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The Application of Fuzzy Logic to Assess the Performance of Participants and Components of Building Information Modeling

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ABSTRACT

In the last decade, the use of Building Information Modeling (BIM) as a new technology has been applied with traditional Computer-aided design implementations in an increasing number of architecture, engineering, and construction projects and applications. Its employment alongside construction management, can be a valuable tool in helping move these activities and projects forward in a more efficient and time-effective manner. The traditional stakeholders, i.e., Owner, A/E and the Contractor are involved in this BIM system that is used in almost every activity of construction projects, such as design, cost estimate and scheduling. This article extracts major features of the application of BIM from perspective of participating BIM components, along with the different phrases, and applies to them a logistic analysis using a fuzzy performance tree, quantifying these phrases to judge the effectiveness of the BIM techniques employed. That is to say, these fuzzy performance trees with fuzzy logic concepts can properly translate the linguistic rating into numeric expressions, and are thus employed in evaluating the influence of BIM applications as a mathematical process. The rotational fuzzy models are used to represent the membership functions of the performance values and their corresponding weights. Illustrations of the use of this fuzzy BIM performance tree are presented in the study for the uninitiated users. The results of these processes are an evaluation of BIM project performance as highly positive. The quantification of the performance ratings for the individual factors is a significant contributor to this assessment, capable of parsing vernacular language into numerical data for a more accurate and precise use in performance analysis. It is hoped that fuzzy performance trees and fuzzy set analysis can be used as a tool for the quality and risk analysis for other construction techniques in the future. Baldwin's rotational models are used to represent the membership functions of the fuzzy sets. Three scenarios are presented using fuzzy MEAN, AND and OR gates from the lowest to intermediate levels of the tree, and fuzzy SUM gate to relate the intermediate level to the top component of the tree, i.e., BIM application final performance. The use of fuzzy MEAN for lower levels and fuzzy SUM gates to reach the top level suggests the most realistic and accurate results. The methodology (fuzzy performance tree) described in this paper is appropriate to implement in today's construction industry when limited objective data is presented and it is heavily relied on experts' subjective judgment.

Keywords: BIM, Building Information Modeling, construction, construction management, construction performance, fuzzy set, fuzzy logic, fuzzy rotational model, fuzzy Baldwin's model, fuzzy performance, performance tree

INTRODUCTION

Building Information Modeling (BIM), referring the digital representation of integrated building components such as technical drawings, scheduling, estimating, and other building parameters, e.g., spatial and temporal dimensions, often accompanied by the use of augmented reality, virtual reality, or merged reality, has been gradually assimilated into almost every activity for modern construction projects, including design, scheduling, estimation and maintenance. Studies concerning the traditional BIM have been made by a significant number of scholars and engineers, and as an independent part of the BIM system, numerous VR elements have been introduced and applied to the construction and reconstruction of historic structures [1], [2], [3] and [34]. But the focus of these studies has been on the detailed digital representation of construction processes of the buildings. Eastman [4], a BIM specialist, integrated VR components into the BIM system by simulating construction projects with 3D models that contain digital information of building elements. Information contains not only traditional geometrical shapes of drawings, but also the other information of the components, such as material characteristics, prices, quantity, and vendor information.

Ideally, BIM would integrate all the digital information into a database to be applied into the projects. Because of its "database" functionality, BIM can connect various disciplines in the A/E and construction industries together to complete other aspects of the project, such as scheduling and estimating. In fact, the relatively new Integrated Project Delivery system generally includes BIM to promote collective decision making among the Owner, A/E, GC, subcontractors, vendors, among other key players in the implementation of the building construction process [5]. Aksamija [6] introduced BIM-based analysis tools to provide a method where design and analysis processes can be integrated from the earliest stages of the design, and thus, can assist in design decision-making. Eastman [4] suggested that BIM is not simply a type of software, but rather a multi-tier process which involves human activities. Clearly, a paramount activity in construction operations is making decisions.

One important aspect that is seldom included in the traditional BIM is the use of experiential subjective assessments, which are important in decision making as well as assessing the performance of BIM components. The objective of this paper is to introduce a model incorporating subjective judgment of players in the implementation of building construction that can be applied and integrated into the traditional BIM system. For simplicity, the major participating BIM components considered in the study in this paper are the owner, designer (Architect/Engineer), contractor, subcontractor, and supplier, with particular emphasis on the first three. The phases considered are pre-construction, construction, and post-construction, and the performance assessment includes such BIM components as digital design, estimating and scheduling. Note that future studies may include the expansion and extension of participating BIM components, construction phases and BIM components.

The subjective assessments involved in the decision-making process for the stakeholder integration, construction phase, and BIM components are commonly characterized by imprecise notions that are hard to define and not quantifiable. However, the importance of these notions cannot be underestimated, especially since most decision processes would eventually incorporate and depend on these notions. The manipulation and operation of these notions can be implemented through the use of *fuzzy sets* and *fuzzy logic*, concepts which have existed for over a half century [7] and have been used in numerous areas including construction engineering [8], [9], [10], [11], [12], though not as of yet in the BIM system. In this paper, fuzzy sets are employed to quantify and mathematize the qualitative notions which abound in making BIM decisions, whereas fuzzy logic incorporates the reasoning process of these decisions to arrive at the best BIM performance of the building construction. In order to do so, this tool is used in association with a performance tree whose branches include the BIM components of the stockholders, i.e., the Owner, Contractor, and Architect/Engineer components. The methodology (fuzzy performance tree) introduced in this paper is fit to implement in today's construction industry when limited data is presented and it is relied on experts' subjective judgment.

The justification for converting the experts' subjective assessment into numerical values was to provide consistent, systematic, and verifiable conclusions. The tradition assessment of evaluating the BIM participants may include a survey. The survey may ask for their response using a *likert* scale. The advantage of the traditional survey is that it is simple to perform and assess, but it may not be accurate since the fuzziness of the *likert* scale range is not taken into consideration. In addition to a traditional *likert* scale survey, there are several other traditional methods for decision-making process, such as Analytic Hierarchy Process (AHP) [35], Analytic Network Process (ANP) [36], and Delphi [37]. This paper introduces another model to assess subjective judgement. Each of the various models has both advantages and disadvantages. One of the advantages that the fuzzy logic with centroid defuzzification method has over the Analytic Hierarchy Process (AHP) is that the centroid defuzzification approach can defuzzify the fuzzy model to make it as precise as it needs for the decision makers, while the AHP only uses the 9-point scale, so occasionally it may be difficult to determine whether one alternative is more important than others. Similarly, the traditional Delphi method only applies to a certain range, and the fuzziness of the range is not taken into consideration. The use of fuzzy logic could likely resolve these issues.

MODEL INTEGRATION

The typical BIM participating components discussed earlier is depicted in Figure I including the owner, architect/engineer, contractors, and building suppliers. Since BIM is an integrated platform and a collaborative platform for project participating components with different disciplines, these participating components need to adapt to the new collaborative processes based on BIM so that the most notable impact of BIM usage is the changing roles of architects, engineers, and builders. BIM's integrated platform suggests, and partners well with, the implementation of collective decision making.

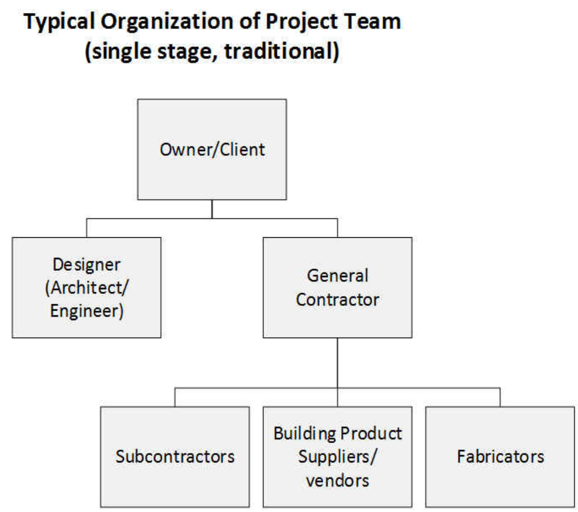

FIGURE I. TYPICAL PROJECT TEAM ORGANIZATION

In this paper, project participating components (Owner, Contractor, and Architect/Engineer or Designer) traditionally go through pre-construction, construction, and post-construction processes. The integration of these stockholders in each construction phase represents the knowledge base, which is employed to construct a decision tree.

Owner

BIM visualization models support and help owners comprehend the increasingly complex building infrastructure and regulatory processes. The owners coordinate the project through fully integrated 3D models of architectural, structural, and MEP (mechanical, electrical and plumbing) systems [13]. The BIM integrates various renderings of architecture, landscape, and interior ornaments, for owners to show to their clients. Furthermore, the owners' representatives from the maintenance and operations staff can provide input and review of the model.

The visual and digital nature of the BIM models has potential as an excellent tool for all project participating components to understand the scope, requirements, and designs of a building project. The rich interactive nature of the information greatly enhances understanding of a project from multiple perspectives [14]. Unlike today's 2D disparate project documentation or even existing 3D models, BIM design and review tools provide highly interactive features that not only allow a user to view the project, but also to query the model and gather a variety of information about the project's components. The information of components can also offer the owner more details of one project. Based on the better understanding of the projects, the communications between participating BIM components which are involved in the project may become smoother over time, so potential problems associated with design and construction errors can be reduced [15].

Aside from this, the use of BIM can help reduce the hassle of project schedules, because BIM-based design and prefabrication can substantially reduce project duration [16]. The BIM model is a parametric model that makes design changes easier and the resulting updates of documentation automatic. This type of BIM application allows owners to better respond to market trends or business missions closer to construction, and allows them to adjust project requirements in collaboration with the design team. The construction schedule often involves multiple organizations, complex sequences of activities, and various task interdependencies that make it difficult for a construction manager representing the owner communicate a schedule to all the various participating BIM components. BIM can provide a series of 4D views of a construction project that helps to reduce multiple schedule-related risks [17].

The building model can also provide complete and accurate information for the building and all its systems. After construction is complete, a model that has been updated with all changes made during construction and systems can provide a useful starting point for managing and operating the building. The owner can employ this information to verify that all the systems are working properly after the building is complete.

Lastly, BIM can provide a variety of benefits to different applications during the facility operation and maintenance phase [18]. Locating building components, facilitating real-time data access, and checking maintainability are just some of the applications that BIM technology can provide during this phase. Using 3D as-built BIM models linked with the operational data of building components can allow facility management to localize the mechanical, plumbing, electrical, and fire safety components while displaying the data relevant to the operational context.

Contractor

When it comes to contractor work, construction planning and scheduling involve sequencing activities in space and time, considering procurement, resources, spatial constraints, and other concerns throughout the life of the project. Traditional approaches, however, cannot fully capture the spatial features of these activities and do not link them to the design or building model. There are two kinds of strategies in BIM that can help contractors address these problems.

The first method is BIM's 4D integration, which allows the contractor to connect a construction plan with the 3D objects in a digital model [19]. The 4D scheduling tools enable the contractor to visually plan and coordinate activities in the context of space and time. This 4D view of a construction project gives substantial insights into how the building will be constructed and tracks down sources of potential problems and opportunities for possible improvements, even before construction begins [4]. Therefore, contractors can review 4D simulations to ensure that the construction plan is feasible and efficient as possible, potentially saving thousands of dollars in wasted time and materials. They can even compare different schedules quickly as a project continues, allowing them to quickly detect whether construction is on track or behind schedule.

The second approach is to use BIM tools that incorporate 3D digital objects and construction method information to optimize activity arrangement [20]. The 4D model captures both the temporal and spatial aspects of a schedule and communicates this schedule more efficiently than a traditional planning method. Contractors and other participating BIM components can review 4D simulations to ensure that the plan is feasible and efficient as possible.

The BIM provides not only a virtual building model but also a parametric model. As the design matures, a contractor can rapidly extract more detailed spatial and material quantities directly from the BIM parametric model [14]. All BIM tools have the capability to retrieve component counts, area, and volume of spaces, material quantities, etc. and to report these in various schedules. Such information is more than adequate for producing approximate cost estimates. This BIM-enabled estimating approach can reduce the time needed to achieve accurate cost estimates, thus allowing the contractor to make more informed decisions. Based on the data of 32 major projects, the Stanford University's Center for Integrated Facilities Engineering (CIFE) reported that the accuracy of BIM-based estimates was within 3% of the actual cost, with up to 80% time reduction in generating these estimates [21]. By linking the design model with the estimating processes, the project team can also speed up the quantity take-off and overall estimating process and get faster feedback on proposed design changes.

As the general contractor, coordinating subcontractors' activities and designs constitutes a significant part of the job. Using the building model, all of the major subcontractors can participate in detailing their portions of the work, such as expedited construction, facilitating off-site fabrication of assemblies, and reducing field work [15]. This reduces the number of clashes and gives enough information to correct conflicts before they actually become problems in the field. This enables increased offsite prefabrication and reduces field cost and time, improving overall accuracy. Contractors are thus able to exchange more accurate BIM information with fabricators, saving time by verifying and validating the model beforehand. This also reduces errors and allows fabricators to participate earlier in the pre-planning and construction process. On the other hand, using 3D or 4D site coordination models, the contractors can plan for site logistics, develop traffic layouts, and identify potential hazards at the job site, which can aid in preparing a more realistic site safety plan [16].

In the construction phase, contractors need to prove the fabrication of building components at the site to verify that performance specifications are met. If design errors or clashes are identified, the contractor must spend more time repairing them. The BIMs are created to scale in a 3D space, and all the building components are described in the shared semantic models. Given any level of detail, all major building systems can be instantly and automatically checked for interferences [22]. In this way, BIM-enabled clash detection tools allow automatic geometry-based clash detection to be combined with semantic and rule-based clash analysis or identifying qualified and structured clashes [4]. For example, this process can verify that piping does not intersect with steel beams, ducts, or walls.

Azhar et al. [15] presented a case study that illustrated the use of BIM whereby a general contractor can minimize design errors via clash detections. The general contractor of the case project combined the architectural model, structural, and MEP systems drawings and then converted them into unified 3D BIM models. With this method, the collisions and clashes were detected in advance during the preconstruction and construction phases, and then the general contractor was able to obtain significant cost and time savings.

Designer (A/E)

For a building project, the biggest decisions regarding the value, performance, and cost are made during the conceptual design phase. The differentiating services that design firms can offer to clients within the concept design phase are both their critical capabilities and a collective competitive advantage. Concept design based on early analysis feedback is especially important for projects involving medium or high levels of information development.

Today, a growing number of 3D concept design tools balance the need to support the intuitive and creative thinking processes when a basic design scheme is first being defined and explored, with the ability to provide both quick assessment and feedback based on a variety of simulation and analysis tools, thus allowing for a more informed design [4]. These lightweight, intuitive tools provide a series of functionalities that are essential for preliminary design, including 3D sketching, space planning, environmental analysis, site development and typological identification of all building systems.

With these visualization tools, the project team can interactively evaluate the design solutions against the user requirements and specifications. For instance, the conceptual design usually involves identifying the "type" of each building system, including structural, exterior envelope, energy and HVAC, lighting, and vertical circulation. This information is needed to generate initial cost estimates at an early stage, thereby verifying that the project is within an economic scope and satisfying the program. Concept design helps the project address sustainability and energy efficiency, cost, and value analysis during the early design phase.

Before BIM, architects used 2D CAD to design buildings and communicate with the owners and engineers. The architects would have to revise the preliminary design several times, attend numerous meetings with the owners and the structural and the mechanical engineers to reach a final design plan. With the BIM 3D model, visual representation exists not only of the building form and materials, but also of the structural and mechanical systems. This means that the architectural design can be integrated with structural analysis and the MEP (mechanical, electrical, plumbing). These models are linked together by the project manager or designer so that potential errors and inconsistencies are accessible in the early stage of the project [23].

Working in a shared BIM 3D model, designers from different disciplines can collaborate with the final model and the revisions that occur during the design phase. Thus, BIM use among a project team improves design review feedback, reduces errors, lowers contingency issues, and leads to faster construction. The BIM system also brings all design disciplines together so that it can systematically check for hard and soft clashes and visually for other kinds of errors. Conflicts can be identified before they are detected in the construction field. With the BIM system, coordination among participating designers is enhanced, and design errors are significantly reduced [23]. This BIM process accelerates the construction schedule, reduces clashes, cuts down costs, and provides a smoother process for the entire project team.

Another benefit of BIM-based collaboration design is that the designers can react quickly to design or site problems. Because the BIM model carries all the information of "smart objects," the cascaded updates of a suggested design change for other objects will be made automatically based on the established parametric rules

[19]. Furthermore, design adjustments can be resolved more quickly because changes can be shared, visualized, estimated, and addressed in a collaborative BIM system. By contrast, the traditional paper-based system may need more time and may lead to design errors more easily. It is evident that BIM's advantage in sharing information improves both the quality and the communication, reducing errors and omissions.

Linking the building model to energy analysis tools allows for evaluation of energy use during the early design phases, which is impossible to use traditional 2D tools that require a separate energy analysis at the end of the design process, giving the designer a narrow time frame to make modifications that could improve the building's energy performance. Building performance simulations have been a critical part of the design process for energy efficient and high-performance buildings, thus helping designers access the environmental and energy impacts of design decisions [4]. BIM-based analysis tools provide a method where design and analysis processes can be integrated from the earliest stages of the design, and can also assist in design decision-making [24]. As early as the conceptual phase, the analysis should focus on the bigger design aspects, such as climate information, orientation, passive strategies, and building massing.

The BIM-based method can provide energy performance measures with actual quantifiable data and not rules-of-thumb, and can use detailed building models to simulate, analyze, and predict the behavior of the building system. Therefore, designers using BIM tools have the ability to easily estimate the impacts of multiple design alternatives. Table I lists all the major features along with their relationship among the participating BIM components in each construction phases. The table is essentially the knowledge base employed for the study in this paper. These features are not directly quantifiable; they are qualitative in nature and characterized by subjective

TABLE I. MAJOR FEATURES OF BIM APPLICATION AND THE RELATIONSHIP AMONG CONSTRUCTION PARTICIPANTS

	Pre-Construction	Construction	Post-Construction
Owner	· BIM visualization enables a better understanding of the proposed design.	· BIM helps reduce problems during construction related to design errors and coordination issues. · The use of BIM generates a beneficial impact on project schedules.	· BIM can provide the owner with an accurate model of the structure as well as an asset list of all components. · Operations can be simulated to evaluate building performance and maintain-ability.
Contractor	· BIM gives contractors the ability to envision a facility prior to its actual construction (e.g. prefabrication). · BIM enables clash detection, and also location of incompatibilities and incon-sistencies among subcontractors.	· BIM helps manage workflow, including construction schedules, material tracking, and project management. · A single shared BIM model reduces information loss and can reflect changes in real time, resulting in fewer pro-blems and thus saving expenses.	
Designer	· BIM analysis, simulation, and inte-ractivity capabilities can produce a more well-reasoned design. · BIM enables early incorporation of sustainability features in building design to predict environmental or sustainability performance.	· BIM reduces change orders, saving on the corresponding costs, and can help designers locate inconformity between construction and design more easily. · BIM enables collaboration between multiple design disciplines and skilled contractors/engineers.	

judgments that are imprecise, yet they are extremely useful for making collaborative decision. When some or all of these characteristics are considered together, it may difficult for the experts or decision makers to understand the final BIM performance using statistic or other traditional quantitative rating methods. To make a decision for the BIM features, these features are first arranged into a specific type of decision tree, namely, Performance Tree that branches according to the stockholders. Each path of the tree is further expanded to reach the basic events (BE). Thus, the Performance Tree is the knowledge representation of the knowledge base of the BIM features.

BIM PERFORMANCE TREE

The BIM Performance Tree (BPT) shown in Figure II represents the path of knowledge discussed earlier and summarized in Table I. In this BPT, "BIM Application: Final Performance" is selected as the tree's Top Event, which is expanded into the BIM stockholders: Owner, Contractor and A/E. Each of the components is then expanded into its lower events. For example, the Owner has basic events of BE101 (visualization models in the preliminary design phase), BE102 (time reduction due to schedule management), and BE103 (graphical models depicting potential failures and other problems). Table II summarizes the basic events extracted from the knowledge base compiled in Table I.

TABLE II. BASIC EVENTS AND THEIR DESCRIPTIONS

Basic event	Description
Owner	
BE101	BIM provides better visualization for project stakeholders in the preliminary design phase.
BE102	The owner can reduce time to market through BIM-based project schedule management.
BE103	BIM can provide an accurate structure model and suggest performance improvements.
Contractor	
BE104	BIM integration allows the contractor to link construction planning with the design model.
BE105	BIM enables clash detection and can locate incompatibilities among subcontractors.
BE106	BIM helps manage workflow, including scheduling, material tracking, and management.
BE107	The contractor can produce efficient and more accurate cost estimate with BIM model.
Designer (A/E)	
BE108	BIM 3D visualization and interactivity can help produce a more well-reasoned design.
BE109	BIM-based analysis can improve the building`s energy efficiency and sustainability.
BE110	BIM system reduces change costs through the powerful ability of conflict detection.
BE111	BIM enables collaboration between multiple skilled design disciplines and engineers.

The relations between the upper and lower events are maintained using logic gates such as fuzzy AND, OR, SUM, and MEAN gates as shown in Figure II. For example, the occurrence of the Performance of the Top Event is contributed to by the performance of the Owner, Contractor and A/E through the use of a fuzzy SUM gate. In turn, the performance of the Owner is contributed by the fuzzy MEAN of the basic events BE101, BE 102 and BE103.

The choice of these gates is also subjective; for example, instead of a fuzzy MEAN gate, one can use fuzzy AND or fuzzy OR gates to connect the lower to the upper events. The extent of the contribution (weight) of each lower event is indicated by its importance; for instance, the contribution of BE101 to the Owner's performance is considered to be *very important* (*VI*).

Notice that the fuzzy sets ranging from *fairly important* to *absolutely important* are used to measure the extent of the contribution of the performance of lower event to the upper event. In turn, the performance of an event is labeled (rated) subjectively in a range from *very low* to *very high*, depending on the decision makers when assessing it. These assessments or phrases (linguistic expressions) are represented by fuzzy sets and summarized in Table III.

TABLE III. PERFORMANCE AND IMPORTANCE VALUES

PERFORMANCE VALUES
High
Very High
Fairly High
Low
Very Low
Fairly Low
IMPORTANCE VALUES
Absolutely Important
Very Important
Important
Fairly Important

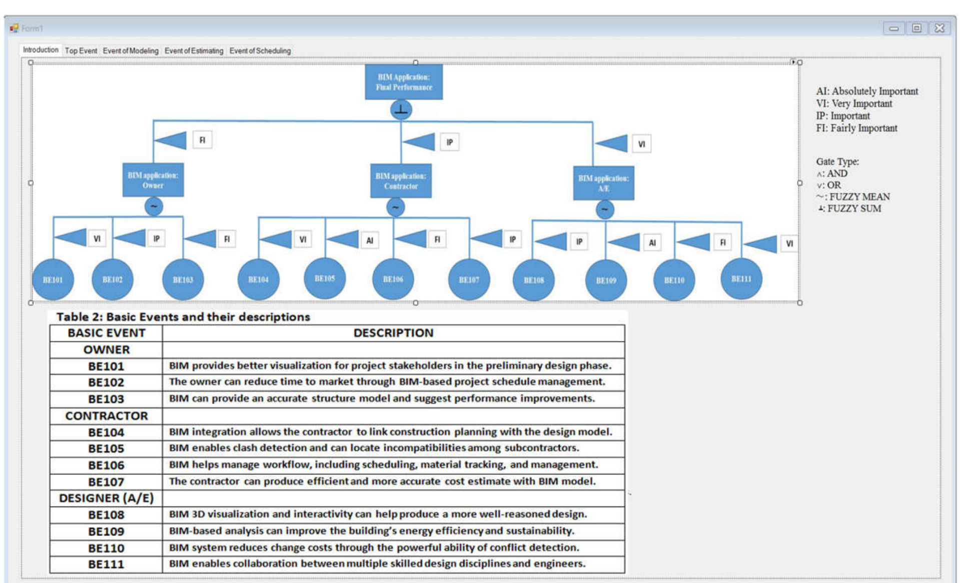

FIGURE II. FUZZY BIM PERFORMANCE TREE

THE FUZZY SET MODELS

Fuzzy sets relate the membership value (μ_{xi}) to the fuzzy element (x_i) in pairs. For example, *high* or *positive* BIM performance is represented by a membership function that consists of pairs of $\mu_{high}(p)|p$. Fuzzy set models can be divided into translational and rotational models. Within the translational model, subjective linguistic evaluations are translated into membership functions. Hadipriono [8] introduced these models to evaluate construction performance; more recently, Yang et al. [25] employed them to evaluate the construction of the Great Wall of China. By contrast, in rotational models, subjective judgments are set by the ramp membership function, which are linear or nonlinear functions that connect two rotational points [9]. One specific rotational model introduced by Baldwin [26]. Baldwin's model uses a line (curved line or straight line) that connects one or two rotational points to represent a linguistic value [9] [27]. The hedges, for example for performance, are classified by as follows:

$$\mu_{very\,high}(p) = [\mu_{high}(p)]^2 \quad \text{Eq. (1)}$$

$$\mu_{fairly\,high}(p) = [\mu_{high}(p)]^{0.5} \quad \text{Eq. (2)}$$

$$\mu_{not\,high}(p) = 1 - \mu_{high}(p) \quad \text{Eq. (3)}$$

$$\mu_{low}(p) = \mu_{high}(1-p); \quad \text{Eq. (4)}$$

in which $\mu_{high}(p)$ is the membership values of *high* and *p* is its fuzzy elements, both are established within [0, 1].

The membership function is continuous: they contain continuous pairs of membership values and their corresponding fuzzy elements. For simplicity, Table IV summarizes these pairs in a discretised form, which is converted into ramp functions as displayed in Figure III. The same membership functions are applied to the values of the importance (weight) of BIM components. Notice that in this study, the membership functions rotated along the y = x axis are deemed as having positive characteristics, such as (*high*, *fairly high*, and *very high* performance and *important*, *fairly important*, and *very important* weight), while those rotated along the y = 1-x axis are deemed as having negative characteristics, such as (*low*, *fairly low*, and *very low* performance and *unimportant*, *fairly unimportant*, and *very unimportant* weight). In addition, the horizontal line on top and bottom of the model represent *undecided* and *impossible*, respectively. The vertical lines on the right and left represent *absolutely high* and *absolutely low*, respectively. These membership function values can be changed based on the experts' judgement, although this is beyond the scope of this paper.

TABLE IV. MEMBERSHIP FUNCTIONS FOR BIM PERFORMANCE VALUES

Performance values	Membership functions*
High	[0|0, 0. 1|0. 1, 0. 2|0. 2, 0. 3|0. 3, 0. 4|0. 4, 0. 5|0. 5, 0. 6|0. 6, 0. 7|0. 7, 0.8|0. 8, 0. 9|0. 9, 1. 0|1. 0]
Very high	[0|0, 0. 01|0.1, 0. 04|0. 2, 0. 09|0. 3, 0. 16|0. 4, 0. 25|0. 5, 0. 36|0. 6, 0. 49|0. 7, 0. 64|0. 8, 0. 81|0. 9, 1. 0|1.0]
Fairly high	[0|0, 0. 32|0. 1, 0. 45|0. 2, 0. 55|0. 3, 0. 63|0. 4, 0. 71|0. 5, 0. 77|0. 6, 0. 84|0. 7, 0. 89|0. 8, 0.95|0. 9, 1. 0|1. 0]
Low	[1|0, 0. 9|0. 1, 0. 8|0. 2, 0. 7|0. 3, 0. 6|0. 4, 0. 5|0. 5, 0. 4|0. 6, 0. 3|0. 7, 0. 2|0. 8, 0. 1|0. 9, 0|1. 0]
Very low	[1|0, 0. 81|0. 1, 0. 64|0. 2, 0. 49|0. 3, 0. 36|0. 4, 0. 25|0. 5, 0. 16|0. 6, 0.09|0. 7, 0. 04|0. 8, 0. 01|0. 9, 0|1. 0]
Fairly low	[1|0, 0. 95|0. 1, 0. 89|0. 2, 0. 84|0. 3, 0. 77|0. 4, 0. 71|0. 5, 0. 63|0. 6, 0. 55|0. 7, 0. 45|0. 8, 0. 32|0. 9, 0|1. 0]
Undecided	[1|0, 1|0. 1, 1|0. 2, 1|0. 3, ⋯, 1|1. 0]
Impossible	[0|0, 0|0. 1, 0|0. 2, 0|0. 3, ⋯, 0|1. 0]
Absolutely high	[0|0, 0|0. 1, 0|0. 2, 0|0. 3, ⋯, 1|1. 0]
Absolutely low	[1|0, 0|0. 1, 0|0. 2, 0|0. 3, ⋯, 0|1. 0]

*Represented by pairwise membership values and elements, e.g., $[\mu_{high}(p)|p]$

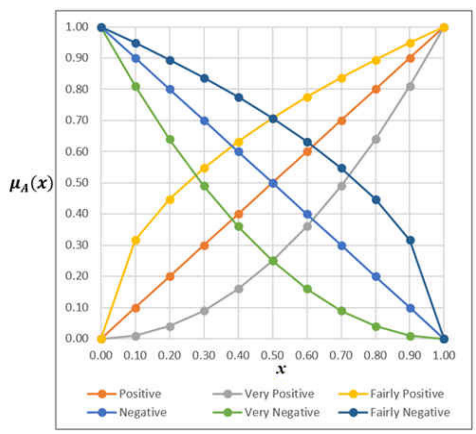

FIGURE III. BALDWIN'S ROTATIONAL MODEL FOR POSITIVE AND NEGATIVE VALUES AND THEIR HEDGES

Integrating BIM Performance and Importance

Each component has performance and importance values that need to be integrated that is performed using the alpha-cut method similar to that conducted in an earlier study [33]. The α-cut of a fuzzy set A is the crisp set ${}^{\alpha}A$, which contains all elements of the universal set X whose membership grades in A are no less the specific value of α [28]. That is:

$$ {}^{\alpha}A = \{x \in X \mid \mu_A(x) \geq \alpha\}; \qquad \text{Eq. (5)} $$

where $\mu_A(x)$ is the membership value of a fuzzy set A cut at an α elevation (α-cut). The values less than α-cut value is ignored while only the values above α-cut are considered for evaluation. Therefore, each fuzzy set can be fully represented by its α-cuts. The degree of belief is termed as "α level". The α-cut method can be used in different fuzzy set models such as the triangular, rotational and angular models [29] [30]. In Baldwin's model, the membership functions, which are monotonically increasing or decreasing, represent the fuzzy numbers. At any α level, which is the cut at any number of y-value, the fuzzy element can be found as the x-value of corresponding cut level. As an example, Figure IV shows the fuzzy element of 0.36 that corresponds to the membership value at 0.6 for the curve that represents *fairly high* (note that in the universe of Performance, the value *fairly high* is represented by the membership function similar to *fairly positive*, etc.)

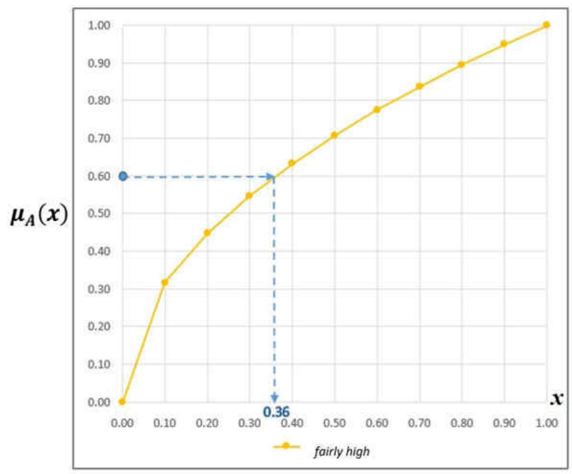

FIGURE IV. AN Α-CUT LEVEL AT 0.6 FOR FAIRLY HIGH

To integrate the performance of basic events and their importance, the fuzzy product (multiplication) is employed. At any α-cut level, the fuzzy element at x axis is multiplied by that of the corresponding importance value. Figure V shows the process of integrating *high* and *fairly high*. For instance, at the α level of 0.6, the fuzzy elements of *high* and *fairly high* are 0.6 and 0.36, respectively, whose product is 0.216. This yields a fuzzy element of 0.216 for a membership value of 0.6. A successive process of cutting at various α levels will produce the top curve of *close to fairly high* performance value of a BIM component.

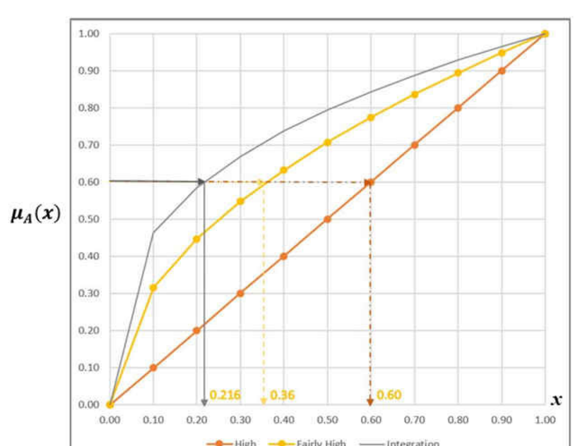

FIGURE V. INTEGRATING HIGH AND FAIRLY HIGH TO PRODUCE CLOSE TO FAIRLY HIGH

This operation takes care of the integration between the value of each basic event and its corresponding importance value in the BPT shown in Figure II. As an example, the product of the performance value of BE101 and its importance will contribute to the performance value of the Owner component in BIM application. A similar process is instituted for BE102 and BE103. The contributions of these basic events are aggregated through the use of fuzzy gate AND, OR, or MEAN. In turn, the contributions of these three components (Owner, Contractor and A/E) to the top event (BIM Application: Final Performance) are summed up using a fuzzy SUM gate [31] [32]. These gates are described next.

THE FUZZY GATES

The four fuzzy gates used in this BPT are AND, OR, MEAN, and SUM gates. The operations of AND and OR gates mimics the tradition intersection and union of two crisp sets, but in this case, two fuzzy sets. For example, the intersection and union of *very positive* AND *negative* performance values are depicted as the hatched regions in Figures VI and VII, respectively. The membership functions for AND and OR gates are found in Eqs. 6 and 7 by taking the minimum and maximum membership values, respectively [33]:

$$\mu_i(x) = Min\,[BE_i(x)] \qquad \text{Eq. (6)}$$

$$\mu_i(x) = Max\,[BE_i(x)] \qquad \text{Eq. (7)}$$

The fuzzy MEAN gate is found by using the average value of basic events in each performance branch that yields [31]:

$$\mu_i(x) = \frac{\Sigma_{i=0}^{n} BE_i(x) w_i(x)}{\Sigma_{i=0}^{n} w_i(x)} \qquad \text{Eq. (8)}$$

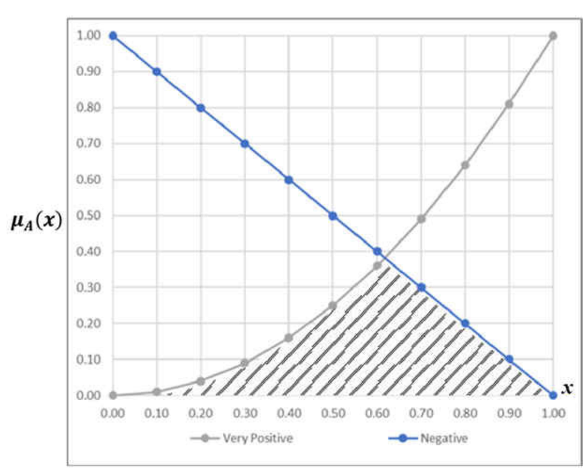

FIGURE VI. FUZZY AND FOR VERY POSITIVE AND NEGATIVE PERFORMANCE VALUES where $\mu_i(x)$ is the α-cut of membership function of fuzzy MEAN, $BE_1(x)...BE_n(x)$, are performance values of basic events, and $w_1(x)...w_n(x)$ are the corresponding importance or weight. In essence, fuzzy MEAN membership function is found by taking the average of the membership values of the basic events. Figure VIII illustrates the fuzzy MEAN of *very positive* and *negative* performance values.

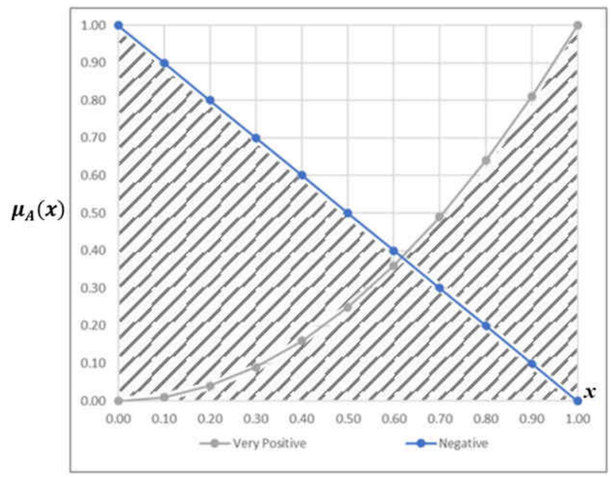

FIGURE VII. FUZZY OR FOR VERY POSITIVE AND NEGATIVE PERFORMANCE VALUES

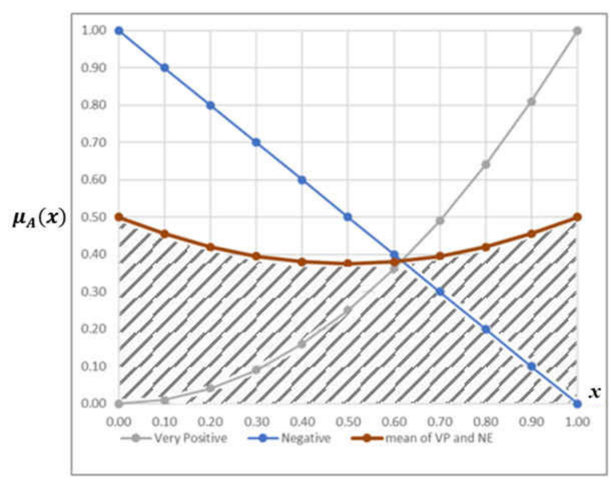

FIGURE VIII. FUZZY MEAN OF VERY POSITIVE AND NEGATIVE PERFORMANCE VALUES

The final BIM performance, i.e., the top event shown in Figure II, is found by summing up the results of the three branches (lower events). The fuzzy SUM gate is used here to include all contribution by the three major participating BIM components (Owner, Contractor, and A/E) to the final performance of the BIM application. Based on Weber's Archimedean measure, the fuzzy SUM yields the membership function, μ_{BIM}, of BIM Application Performance (top event in the BPT) as shown below [31] [33]:

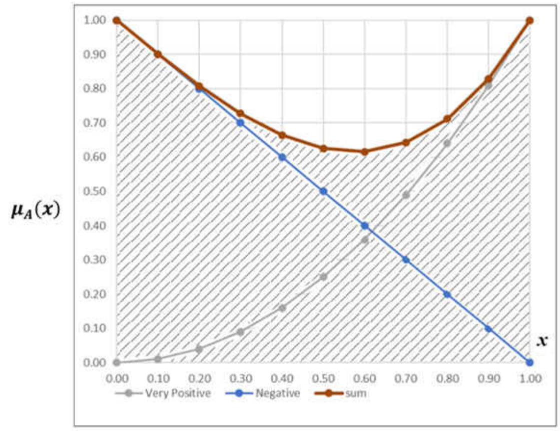

FIGURE IX. FUZZY SUM OF VERY POSITIVE AND NEGATIVE PERFORMANCE VALUES

$$\mu_{BIM} = 1 - \exp[\Sigma_{i=0}^{n} \ln(1 - \mu_i(x) w_i(x))] \qquad \text{Eq. (9)}$$

where $\mu_i(\alpha)$ is the membership value at α-cut level of each basic event, and $w_i(\alpha)$ is its corresponding importance (weight).

Once the integration of membership functions using the α-cut method and the activation of the fuzzy gates are completed, then the membership function of the BIM final performance would be automatically produced. Three scenarios are presented in the following case illustrations.

ILLUSTRATIONS

Depending on the BIM projects and conditions, users of this BPT can select any of the four gates to connect the lower to the intermediate levels of events. However, the use of uniform gates is expected in these scenarios since the characteristics of the intermediate levels are still within the same universe of discourse of stockholders. In the first scenario, the fuzzy MEAN gates are used to connect all lowest events (basic events) to the intermediate events (stockholders), while the fuzzy SUM is employed to represent these stockholders performance to the top event. Figure X depicts this arrangement. Users may wish to enter the values of basic events and their corresponding weights. For example, in the first path of the left-most branch in Figure X, a user rates the performance of BE101, BE 102 and BE 103 as *very high*, *fairly high* and *low*, respectively, with the corresponding weights as *very important*, *important*, and *fairly important*. This produces a performance value of the Owner (not shown in the figure) that contributes to the top event with a weight of *fairly important*. The product of the Owner's performance value and its weight is shown in bottom left of Figure X. This represents the Owner's contribution to the top event of BIM Final Performance. A similar process is performed for the remaining branches of Contractor and A/E yielding the membership functions on the bottom of Figure X. Finally, using the fuzzy SUM gate, the contributions of the three branches are summed up to produce the right most membership function.

Similar procedures are instituted in the second and third scenarios, whose results are displayed in Figures XI and XII. In the second scenario shown Figure XI, fuzzy AND gates are employed to connect all basic events to the stockholders components, while fuzzy SUM is used to represent their contribution to the top event. The third scenario in Figure XII displays the use of fuzzy OR gates to reach the intermediate level of events, which in turn, maintains the fuzzy SUM to reach the top event. The final performance results of the three scenarios are extracted from the right-most bottom graphs of Figures X, XI and XII.

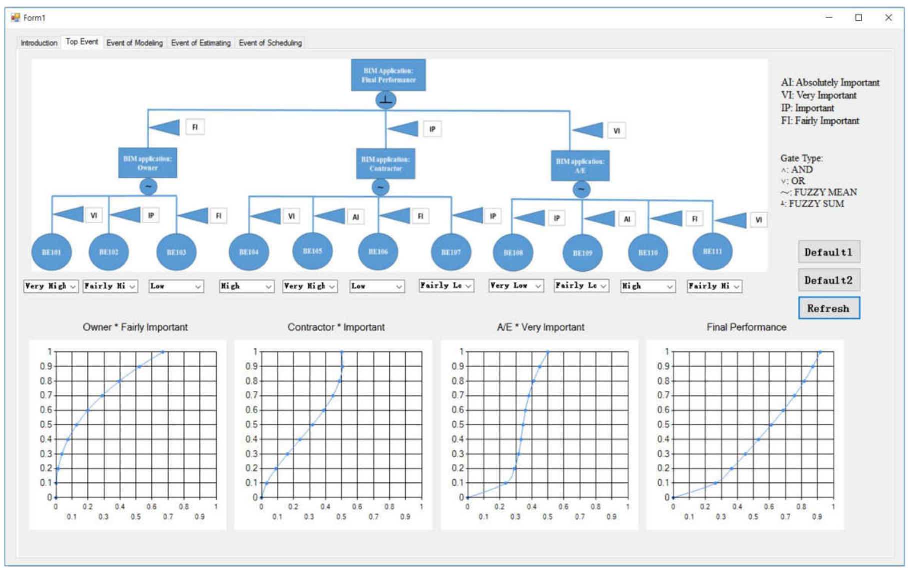

FIGURE X. PERFORMANCE TREE OF THE BIM APPLICATION WITH FUZZY MEAN AND SUM GATES

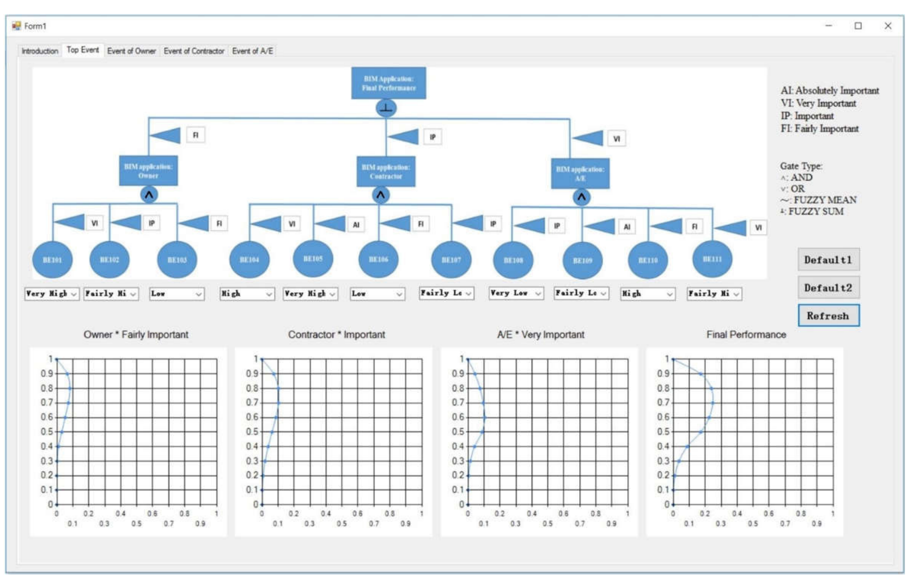

FIGURE XI. PERFORMANCE TREE OF THE BIM APPLICATION WITH FUZZY 'AND' AND 'SUM' GATES

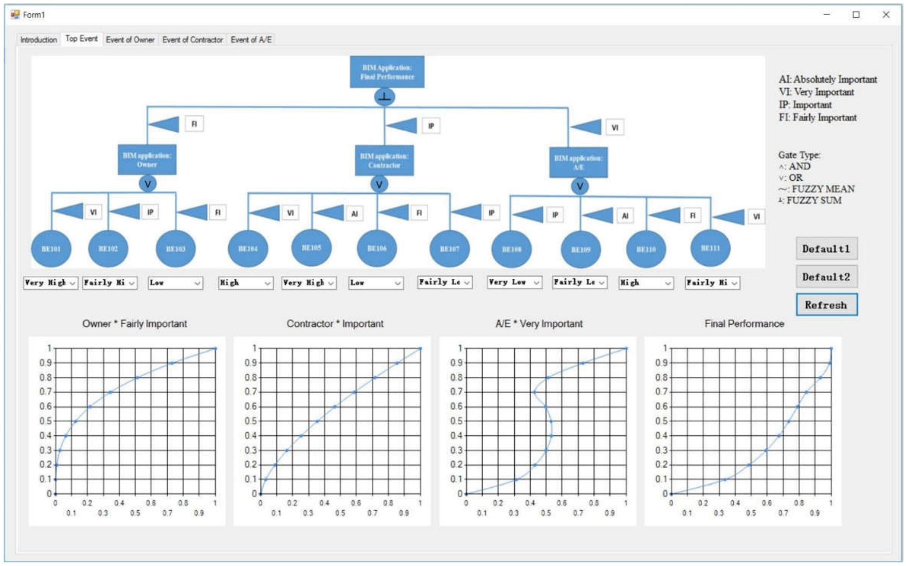

FIGURE XII. PERFORMANCE TREE OF THE BIM APPLICATION WITH FUZZY 'OR' AND 'SUM' GATES

DISCUSSIONS OF RESULTS

The detailed membership function of the result in first scenario is shown in Figure XIII. By comparing with standard Baldwin's models in Figure III, this value may be interpreted as *around high* construction performance with BIM application. Interpretation of this result often requires a defuzzification procedure. The top event is the combination of different basic features and the scope of the application (how many different participating BIM components). Additionally, among the application for these participating BIM components, these features can reflect different phases of the BIM application. Because fuzzy SUM gate considers the combination of lower events to the upper event and fuzzy SUM operation induces an accumulating effect on input values, the top event which integrates all features, participating BIM components, and phases needs to be calculated using fuzzy sum operation.

Figures XIII to XV show different scenarios when evaluating the middle level events; they are reprinted from the bottom right sides of Figures X, XI and XII, representing the use of MEAN, AND and OR gates. Different users may have different evaluations of BIM application of construction performance, and thus different choice of gates linking the lowest to the intermediate levels of the tree. For consistency, it is recommended the uniform use of either one of these gates that links these levels; yet, should certain condition appears, mixed gates can also be considered.

For the first scenario in which fuzzy MEAN gates are used to link the first lower levels of the tree, the results from Figure X is reprinted in a more detailed fashion as shown in Figure XIII. Visually, in comparison to the standard Baldwin's models shown in Figure III, the line in Figure XIII shows the final performance of BIM application to the construction process as *around high*. Approximating the centroid of the curve required the use of trapezoidal interpolation, i.e., calculating the centroids and areas of the trapezoids formed by the Cartesian coordinates of the curve and the lengths of the x-axis below each segment. The centroid coordinates of the overall curve were determined with the following equations:

$$x = \frac{\Sigma x_i{}^* A_i}{\Sigma A_i} \qquad \text{Eq. (10)}$$

$$y = \frac{\Sigma y_i{}^* A_i}{\Sigma A_i} \qquad \text{Eq. (11)}$$

where x_i and y_i are the midpoint values of the x and y coordinates for each trapezoid i, and A_i is the area of each trapezoid i.

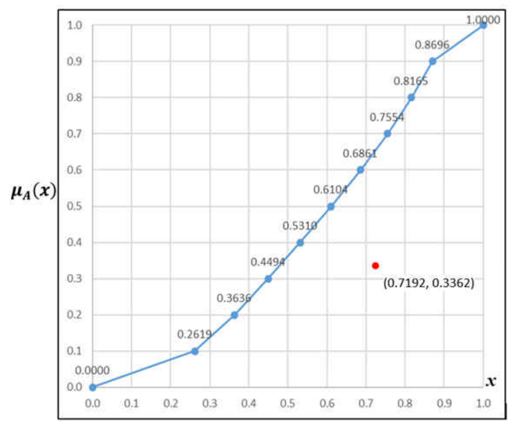

FIGURE XIII. BIM FINAL PERFORMANCE: USING FUZZY MEAN TO REACH THE INTERMEDIATE LEVEL

Note that the centroids of Baldwin's positive values of the membership functions are determined primarily by the values of the x-coordinates ranging from 0.5 to 1.0, while for the negative values from 0.0 to 0.5. The y-coordinates do not in general have much effect in defuzzification process [25]. In the first scenario, the x and y value of centroid of this final performance are **(0.7192, 0.3362)**, the location of which is shown in Figure XIII, which is consistent with ***around high*** BIM application performance.

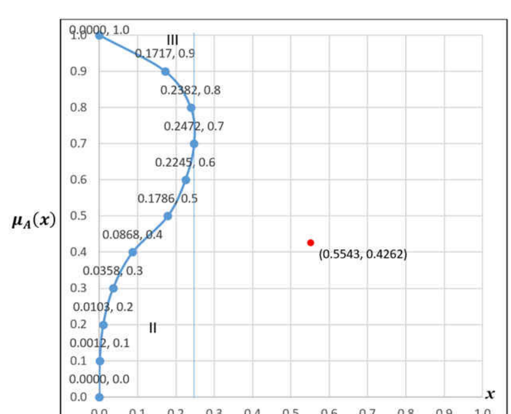

FIGURE XIV. BIM FINAL PERFORMANCE: USING FUZZY AND TO REACH THE INTERMEDIATE LEVEL

In the second scenario for fuzzy AND gates in middle-level-events, visual indication of the line in Figure XIV suggests *almost fairly high* construction performance due to BIM application. Still visually, due to the shift of the rotational axis on the top of the line, interpretation of the line may not be straightforward. Hence, defuzzification by the centroid method may help.

The calculation process of the centroid for this non-monotonic curve begins with dividing the area to the right of the curve into three separate portions: one rectangle *I*, starting from the maximum *x* coordinate to $x = 1.0$, and two curved regions *II* and *III*, as shown in Figure XIV. The centroid for region *I* is simply 1-(1-MIN_I)/2, where MIN_I is the leftmost *x* coordinate that can be reached by any point in the region (i.e. the maximum *x* coordinate in the array, *x* = 0.2472). The other two centroid *x* coordinates are then calculated for regions *II* and *III*, using Equations 10 and 11. The three regions thus have centroid *x* coordinates of 0.6236, 0.1600, and 0.1430, respectively, and applying Eq. 5.1 gives a total centroid *x* coordinate of **0.5543**. Using Eq. 11 to calculate the *y* centroid coordinate results in x and y values of the centroid of this final performance of **(0.5543, 0.4262)**, as shown in Figure XIV, consistent with the value of ***almost fairly high.*** Note that the line loses its rotational characteristic, especially at its top right.

Visually, in the third scenario for fuzzy OR gates in middle-level-events, the line in Figure XV shows the final BIM performance as *close to very high*. Using Eqs. 10 and 11, the x and y value of centroid of this final performance are **(0.7414, 0.2885)**, the location of which is shown in Figure XV. This scenario yields an x-coordinate of the centroid located further to the right; this is consistent with an assessment value of ***close to very high*** BIM application for construction performance.

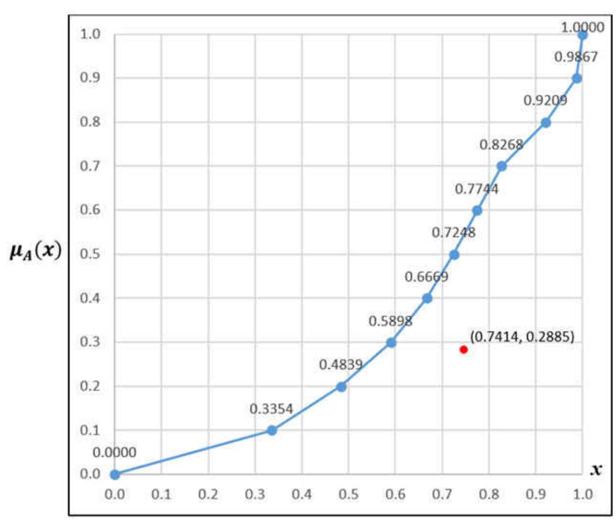

FIGURE XV. BIM FINAL PERFORMANCE: USING FUZZY OR TO REACH THE INTERMEDIATE LEVEL

SUMMARY AND CONCLUSION

This research introduces a new method capitalizing on the use of subjective assessments associated with the application of BIM to enhance construction performance. Although stakeholders and other performance factors can be numerous, for the sake of simplicity, this study focused solely on the participation of the Owner, Contractor, and Designer (A/E) (though other factors could potentially be considered in future studies). From the perspective of the Owner, BIM provides better visualization for project participating BIM components in the preliminary design phase, and helps Owners with improving schedules and reducing the time needed to ready the project for market release. Additionally, the BIM building model is beneficial for facility operations and management during the post-construction phase. The BIM integration also allows the Contractor to link the construction planning with the design model. With the BIM parametric model, the Contractor can also produce cost estimates efficiently and accurately; furthermore, the BIM-supported trade and coordination systems smooth the process of fabrication and procurement during the construction phase. Finally, for the Designers (A/E), the BIM 3D visualization enables them to interactively evaluate the concept design alongside other participating BIM components. More importantly, the integrated model and data from BIM promote the collaboration of multiple design disciplines, so that the redesign or remake costs can be avoided through conflict detection.

This study employs fuzzy performance tree methods to represent the knowledge path of qualitative assessment of BIM application to construction performance and to quantitatively evaluate these assessments. In this way, the research converted these subjective linguistic expressions into numeric fuzzy membership functions. To accomplish this, the study used Baldwin's fuzzy rotational model to represent the assessment values of the performance of each BIM component and its importance to the overall performance. Each path of the performance tree describes the contribution of the lower to the upper components and their relationships. The model thus gives both the ranking of these contributions to the final construction performance due to BIM application and the visual imagery of said contributions in graph form.

Three scenarios relating the lowest to intermediate levels through fuzzy MEAN, AND and OR gates are introduced to illustrate the concept. Using the fuzzy MEAN, the first scenario produced *around high* value of BIM application construction performance, and yields the most realistic result both visually and quantitatively. Essentially, the MEAN gates consider all input values and aggregate them using fuzzy average operations. The second scenario, using the AND gate, yields the most difficult result to interpret visually; though it still produced *almost fairly high* overall BIM performance quantitatively, these gates may not represent the most realistic relationship between the lowest and intermediate levels, as only the intersecting information is considered (analogous to the intersection operation in the traditional crisp set theory). In addition, the line loses the rotational features that makes it hard to interpret visually. The same concept applies to the third scenario in which OR gates are employed, in which only the maximum input values are considered (analogous to the union operation in crisp sets), yielding the least conservative result. Based on these scenarios, the fuzzy MEAN gates seems to produce the most realistic and accurate result.

However the outcome, the fuzzy decision tree appears to be a solid starting point for performance analysis in BIM and other construction management methods. Future studies may improve upon both the decision tree structure and the knowledge base used as a basis by working in additional performance factors, participants, and levels of decision complexity.

As stated, this paper introduces another method to convert the qualitative evaluations into numerical values to deal with the ambiguity of the existing assessments. This paper briefly discusses the differences between the existing methods, such as AHP and Delphi, and the proposed assessment. However, the accuracy of the evaluation on the proposed assessment, compared to the existing methods, needs to be tested in future studies.

The methodology (fuzzy performance tree) introduced in this paper is suitable to apply in today's construction industry when limited data is presented and it is heavily relied on experts' subjective judgment.

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