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Model Development of Constructability

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Abstract: The choice of the construction system is a multivariate decision making with criteria that vary from one project to the other, depending on the particularities and constraints imposed on the builder. This research develops a tool that measures the constructability of various construction projects. The decision making logic is based on fuzzy set theory (FST). FST is used to address uncertainties in decision making. The tool is generic enough to allow the user to encompass the criteria of the project at hand and to select the construction system best suited for its execution. The objective of this research is the development of the decision support model and the demonstration of its use. This research also furnishes an extensive environment for further development. It provides the blueprint to achieve the overall goal of assessing the project constructability and smoothes the path for further refinement of the rules to be used at each step of the overall model. Through this model users are able to predict the feasibility of a project, and determine the most advantageous system to be used for its implementation. An analysis of the model illustrates that the results are accurate and the system demonstrates utility for practical use.
Key words: Fuzzy Set Theory; Constructability; Modus Ponen

INTRODUCTION

One of the earliest definitions but yet a succinct one of constructability is: the general meaning of constructability involves construction-oriented input into the planning, design and field operations of a construction project (Pepper, 1994).

The major criteria in constructability include cost, scheduling, quality and safety. The success and importance of the constructability review team is measured by the extent to which they anticipate construction problems and their ability to solve them at the onset. The project constructability is measured by the extent to which the execution and the construction are facilitated.

CURRENT METHODS FOR ASSESSING CONSTRUCTABILITY

Previous approaches that attempted to quantify constructability include; regression, simulation and expert systems:

The Regression Analysis Approach. As an example of constructability measure, the cost of the concrete can be estimated using this technique as follows: Due to the substantial impact of the formwork on the cost of a concrete structure, which sometimes exceeds the cost of the concrete and reinforcement, it is a logical

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approach to improve the constructability of this major item. To accomplish this, the following equation is used:

$$\sum_{i=1} AijX = \text{Y}j$$

Where:

A= area of the beam

X= productivity rate

y= Total man-hour

n= total number of unknown productivity rate.

j = floor number

Table 1
Sample Spreadsheet for Regression Analysis. Touran (1988)

Floor # (man-hour)	Sides (ft^2)	Soffit (ft^2)	Bulkhead (ft^2)	Beam-slab (ft)	Blockout (ft^2)	Total
1	A_{11}	A_{21}	A_{31}	A_{41}	A_{51}	Y_1
2	A_{12}	A_{22}	A_{32}	A_{42}	A_{52}	Y_2
	...	...	...	...	...	
...	...	...	...	.. .	'''	
n	A_{1n}	A_{2n}	A_{3n}	A_{4n}	A_{5n}	Y_n

The values for Y_i can be taken from the progress report. The values of the A $_{ii''s}$ can be computed from the building drawings. The unknown components are the productivity rates, $X_{i's}$, that need to be quantified. For example for determining constructability of Floor 1 there is:

$$A_{11}X_{11}+A_{21}X_2+A_{31}X_3+A_{41}X_4+A_{51}X_5=Y_1$$

A_{11} = area of beam side (ft^2) Floor 1

$A_{2[}$= area of beam soffit (ft') Floor 1

$A_{31}=$ area of beam bulkhead (ft2) Floor 1

$A_{41}=$ length of beam-slab intersection (linear feet) Floor 1

$A_{51}=$ area of beam blockout (ft2) Floor 1

X_1, X_2, X_3, X_4, X_5, = productivity rates for beam side, beam soffit, beam bulkhead, beam-slab intersection, and beam blockout respectively.

$Y_1 =$ total man-hours spent in Floor 1 on beams.

Similar equations can be constructed for each floor.

The less the number of variations in each floor, the more similar these equations should be from one floor to another. Therefore, the general problem is reduced to finding values for X's that fit into all the developed equations (one per floor) as closely as possible. It is suggested that a multiple regression analysis be performed on the data. After the values of X's are computed, the results should be compared to the results of analyses performed on similar projects. If those X's are comparable, then these calculated productivity rates can be used for future jobs.

Limitations of the Regression Approach.The reason for the discrepancy is that it is difficult to imagine a situation in construction where productivity rates remain "absolutely" constant for every floor.

The simulation approach. For the simulation models to be used effectively, they should capture the critical characteristics of the system. An advantage of the simulation approach is that the results from different scenarios can be compared. Simulation modeling is used to generate information valuable to the decision maker. However, it does not provide an optimal solution to a problem; it emulates the behavior of a system following a particular scenario, and evaluates the system's performance.

A model is not considered sound unless it goes through two essential phases, namely model verification and model validation. The model verification proves that the model works correctly and that it is flawless *(bugfree).* The validation ensures that the model is an accurate representation of the real life system.

The simulation is inherently a non-generic representation; it is related to a particular project on hand. It is a case by case analysis that encompasses the important characteristics of a particular situation.

Limitations of the Simulation Approach. The task of validation in a construction environment is particularly hard and practically unfeasible because of the uniqueness of each construction project. A comparison with a real life situation as dictated by the validation process is unavailable due to the particularities of different constructions.

Potentials of Fuzzy Set Theory for Constructability Assessment. Engineering has been a leader among all applications of Fuzzy Set Theory (FST). Various engineering disciplines have been affected by the rise of this theory and its methodology has left a profound impact on how to approach today's problems. However, among those disciplines the civil, and more particularly the construction engineering are prone to adopt FST.

When compared to other engineering branches, construction is fundamentally different, especially from the design point of view. This is primarily because the structural theories are rarely a perfect match to the design problem. Also, from the execution aspect, each project is definitely unique in its characteristics and situation. FST provides us not only with a powerful representation of uncertainties, but also with a meaningful representation of vague concepts better expressed in natural language. The main advantage of a model based on FST is that it is consistent with the uncertainty in human perception of the constructability issue. The inherent uncertainty and the seemingly impossible exact prediction of a constructability value of a project make FST particularly suited for use as an assessment tool. Fuzzy logic, which is defined in the literature as "an infinite-valued logic discipline that allows a proposition to have a value other than true or false," seems to be the appropriate approach responding to the extremely wide number of factors (trades and activities) that are interrelated with a high degree of complexity. In construction this complexity makes the decision maker hesitant to choose between black and white. In many instances, a gray area is the appropriate position.

Moreover, FST provides approximate reasoning to better handle partly-defined, or incomplete, information as is the case in construction engineering. It is also a suitable technique to deal with the out of control factors: site, labor, equipment, climate, unforeseen circumstances, time dependence situations, and regulations.The quantification of these factors and the capturing of their uncertainty could be best represented by a discipline which is both a science and an art. This area should be based on subjectiveness and expertise, yet structured enough for the purpose.

Assessing a construction system as being the most suitable for field use constitutes a decision based on intuition and heuristic experience. Intuition, experience and judgment are precisely the ingredients needed to form a set of linguistic rules in which the words are defined as fuzzy sets. Only an imprecise description of the system is needed rather than the detailed mathematical model that is the design basis for traditional expert systems and simulation approaches. This ability in dealing with non-crisp data provides great incentive for the application of fuzzy logic to determine the degree of constructability of a system for a particular project.

History and Differences with Traditional Theories. Fuzzy logic is not a new approach but rather an old technology that was developed for few decades. It was developed by Lotfi Zadeh in 1964. Fuzzy logic has broad implications on the way we think and make decisions. Fuzzy principles are different from probability theory in the sense that everything is a matter of degree; there are no sharp boundaries between true and false, between one state and another. These are all revolutionary notions challenging the well-established concepts upon which many scientific laws were built centuries ago. Fuzzy logic caused a paradigm shift, firing a strong opposing movement and a lot of controversy. On the one hand, it mimics the work of the human brain, makes machines more intelligent.

The Membership Concept. The use of the membership concept as an approach to handle uncertainty became explicit to researchers several decades ago around (1960) with the publication of a seminal paper by Zadeh (1965) where FST was introduced. It is agreed that his paper was the turning point in the evolution of the modem concept of uncertainty. Zadeh demonstrated that membership in a fuzzy set is not a matter of affirmation or denial but rather a matter of degree. This new paradigm created by Zadeh is best explained by Klir and Yuan (1995) "the proposition (x is a member of A) is not necessarily either true or false, as required by two-valued logic, but it may be true only to some degree, the degree to which x is actually a member of A." The significance of Zadeh's paper was that it challenged not only probability theory as the sole agent of uncertainty, but the very foundation upon which probability theory is based: the Aristotelian two-valued logic.

FST is based on the concept that human thinking emanates from previous experience and that it is seldom mathematically precise. Fuzzy sets allow an object to have a partial membership in a set. It opens the door to the fact that propositions can have values between true and false. The fuzzy set covers the entire range of possibilities and it is this range that replicates the kind of reasoning humans routinely use. Fuzzy sets are primitive types of data that are used like adjectives in natural languages. It is the linguistic expression capability that makes FST particularly suitable to use as a tool for comparing the constructability of different systems.

The power of the linguistic terminology is best explained by Kuan, Lin and Chia (1992) who demonstrated that the design of the object to be controlled does not need to be expressed mathematically for the fuzzy logic to be used as a controller. It is also mentioned that "the method does not require a detailed mathematical model of the object to be controlled. The design is based on a set of linguistic rules that were adopted from the human operator's experience".

The essence of FST is that control variables can belong to more than one set, depending on their value. The membership in any set could be computed using a membership function and ranges from 0 (null membership) to 1 (full membership). In introducing FST, the intent was to provide a rapprochement between the abrupt transition from total belonging and non-belonging in a set as suggested by classical set theory.

Knowledge Representation and the Fuzzy Rules. The parameters affecting each of the criteria are expressed in the form of IF/THEN rules. For example, the cost criterion has parameters that are expressed as being the rules affecting principally the cost. Often the same parameters are affecting more than another criteria among the four mentioned. In this case, the same rule is applied to the other criteria it affects.

The Fuzzy Linguistic Variables. Depending on the construction system being studied, for which constructability is being assessed, the rules are fired only if they apply to the system. Not all the rules will fire. They won't fire if they do not apply to the system. If on the other hand, if they apply to the system, they will fire. But they will fire to a degree, and they will not all fire to the same degree. The degree of firing depends on two variables:

A. The importance of the criteria in relation to the other listed criteria is represented by (w) which is assigned a value between (0-1).

B. The fuzzy level of the rule is depending on the membership of the rule; the extent by which the rule is involved in the set, in other words the fuzzy level of the rule (high, medium or low) depends on the extent of inclusion of the rule in the set. The level is determined to be (high) if the extent of inclusion of the rule is big.

The Determination of (w) and of the Applicable Fuzzv Term. Now, the determination of both: the importance of the criteria in affecting the assessing criteria listed as (w), and the fuzzy set applicable to each rule (high, medium or low), is crucial to the calculation of the constructability of the construction system:

A. The (w) is determined by the developed questionnaire that is answered through interviewing the experts. In this case, the experts are project managers.

Through the questionnaire, the project managers assigned a weight (w) to each criterion. Then, an aggregation technique is used and a fuzzy weighted mean (FWM) is determined for the four criteria collectively. The weight assigned to each of the four criteria is dependent on the type of project: residential (single family or multistory building), commercial or industrial. It is also dependent on the geographic location of the project. For example, the safety issue is much more important in the States than it is in a developing country. So, the values for $W_1,\ldots W_4$ will be determined as per the above context. Again, the fuzzy weighted mean equation is applied to produce the overall constructability value for the construction system.

B. As for the determination of the level, expressed in fuzzy terms (high, medium or low) that will imply the degree of membership of the rule, it is determined from the information collected from the text analyses and from the users of the systems. The value of this variable is determined from the available literature by a set corresponding to each level. The reports, brochures, catalogs and tests published by the manufacturers and by interested parties will demonstrate the particularities of the system and will shed light on the way it is used. This information will help in determining the fuzzy term or level applicable for each of the rules.

Development of Membership Function. In this respect, we are dealing with three levels: High, Medium, and Low. Each of these fuzzy terms has a set that is representing the level:

High

{.3/1, .6/2, .8/3, 1/4}

Medium

{.5/1, 1/2, .3/3, 0/4}

Low

{1/1, .5/2, .4/3, 0/4}

As shown in the above sets, the scale where the membership appears is on a base scale from 1 to 4. The high degree of inclusion is represented by a full membership of 1 on the scale. The membership decreases gradually as you go lower on the scale to eventually reach a 0 degree of membership at the lower extreme of the scale which is 1. The opposite is true to represent the fuzzy term of "low" expressing a low degree of membership at the top of the scale and full membership at the beginning of the scale.

Aggregation and Mathematical Modeling. Having determined from the above, both the (w) for each criteria and the level described by the fuzzy set attached to each rule, the value of constructability of the construction system is calculated using the fuzzy mean weighted value (FMW) equation. Then, the same applies to the calculation of the constructability of the project. The fuzzy weighted mean value equation is:

Fuzzy mean weighted value = FMW = $\sum^{n}_{i=1} wR/\sum^{n}_{i=1} w$

R = The linguistic variable's degrees of membership are summed using fuzzy addition and the result yields the value of R.

So, the value is obtained using fuzzy addition, multiplication and division. Even though the sought overall constructability value is attained through the above analysis, an important concept should be clarified to the user (decision maker) that shows that the constructability value determined for each criteria (cost, quality, schedule and safety) should be far more decisive to the choice made on the construction system than the calculated overall construction system constructability value.

The dependencies mentioned above related to type of structure, location and other factors, demonstrate that a judgment call is necessary. In other words, it is not necessarily the construction system with the highest overall constructability value that is the ideal one. It is rather, the construction system whose constructability values related to the main criteria (cost, quality, schedule and safety) match the best, the values assigned to each of those criteria by the project manager. The project manager, depending on the project on hand, with its particular circumstances and characteristics will determine a targeted constructability value for each of the above criteria. The construction system that fits the best the assigned value and which minimizes the discrepancies between the target and the provided value is to be picked up for the execution. The best compatibility at the criteria level is the goal.

Constructability Criteria. As defined by the Association of Civil Engineering (ASC) the constructability criteria are mentioned to be: Cost, Quality, Scheduling and Safety. With the exception of safety, quality supersedes the other main attributes of constructability. If the project outcome does not eventually produce facilities that are suitable for their intended use due to poor quality (i.e., a leaking roof), a lot of resources and time have simply been wasted. The constructability review team has a primary obligation to determine at the project onset, those elements that require special quality control. They need to attach special importance to a review of material and equipment requirements in order to ensure adequate quality in the planning phase.

If cost is the bottom line in many issues in life, it is even more so in construction. Effort should not be spared in the process of the glorification of the dollar. A financially sound project may not be the sole key to success but it is undoubtedly a necessary factor contributing to project constructability. Project constructability is enhanced when construction efficiency is considered in specification development. Some of the most important decisions at the corporate level are to decide on the projects to bid and to decide on the resource allocation during both the bidding and the execution phases. At the site level, the project manager needs to dedicate a considerable amount of his cognitive capabilities to the decision process related to the practical procedures of the execution and to the sequence of activities. It is recognized that the core of the Decision Support System (DSS) enabling project managers, for example, to allocate resources, to sequence activities, and to request alterations resulting in change orders, is highly judgmental.

Implementation and Outcome. The available literature provides a reasonable amount of material on the benefits of constructability. Previous studies defined constructability, analyzed it and different implementation procedures have been discussed. Furthermore, studies were successfully conducted to layout structured methodologies which would improve the constructability of the projects. However, despite the advance in the construction methods, there are no efficient tools to assess constructability. The shortcomings in the literature appear to be in reaching an agreement on the discipline and/or the methodology used to assess and to quantify the constructability. This paper introduces a methodology leading to a model based on FST.

As an experiment, three specific projects of above $10 million were considered in the Great Orlando area. Each project is executed by a different construction company. The Project Managers of each construction company were interviewed and asked to develop relevant fuzzy rules and to assign weights of or evaluation indicating the importance of each of the four constructability criteria as they relate to circumstances of their respective projects.

Table 2

The Profect Managers' assessments

Project #	Cost	Quality	Schedule	Safety
Project 1	.3	.2	.2	.3
Project 2	.3	.2	.1	.4
Project 3	.1	.3	.3	.3

The following calculations quantify the constructability of the Half-Tunnel construction system.

Applying the Modus Ponens format to each of the considered rules will generate a conclusion (the constructability of the rule) and collectively, the conclusions of each criterion will produce the Truth Value (the constructability of each criterion). Thus assuming hypothetically, the Truth Values for each criteria are as follows:

The Cost criteria Truth Value = Constructability of the Cost criteria 0.4

The Quality criteria Truth Value = Constructability of the Quality criteria 0.6

The Schedule criteria Truth Value = Constructability of the Schedule criteria 0.8

The Safety criteria Truth Value = Constructability of the Safety criteria 0.5

Thus based on the model, the assessment of the constructability for each criteria in linguistic terms is:

- The Cost constructability is low.
- The Quality constructability is high.
- The Schedule constructability is very high.
- The Safety constructability is Medium.

The constructability of the Half-Tunnel construction system for the specific projects referred to based on the above expressed five rules limitation is quantified to be:

$\text{FMW} = \sum^{n}_{i=1} wR$

So, for Project # 1

FWM = (0.3) (0.4) + (0.2) (0.6) + (0.2) (0.8) + (0.3) (0.5) = 0.55

For Project # 2

FWM = (0.3) (0.4) + (0.2) (0.6) + (0.1) (0.8) + (0.4) (0.5) = 0.52

For Project # 3

FWM = (0.1) (0.4) + (0.3) (0.6) + (0.3) (0.8) + (0.3) (0.5) = 0.61

The above demonstrates that the Half-Tunnel system is producing the best constructability for project # 3 and the least constructability for project # 2.

DISCUSSION AND CONCLUSION

This example clarifies the objectives of the study. In addition to providing a valuable theoretical contribution to the body of knowledge, this model provides the blueprint to achieve the overall goal of assessing the project constructability and smoothes the path for further refinement of the rules to be used at each step of the overall model. This will demonstrate the means of comparing the constructability of separate construction systems as applied to particular projects. The model could also be used for the purpose of project prioritization, determining the extent to which a particular project is constructible. Through this model construction companies, as well as owners, will be able to predict the feasibility of the project, and will determine the most advantageous construction system to be used for its implementation. On the practical side, the tool that is made available to the industry through this study may prove to be valuable for the prediction of success and for the prioritization of investments. It is expected that construction companies will welcome such an endeavor. Finally, this is a comprehensive approach to deal with multi-attribute variables in an uncertain and vague environment that is yet perceivable by humans.

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