has two proportions of $P_{R,f}(M)$ and $P_{R,f}(H)$. Similarly, in case of $(0.5 < R_f < 0.75)$, R_f has two proportions, $P_{R,f}(M)$ and $P_{R,f}(H)$. In both of these cases, the proportions shall be mapped separately to the decision matrix, and the results will be added, as per the case. It implies that if R_f the value is categorized as Medium (M) and High (H), and then mapped to the decision matrix against the design-bid-build (DBB) method; the $P_{R,f}(M)$ shall be multiplied by 1 (the cell entry of the decision matrix in the case of DBB and Medium (M) financial risk category) and $P_{R,f}(H)$ is multiplied by 0 (the cell entry of the decision matrix in the case of DBB and High (H) financial risk category) (see **Figure 5**). The results of these multiplications shall then be added. That is, for any contractual delivery method $z, z \in [1, Z]$ the overall suitability score $S^z_{R,t}$ of this method with respect to the risk R financial category f is estimated as follows in Eqn.(1).

$$S^z_{R,f} = s^z_{R.f,L} * P_{R,f}(L) + s^z_{R.f,M} * P_{R,t}(M) + s^z_{R.t,H} * P_{R,t}(H), \forall z \in [1, Z]$$

Eqn. (1)

$s^z_{R.f,L} = 1$ if a project delivery method z is suitable for the Low (L) financial (f) risk (R) condition, and $s^z_{R.f,L} = 0$ otherwise (not suitable). $s^z_{R.f,M} = 1$ if project delivery method z is suitable for the Medium (M) financial risk condition, and $s^z_{R.f,M} = 0$ otherwise. $s^z_{R.f,H} = 1$ if project delivery method z is suitable for the High (H) financial risk condition, and $s^z_{R.f,H} = 0$ otherwise.

At this point, a relationship is established between the suitability of a delivery method and the financial risk posed on the mega project by the stakeholders. This relation is a function of the intrinsic response of a specific project delivery method to the estimated financial risk associated with the mega project. By following similar estimation and mapping procedures, we can establish the suitability of project delivery methods against various types of risks, constraints, and opportunities that are associated with the mega project. Finally, by accumulating these results, the overall suitability indices of all delivery methods are estimated.

As discussed earlier, the system user may incline more/less weight to the different categories of risk, constraints and opportunities and the respective differential weights to the corresponding elements of each category. To empower the decision-making, the priority weights of different categories are combined with the mapping results to estimate an index that reflects the suitability of a particular delivery method for the mega project under study. Finally, the overall "absolute" score of each delivery method is provided in Eqn. (2).

$$S^z = S^z_R.W_R + S^z_C.W_C + S^z_O.W_O, \forall z \in [1, Z]$$

Eqn. (2)

where,

represents the project delivery method. z is the total number of project delivery methods under consideration. S^z_R, S^z_C, S^z_O and represent the overall mapping scores of all the elements of risks, constraints, and opportunities, respectively. Besides, the overall score of risk (S^z_R) is the summation of the scores of each risk category times their relative weights and is shown in Eqn. (3).

$$S^z_R = S^z_{R,t} \cdot W_{R,t} + S^z_{R,o} \cdot W_{R,o} + S^z_{R,f} \cdot W_{R,f} + S^z_{R,m} \cdot W_{R,m} + S^z_{R,e} \cdot W_{R,e}$$

Eqn. (3)

Where,

$S^z_{R,t}$, $S^z_{R,o}$, $S^z_{R,f}$, $S^z_{R,m}$, and $S^z_{R,e}$ represent the score mapping results of the technical, organizational, financial, management and economic risks, respectively for the z delivery method. Similar expressions were written for S^z_C and S^z_O.

To estimate the relative scores, the maximum absolute score is estimated as follows:

$$S_{max} = Max\{S^z = S^z_R.W_R + S^z_C.W_C + S^z_O.W_O, \forall z \in [1, Z]\}$$

Eqn. (4

The standardized score $\widetilde{S^z}$ of any delivery method, z is then estimated using Eqn.(5).

$$\widetilde{S^z} = S^z / S_{max}, \forall z \in [1, Z]$$

Eqn. (5)

The index $\widetilde{S^z}$ - referred to herein as the contractual delivery method index- reflects the suitability of the corresponding delivery method on an ordinal scale from 0 to 1. The DSS estimates the index value for each chosen delivery method and stakeholder combination. The higher the value of $\widetilde{S^z}$, the more suitable the method is and vice versa. A comparison of $\widetilde{S^z}$ values for all the delivery methods under consideration can help in determining which of the methods is the most suitable for the mega-contractual delivery.

4.3 *Model Calibration*

To calibrate the model which contains multiple factors, a two-stage calibration procedure was deployed, which includes first the calibration of the fuzzy model itself, and then the calibration of the decision matrix of the delivery methods.

4.3.1 Calibration of the Fuzzy Model

The fuzzy model calibration entails the validation of the importance levels of all the indicators of risks, constraints, and opportunities. It also entails verifying the strength of the relationships of the indicators and the model outcomes. For the calibration purposes, an online questionnaire survey was developed and distributed among experts of mega projects worldwide. The opinions of 192 experienced participants were collected and utilized for this purpose.

4.3.2 Calibration of the Decision Matrix.

The construction of the decision matrix (that maps the suitability of the various delivery methods to the various levels of risks, constraints, and opportunities) was a somewhat challenging task yet vital as the expertise in mega-project management is rare and mostly limited to one or few project delivery methods. Therefore, our approach was to rely on the collective wisdom and experience of the group of experts (available in the form of best-practice guidelines) instead of floating a questionnaire for the verification of the decision matrix. The available guidelines for using various delivery methods in the literature (such as PMI guidelines) were coded in the form of the decision matrix. The coded guidelines were then carefully audited by several experts to ensure the validity of the suitability indices of the various delivery methods (Al- Nahyan et al., 2018a).

4.4 *Model Output and Reports*

The best suitable delivery methods are documented in output report based on the estimated index standardized values. The developed system displays two reports as indicated in Figure 9, 10, and 11. It gives the decision maker more options to ease decisions. As shown in Figure 10, report type I enables the user to identify the top recommended project delivery methods and stakeholder entities that are likely to achieve best project performance and success (ranked by their standardized indices). As indicated in Figure 11, report type II enables the user to optimize the selection of the best stakeholder entities for a specific delivery method.

5. Illustrative Example

A hypothetical test case was recognized to demonstrate the application of DSS in the appropriate selection of contractual delivery methods in mega infrastructure projects. The DSS assists the clients or decision makers in identifying the best contractual delivery method based on the user-defined inputs corresponding to the project environment and stakeholder involvement. The CDM selection process based on user or client requirements is illustrated by a stepwise procedure in the following section.

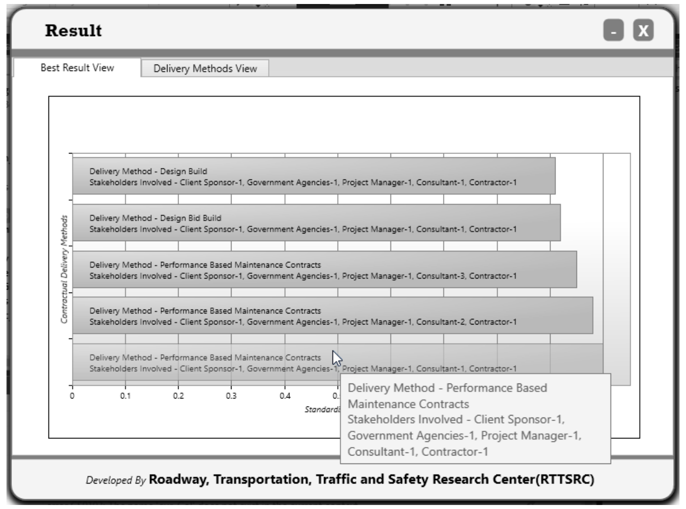


Figure 10. Report Type I: best project delivery methods and involved stakeholders' entities

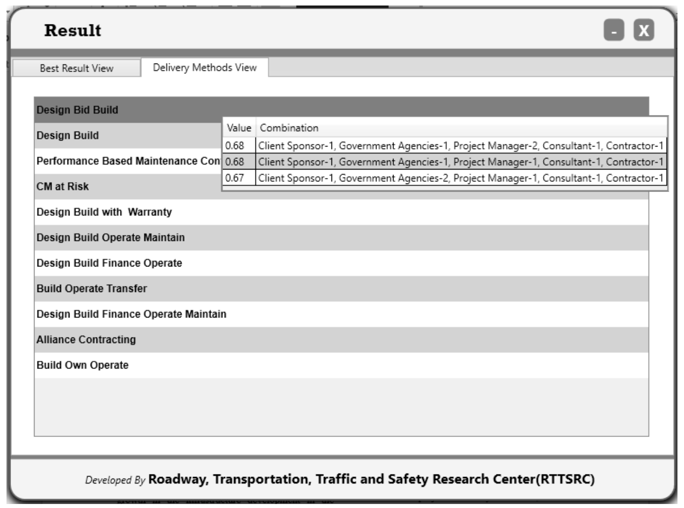


Figure 11. Report Type II: suitability indices and stakeholder combinations for specific delivery methods

5.1 Step 1: User inputs for DSS

As mentioned in Section 4.1.5, the DSS offers the flexibility to prioritize amongst different elements and group/category of elements on a ratio scale. The user can set preferences by assigning differential weights to different categories and elements. As a study example, the default priority set (equal weights) for different categories indicated as 1:1:1 and equal proportionate of separate elements of each category was considered.
Secondly, the user can rate the stakeholder importance level for different project stages, which is based on his understanding and expectations of the project. The sample inputs of importance rating provided for separate stakeholders considered in the illustrated example is shown in **Table 1**. Besides, the user can define multiple entities of similar stakeholder class and provide differential ratings of the importance levels for the multiple entities.

Lastly, the user also provides a qualitative assessment of the indicators of different elements, which is based on their domain knowledge and expertise level. The user indicates the subjective levels of the indicators of different elements at the project level. Besides, individual elements such as technical risk, and organizational risk may vary across the stakeholders, and therefore, the indicators of these elements are judged for each of the concerned stakeholders involved in the megaproject life cycle. For instance, the indicator of technical risk, namely, the level of technical competency is qualitatively judged for the stakeholders involved in the project. The qualitative measures of the indicators of different elements are arbitrarily selected for s_R^z the illustrative example.

Rating of Stakeholder Importance in Project Stages

Project Stages	Client or Sponsor	Govt. Agency	Project Management	Consultant	Contractor
	Project Stakeholders				
Planning	9	8	7	6	3
Scoping	8	7	6	7	2
Design	6	6	5	9	2
Tendering	7	5	7	6	6
Scheduling	5	5	9	6	7
Construction	4	4	8	4	9

STAKEHOLDER IMPORTANCE RATING SCALE

1	2	3	4	5	6	7	8	9
LOW								HIGH

Table 1. Sample inputs for the stakeholder importance rating across different project stages

5.2 Step 2: Fuzzy Model

The DSS converts user-defined inputs of indicators to numeric levels before sending them to the fuzzy inference engine. The fuzzy engine constitutes the rule block that hosts a set of rules, where each unique combination of the indicator levels corresponds to a specific linguistic output as shown in **Table 2**. Subsequently, the fuzzy term of different elements is defuzzified to numeric levels by the inference engine and returns the value to the system. The fuzzy outputs obtained for the project and stakeholder-based elements based on the user-defined inputs of sample test case is shown in **Table 3** and **Table 4**, respectively.
The estimates of the elements are determined by combining the numeric values with the importance weights collectively posed by all the stakeholders, and the values lie between 0 to 1. This applies only to the stakeholder-based elements, whereas the numeric values for the project-based elements remain the same as obtained from the fuzzy inference engine. The obtained overall numeric estimate of each element is fuzzified based on probability set of rules preset by the system. The overall output is mapped onto the decision matrix as detailed in Section 4.1.4. Finally, the mapped values are determined for all the identified elements and aggregated to determine the suitability index of each contractual delivery method on an ordinal scale of 0 to 1. Likewise, the suitability index is estimated and compared for all the listed CDM in the system to determine the most suitable one for the attributes given by the user. The higher the suitability index of CDM, the more it is recommended by the DSS to adopt.

SAMPLE OUTPUTS OF FUZZY ENGINE WITH USER-DEFINED INPUTS FOR INDICATORS

Class of Elements	Indicators	USER RATING: Scale*	USER RATING: User Input	Rule-based Fuzzy Output
RISKS				
Economic	a. Cash Flow level in the market	5	VERY HIGH	**LOW**
	b. Human Development Index (HDI)	5	HIGH	
	c. Country' Inflation Rate	5	VERY LOW	
	d. Country's Overall GDP	2	TRUE	
	e. Population Size	5	VERY HIGH	
	f. Level of Unemployment	5	LOW	
CONSTRAINTS				
Institutional	a. Budget constraint to the project	2	TRUE	**MEDIUM**
	b. Capability to supervise the project	3	HIGH	
	c. Changes in objectives & scope of work	3	LOW	
OPPORTUNITIES				
Return on Investments	a. Capital Assets	5	HIGH	**LOW**
	b. Level of Profit	5	VERY LOW	

***RATING SCALE:**

5 point scale					3 point scale			2 point scale	
VL	L	M	H	VH	L	M	H	T	F
Very Low	Low	Medium	High	Very High	Low	Medium	High	True	False

Table 2. Sample Inputs and Outputs of Fuzzy Inference Engine

RULE-BASED OUTPUTS FROM FUZZY ENGINE	
Project Based Elements	**Fuzzy Outputs**
Economic Risk	LOW
Institutional constraints	MEDIUM
Performance constraints	HIGH
Financial Audit constraints	HIGH
Regulatory constraints	MEDIUM
Government Policies	MEDIUM
Return on Investments	LOW
Institutional Transparency	MEDIUM

Table 3. The fuzzified outputs for the elements influencing CDM selection at the project level

RULE-BASED OUTPUTS FROM FUZZY ENGINE					
	Project Stakeholders				
Stakeholder-based Elements	Client or Sponsor	Govt. Agency	Project Management	Consultant	Contractor
Technical Risk	LOW	HIGH	HIGH	HIGH	HIGH
Organizational Risk	LOW	HIGH	HIGH	HIGH	HIGH
Financial Risk	LOW	HIGH	HIGH	HIGH	HIGH
Project Management Risk					
I. Communication	LOW	HIGH	HIGH	HIGH	HIGH
II. Coordination	LOW	HIGH	HIGH	HIGH	HIGH
III. Decision making	LOW	HIGH	HIGH	HIGH	HIGH
IV. Knowledge sharing	LOW	HIGH	HIGH	HIGH	HIGH

Table 4. The fuzzified outputs for elements influencing CDM selection at the stakeholder level

5.3 *Step 3: Output Interface*

As discussed earlier, the DSS system generates two report documents; the first one (Figure 10) entails the most recommended CDM for the user-defined attributes of stakeholders and project elements. Besides, in the second report, the DSS helps to identify the most suitable stakeholder combination for a specific CDM given by the user (Figure 11).

For the illustration of the model, we have considered only seven CDM, namely, DB, DBB, DBFO, DBFOM, PMC, DBOM, and BOT. Based on the sample inputs of priority weights, stakeholder importance ratings, and the indicators assessments, the DSS recommends DBOM and DB as the most suitable contractual delivery methods, and the conventional DBB to be the least considered in the selection process. The above findings were identified for equal weights of different categories like risk, constraints, and opportunities as provided in Figure 12.

To distinguish the influence of a particular category in the CDM selection, the suitability indices were generated for different weights of risk category. Notably, the indices varied with different weights of risk and the respective differential weights of constraints and opportunities as seen in **Figure 12**. The model outputs indicate that most of the contractual delivery methods are suitable for minimal risk condition. Besides, as the risk weight increases beyond 30%, the DBOM and DB are recommended as the most appropriate CDM. Furthermore, the suitability index of the traditional DBB decreases with the increase in project risk and is considered least feasible as the risk weight exceeds 50%. Moreover, the user can also select any specific contractual delivery method whereas the DSS helps to identify the best stakeholder combinations to improve the suitability index of the pre-selected delivery method.

6. Concluding Remarks

A fuzzy-based multi-criterion decision-making technique is used to develop the DSS, to assist the client in the selection of the appropriate project delivery method. The system helps to identify the best delivery method and rank the project delivery alternatives based on factors including project requirements, stakeholders involved, and potential elements of risks, investment opportunities, and constraints. It can be easily tailored to match the user preferences and priority requirements, owing to the dynamic computational structure, and the user can modify it via the GUI interface. The model structure reflects the intuitive judgment of experienced construction industry professionals, as the model is validated using the qualitative information collected from different stakeholder expertise. The input interfaces are easily managed and necessarily do not require substantial data inputs in the selection process.

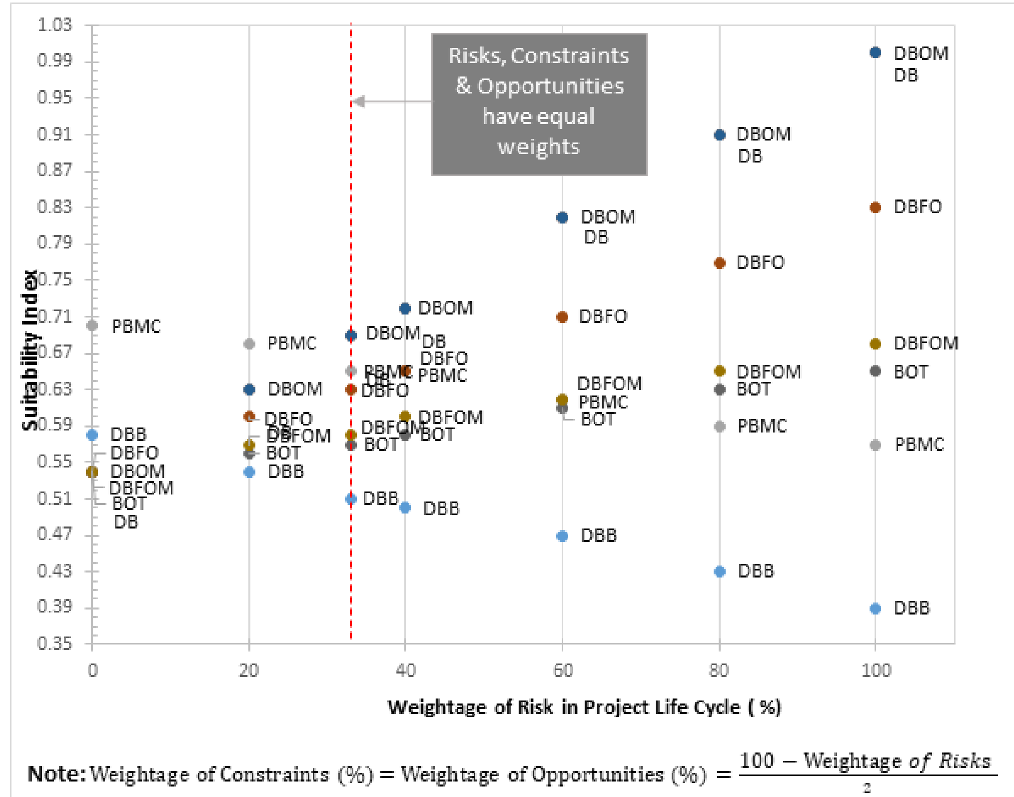


Figure 12. The suitability indices and ranking of delivery methods under varying project risk weights

All the elements of risks, opportunities, and constraints were identified throughout the literature review. In addition, an extensive survey with various stakeholder professionals (more than 150 participants) of mega-projects has assisted in identifying the system elements as well as the indicators. Such surveys were also used to calibrate the fuzzy logic model (in determining the strength and sign of relationships) between the indicators (inputs) and their corresponding element assessment (fuzzy-based output).

The system offers the flexibility to account for the user's preferences of adding and removing project delivery methods, elements of risks, opportunities, and constraints, indicators, weights, stakeholder groups, and entities. Nonetheless, to avoid overloading the user with entries, each time new inputs are entered into the system, default values were stored for ease of retrieval and editing. Finally, the system enables the client to depict best stakeholder entity choices (regarding project delivery methods and stakeholder entities) that would likely provide the best environs for the project to succeed. The DSS model was illustrated with the default factor sets. The DSS model performance was evaluated by varying the weights of project risk, constraints, and opportunities (the critical categories affecting the decision making process). Notably, the findings indicated that most of the delivery methods were equally valid when the project risk was minimal. In addition, the findings recommended the selection of DBOM and DB methods as the project risk increases beyond 50 percent. The conventional delivery method (DBB) was least recommended if the project's risk weight exceeds 30%. With equal considerations to the identified factors, the AHP model recommended DB as the best suitable delivery method as compared to DBB and CMR.

Nevertheless, the existing AHP models overlook the contractual delivery alternatives and ignore the variant interests of the stakeholders on the perceived factors amid different project stages. With the current DSS system, the client can also investigate the specifics of various project stages and study the effects of enhancements or deficiencies of the stakeholders' capabilities (as reflected by indicators).

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AUTHORS:::

MOZA T. AL NAHYAN

Al Nahyan is currently serving as an Assistant Professor of Management, at the College of Business Administration, Abu Dhabi University, UAE. She is also the CEO of MBT Development Corporation. She obtained her Ph.D. in Management from Monash University, Australia in 2013. Her research interests include stakeholder theory, mega project management, risk assessment, qualitative research. Dr. Moza has contributed to several research publications and projects on the management of mega projects taking into considerations the stakeholders' perspectives and implied management risks.

YASER E. HAWAS

Hawas is the recipient of the H.H. Shiekh Khalifa (the UAE President) Education Award in the Category of "Distinguished University Professor in the Field of Scientific Research," for the year 2011-2012. He obtained his Ph.D. from the University of Texas at Austin in 1996. He currently serves as a Professor at the Department of Civil and Environmental Engineering at the UAE University. He also serves as the Director of the Roadway, Transportation, and Traffic Safety Research Center (RTTSRC) at the UAE University. Prof. Hawas primary areas of expertise include the development of Intelligent Transportation Systems, advanced control systems, Megaproject management, traffic network operation and safety analysis.

MOHAMMAD SHERIF

Sherif is working as research associate and computer programmer at the Roadway, Transportation, Traffic and Safety Research Center (RTTSRC) at the United Arab Emirates University, Al Ain, United Arab Emirates. He received the master degree in computer applications from Anna University, Chennai, India, in 2009. His research interest includes Intelligent Transportation Systems (ITS), Connected Vehicles, Transport Security and Project Management. He has interest in developing web and desktop based computer applications as well.

BASIL BASHEERUDEEN

Basheerudeen received his Master Degree in Transportation Engineering and Management from National Institute of Technology (NIT), Tiruchirappalli, India in 2012. After completion, he served a lecturer. Later, he joined as a Research Assistant with Department of Civil Engineering in Indian Institute of Technology, Bombay (IITB), India where he was involved in Transport Planning and Urban Traffic Operation studies. In 2016, he joined as Research Associate in Roadway Transportation and Traffic Safety Research Centre (RTTSRC) at UAE University, Al Ain