Fuzzy Intellectual Capital Index for Construction Firms

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Abstract: Construction firms are now operating in a new era. Gaining and sustaining competitive advantage in this era primarily depends on effective and efficient management of knowledge assets. This paper proposes a performance evaluation model called fuzzy intellectual capital index (FICI) that can guide construction business executives to effectively and efficiently manage their knowledge assets. FICI incorporates an intellectual capital performance measurement model with fuzzy set theory to adequately handle imprecision, vagueness, and uncertainty that prevail in this process. FICI uses the fuzzy-weighted average algorithm to compute the intellectual capital performance of architectural/engineering/construction (A/E/C) firms. It is an internal reporting model that can guide executives of A/E/C firms to evaluate their firm's ability to achieve their strategic objectives and to pinpoint their firm's strengths and weaknesses in order to neutralize threats and to exploit opportunities presented by today's construction business environment. A real-world case study is presented to illustrate the implementation and utility of the proposed model. Implications for practitioners and directions for future research are discussed.

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Introduction

Construction firms are now operating in a new era that is characterized by unprecedented developments in information communicating technologies, intensified competition, increasing globalization, and international partnering. The primary source of gaining and sustaining competitive advantage in this new era is knowledge assets. The surge in the number of research studies (Kululanga and McCaffer 2001; Egbu 2004; Carrillo and Chinowsky 2007), books (e.g., Anumba et al. 2005; Kazi 2005), meetings, seminars, and conferences (e.g., CIB 2005–2008) are explicit testaments to this fact. Therefore, construction firms should develop and/or adopt tools and techniques to manage their knowledge assets if construction firms are to succeed in this new era. Performance measurement models provide construction business executives with meaningful tools and techniques to manage their assets effectively and efficiently. These tools and techniques would allow construction business executives to define, understand, evaluate, and manage their knowledge assets.

Performance measurement modeling has been an important research stream in the literature. The common theme in this important research stream is strong dissatisfaction from traditional performance measurement modeling that solely focuses on measuring financial assets. Several performance measurement models such as the Performance Measurement Matrix (Keegan et al. 1989), the SMART Pyramid (Lynch and Cross 1991), the Balanced Scorecard (Kaplan and Norton 1992), the Tableau de Bord (Epstein and Manzoni 1997), the Performance Prism (Neely et al. 2002), and a number of initiatives such as the Malcom Baldrige Award and European Foundation for Quality Management (EFQM) have been set forth to overcome the limitations of the traditional performance measurement modeling. These performance measurement initiatives mark an important milestone in the evolution of performance measurement modeling. They implicitly acknowledge importance of nonfinancial assets in performance measurement, but they do not provide a systematic and comprehensive framework for measuring knowledge assets. The lack of a systematic and comprehensive framework for measuring knowledge assets has led business practitioners and academic researchers to define new concepts in order to identify, classify, and manage knowledge assets. As a result of these efforts, Intellectual Capital Performance Modeling (e.g., Edvinsson and Malone 1997; Roos and Roos 1997; Sveiby 1997; Pike and Roos 2000; Edvinsson et al. 2000; Roos et al. 2001) has emerged as a key approach for measuring firms' knowledge assets. Intellectual capital performance modeling provides a systematic and comprehensive framework for identifying, classifying, and in turn managing firms' knowledge assets. The primary objectives of intellectual capital performance modeling are twofold: (1) to evaluate a firm in order to communicate its real value to the market or to its stakeholders—External Reporting, and (2) to identify the knowledge assets of a firm in order to manage them effectively and efficiently—Internal Reporting.

Some construction management researchers have also been involved in developing performance measurement models that meet the challenges presented by the new era. These performance measurement models (e.g., Kagioglou et al. 2001; Bassioni et al. 2005; Robinson et al. 2005) primarily build on the Balanced Scorecard (Kaplan and Norton 1996), the EFQM, the Malcom Baldridge Award and/or Key Performance Indicators defined by the Construction Best Practice Program. Yet intellectual capital performance modeling has not been used in any of these set forth models (e.g., Kagioglou et al. 2001; Bassioni et al. 2005; Robinson et al. 2005). Only a few research studies focused on measuring knowledge assets in the construction management literature

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(e.g., Kululanga and McCaffer 2001; Egbu 2004; Carillo and Anumba 2002). This succinct review of the construction management literature highlights the fact that measuring knowledge assets in the construction industry is still in its infancy. The paper presented herein focuses on this developing research area. It presents a simple framework for identifying, classifying, and measuring knowledge assets of construction firms. The proposed framework is a synthesis of intellectual capital performance modeling and fuzzy set theory. The main impetus for using fuzzy set theory (Zadeh 1965) in the proposed framework comes from the fact that developed intellectual capital models use crisp values to measure knowledge assets. Yet the process of measuring intellectual capital takes place under ambiguities, uncertainties, and vagueness. This challenge calls for a model that can cope with inexact information. Fuzzy set theory uses approximate rather than exact modes of reasoning. Therefore, it is a convenient and flexible tool for dealing with ambiguity, uncertainty, and vagueness.

The main objectives of the proposed framework are (1) to assist executives of construction firms to identify and classify their knowledge assets, (2) to provide a foundation on which systems and processes for effective and efficient management of knowledge assets can be built, and (3) to provide executives of construction firms an internal reporting tool to evaluate their firm's ability to achieve their strategic objectives.

Conceptual Foundations

There is an increasing recognition in the construction management literature that knowledge assets are the primary source of gaining and sustaining competitive advantage in today's business environment (e.g., Egbu 2004; Carrillo and Chinowsky 2007; Anumba et al. 2005). The term knowledge assets used herein can be defined as the collection of intellectual resources, as distinguished from physical and financial assets, that comprise the intellectual capital of the firm (Sundarsaman et al. 2005). This definition introduces a new concept, namely intellectual capital (IC) to understand and, in turn, manage knowledge assets. Yet IC is a complex concept and is difficult to define. Different definitions have been set forth in the literature for exploring this complex concept. There is presently no universally acceptable definition of IC (Leon 2002). Nahapiet and Ghoshal (1998) define IC as "the knowledge and knowing capability of a social collectivity such as organization, intellectual community, or professional practice." Stewart (1997) defines IC as "intellectual material—knowledge, information, intellectual property, and experience—that can be put to use to create wealth." Klein and Prusak (1994) define IC as "intellectual material that has been formalized, captured, and leveraged to produce a higher-valued asset." Ulrich (1998) defines IC as "competence $\times$ commitment." Brooking (1996) argues that IC is the term given "to the combined intangible assets which enable the company to function." Finally, Williams and Bukowitz (2001) propose that IC embraces all forms of knowledge, ranging from the abstract (i.e., culture, norms, values, group dynamics, and individual members' knowledge and skills) to the concrete (i.e., presentations, documents, blueprints, process maps). Important underlying concepts in these set forth definitions include the notion that: (1) intellectual capital is something invisible; (2) it is closely related to knowledge and experiences of employees, as well as customers/clients and technologies of a firm; and (3) it offers better opportunities for a firm to succeed in the future.

Several intellectual capital performance models have been set forth, such as the Skandia Value Scheme (Edvinsson and Malone 1997), the Intangible Asset Monitor (Sveiby 1997), the Intellectual Capital Index (Roos and Roos 1997), the digital IC landscape (Edvinsson et al. 2000), and the Holistic Value Approach (Pike and Roos 2000). A succinct review of these intellectual capital models reveals that there are two distinct generations of intellectual capital thinking.

First-Generation Intellectual Capital Thinking: Stocks

The first generation of IC thinking (Edvinsson and Malone 1997; Sveiby 1997) focuses on identifying *stocks* of knowledge assets and measuring a firm's IC. The term "stocks" herein refers to a firm's knowledge assets. The first-generation intellectual capital models propose that the intellectual capital of a firm takes three basic forms: *human capital, structural capital*, and *relational capital*.

Human capital represents the knowledge, skills, and abilities of individual employees to meet the task. It can be considered as a combination of four factors: genetic inheritance, formal education, experience, and social/psychological attitudes about life and business. It is inherent in people and cannot be owned by firms. Therefore, human capital can leave a firm when people leave. It also encompasses how effectively an organization uses its resources as measured by creativity and innovation. It is a firm's combined capability for solving strategic, administrative, and operational problems that prevail in the construction industry.

Structural capital represents knowledge that stays within the firm at the end of the working day. It is the supportive infrastructure that enables employees (i.e., human capital) to function. It can be considered as knowledge that can be used exclusive of the creator—knowledge that has been articulated, codified, and often linked to the existing body of organizational knowledge. The structural capital of a construction firm includes its management philosophy, organizational culture, management processes, procedures, programs, information systems, and techniques that implement and enhance the delivery of products/services (i.e., contracting services, constructed facility). It also includes intellectual property in which various forms of ownership (i.e., patents, trade secrets, trademarks, and copyrights) are protected by law.

Relational capital represents knowledge embedded in organizational relationships with customers, suppliers, stakeholders, and strategic alliance partners (Stewart 1991). It can be defined as "the actual and potential resources individuals obtain from knowing others, being part of a social network with them, or merely being known to them and having good reputation" (Baron and Markman 2000). The relational capital of a construction firm resides in its relationships with external parties, such as clients, subcontractors, construction material vendors, sureties. It is relational capital that enables a construction firm to receive resources (i.e., knowledge, information, labor, material, and legitimacy) from its external environment.

Second-Generation Intellectual Capital Thinking: Interstock Flows

The first-generation IC thinking focuses on identifying stocks of knowledge assets and measuring these knowledge assets The second-generation IC thinking proposes that identifying merely components of IC and, in turn, measuring the stocks of knowledge assets is not enough because the presence of stocks is not

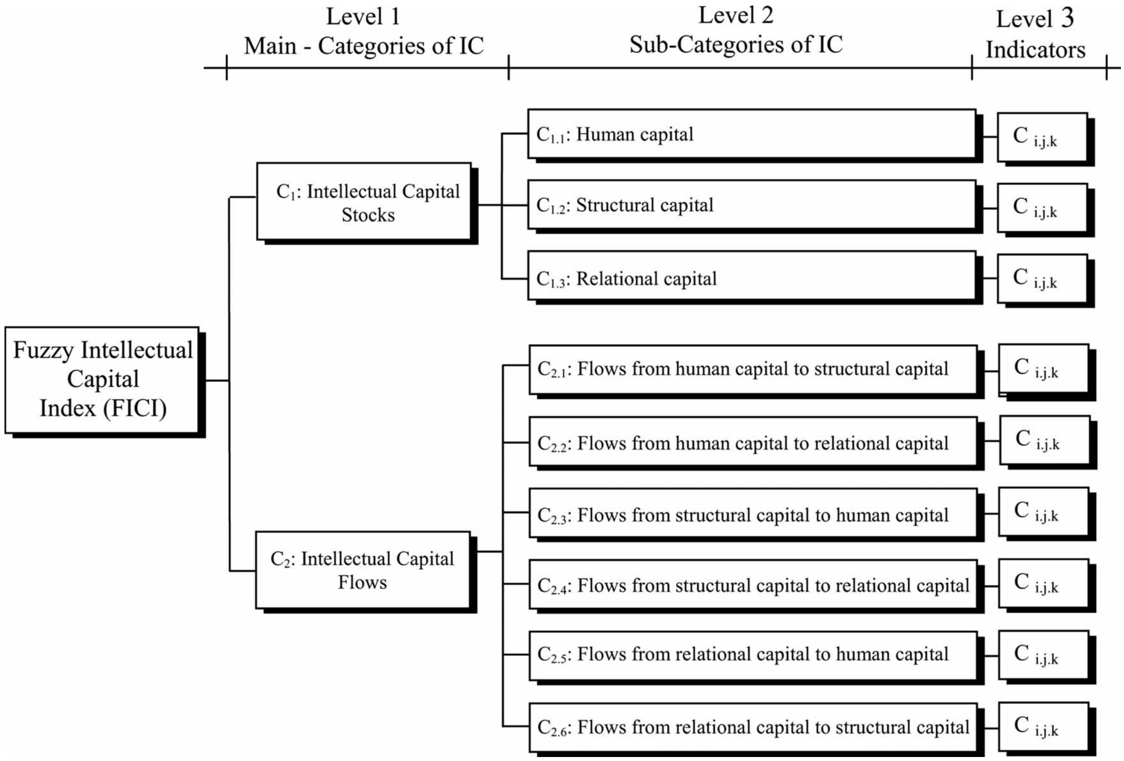

Fig. 1. Hierarchical structure for measuring intellectual capital in construction firms

sufficient to create value (Roos and Roos 1997; Roos et al. 2001). Therefore, it is also essential to measure, and thus measure and manage the flows between stocks of knowledge assets. The term "flows" herein refers to the transformations between stocks of knowledge assets (Roos and Ross 1997).

Using the concepts introduced by two distinct generations of intellectual capital thinking to measure knowledge assets presents a number of benefits to construction firms such as (1) creating a consciousness within the firm that intellectual capital does matter, (2) assisting the firm in conducting a competitive benchmarking exercise, and (3) allowing for strategy formulation, assessment and execution (Marr 2005). It is clear that a systematic approach to measure intellectual capital is quite valuable to construction firms regardless of their size, age, and ownership.

Thus far, the concept of IC is defined, and two distinct generations of IC thinking and their potential benefits to construction firms are discussed. The following section presents a fuzzy set theory-based model for evaluating the knowledge assets of construction firms.

Fuzzy Intellectual Capital Index Model

The fuzzy intellectual capital index (FICI) model presented in this paper builds on the concepts that have been set forth by two distinct generations of IC thinking (e.g., Edvinsson and Malone 1997; Roos et al. 2001) and fuzzy set theory (e.g., Zadeh 1965; Kangari and Riggs 1989; Kao and Liu 1999, 2001; Lin et al. 2006). The basic concepts of fuzzy set theory used in developing the model are presented in Appendix I. The FICI model involves a six-step procedure for measuring intellectual capital in construction firms. These steps are as follows: *Step 1*. Identifying evaluation criteria for measuring intellectual capital. *Step 2*. Constructing the hierarchical structure for the evaluation criteria. *Step 3*. Determining importance weights of the evaluation criteria. *Step 4*. Rating a firm's stocks and its interstock flows. *Step 5*. Computing a firm's fuzzy intellectual capital index. *Step 6*. Linguistic matching using the Euclidean distance.

Step 1. Identifying the Evaluation Criteria for Measuring Intellectual Capital

The first step in measuring the intellectual capital of a construction firm is developing a set of evaluation criteria C_i $(i=1,2,\ldots n_i)$. The first and second generations of intellectual capital thinking propose that the set of evaluation criteria should include intellectual stocks, interstock flows (i.e., transformations between stocks), and indicators for measuring stocks and flows.

Step 2. Constructing the Hierarchical Structure for the Evaluation Criteria

The second step is constructing a hierarchical structure for measuring intellectual capital. The first and second generations of intellectual capital thinking propose a three level hierarchical structure for measuring intellectual capital (Fig. 1). *Level 1* decomposes a construction firm's intellectual capital into two main criteria C_i $(i=1,2)$: intellectual stocks (C_1) and interstock flows (C_2). *Level 2* further decomposes each main criterion into subcriteria C_{ij} $(j=1,2,3,\ldots,n_j)$, where n_j denotes the number of subcriteria of the main criterion C_i. Intellectual stocks (C_1) include tree subcriteria: human capital $(C_{1.1})$, structural capital $(C_{1.2})$ and relational capital $(C_{1.3})$. Interstock flows (C_2) include six subcriteria: flows from human capital to structural capital $(C_{2.1})$, flows from human capital to relational capital $(C_{2.2})$, flows from structural capital to human capital $(C_{2.3})$, flows from structural capital to relational capital $(C_{2.4})$, flows from relational capital to human capital $(C_{2.5})$, and flows from relational capital to structural capital ($C_{2.6}$). *Level 3* includes a set of indicators C_{ijk} ($k = 1, 2, \ldots, n_k$), where n_k denotes the number of indicators for measuring each subcriterion (C_{ij}).

Step 3. Determining the Importance Weights of the Evaluation Criteria

The third step involves identifying the importance weight of each criterion at each level to the firm's long-term strategy. The rationale behind anchoring the importance of each criterion at each level to the firm's long-term strategy is grounded in the common argument that a performance measurement is not valid if it does not consider a firm's long-term strategy (Roos and Roos 1997). The importance weights of evaluation criteria can be obtained by forming an evaluation committee that is composed of construction business executives from different hierarchical levels. Using individuals from different hierarchical levels brings multiple sources of information to the performance evaluation process and in turn enhances its validity. The most common approach used in determining the importance of each criterion is judging its importance with linguistic variables (e.g., *low importance, moderate importance, and very strong importance*) (e.g., Sveiby 1997; Kao and Liu 2001). These linguistic variables can be appropriately represented by using fuzzy triangular numbers (Dubois and Prade 1987). Therefore, these linguistic terms are then transformed into fuzzy triangular numbers. Let $W_{iq} = (l_{iq}, m_{iq}, u_{iq})$ be the fuzzy triangular numbers representing the linguistic importance of each criterion in the evaluation set C_i assigned by the evaluator q ($q = 1, \ldots, s$), where s = number of evaluators involved in the measurement process. The different opinions of the committee members on the importance of each criterion relative to the firm's long-term strategy can be aggregated by using the following equation:

$$W_i = (1/s) \otimes (W_{1i} \oplus W_{2i}, \ldots, \oplus W_{si}), \tag{1}$$

where $\otimes$ = fuzzy multiplication operator; $\oplus$ = fuzzy addition operator; and W_i = average fuzzy importance weight of performance criterion i.

Step 4. Rating the Firm's Current Stocks and Interstock Flows

The fourth step is rating the firm's current stocks and interstock flows. A construction firm's stocks and interstock flows can be evaluated by using a two-stage process: (1) developing a set of indicators for intellectual stocks and interstock flows and (2) rating the construction firm's achievement on each indicator by using linguistic variables. The indicators that are used for measuring stocks and interstock flows should be developed after a thorough discussion with the evaluation committee. The construction industry is a project-based industry. Therefore, the indicators should cover firm-level issues as well as project-level issues. Linguistic variables used for a rating construction firm's achievement on each indicator are then transformed into fuzzy triangular numbers. Let $R_{iq} = (l_{iq}, m_{iq}, u_{iq})$ be triangular fuzzy numbers representing ratings of achievement with respect to each indicator assigned by evaluator q ($q = 1, 2 \ldots, s$) and s = number of evaluators involved in the measurement process. The different opinions of construction business executives on achievement levels with respect to each indicator can be aggregated by using the following equation:

$$R_i = (1/s) \otimes (R_{1i} \oplus R_{2i}, \ldots, \oplus R_{si}), \tag{2}$$

where $\otimes$ = fuzzy multiplication operator; $\oplus$ = fuzzy addition operator; and R_i = average fuzzy performance rating of criterion i.

Step 5. Computing the Firm's Fuzzy Intellectual Capital Index

FICI represents a construction firm's overall IC performance. Therefore, it requires consolidation of fuzzy weights and ratings of *Level 1*, *Level 2*, and *Level 3* criteria presented in Fig. 1. This consolidation process starts from the lowest level *(Level 3)*, proceeds to the midlevel *(Level 2)*, and from midlevel to the highest level *(Level 1)*. The consolidation of average fuzzy importance weights (W_{ijk}) and the average fuzzy performance ratings (R_{ijk}) of *Level 3* criteria (C_{ijk}) provides fuzzy-weighted average performance ratings (R_{ij}) for *Level 2* criteria (C_{ij}). Similarly, consolidation of the average fuzzy importance weights (W_{ij}) and the fuzzy-weighted average performance ratings (R_{ij}) of *Level 2* criteria (C_{ij}) provides fuzzy-weighted average performance ratings (R_i) of *Level 1* criteria (C_i). Finally consolidation of the average fuzzy importance weights (W_i) and the fuzzy-weighted-average performance ratings (R_i) of *Level 1* criteria (C_i) provides the FICI of a construction firm.

The *fuzzy-weighted average* (FWA) method is used to aggregate the average fuzzy importance weights and the average fuzzy performance ratings of *Level 1*, *Level 2*, and *Level 3* criteria. The FWA method for measuring FICI of a construction firm can be defined as

$$R_{ij} = \sum_{i}^{n} R_{ijk} \otimes W_{ijk} \Bigg/ \sum_{i}^{n} W_{ijk} \tag{3}$$

$$R_i = \sum_{i}^{n} R_{ij} \otimes W_{ij} \Bigg/ \sum_{i}^{n} W_{ij} \tag{4}$$

$$\text{FICI} = \sum_{i}^{n} R_i \otimes W_i \Bigg/ \sum_{i}^{n} W_i \tag{5}$$

The above-presented formulation is difficult to solve because it contains fuzzy numbers and fuzzy arithmetic operations (i.e., addition, multiplication, and division). Fuzzy arithmetic operations on fuzzy numbers, particularly the division operation, are difficult to carry out. Different algorithms (e.g., Lee and Park 1997; Guh et al. 2001; Kao and Liu 2001) have been proposed to facilitate the fuzzy arithmetic operations and to compute the FWA presented in Eqs. (3)–(5). The intellectual capital measurement model presented in this paper uses Kao and Liu's (2001) algorithm as it is the most efficient algorithm. This algorithm involves transforming the α-cut solution of a fuzzy-weighted average to a linear fractional program and solving it by linear programming techniques. The transformation process is presented in Appendix II.

Step 6. Linguistic Matching Using the Euclidean Distance

The final step is translating FICI back into a linguistic term. The linguistic approximation method is chosen for this process. The linguistic approximation method translates a quantitative membership function into a linguistic result that can aid decision makers in crafting an appropriate evaluation. It uses a natural language expression set and a distance measure for translating a quantitative membership function into a linguistic term. The natural language expression set includes a number of predefined linguistic terms for an evaluation process. The ICP of a construction firm can be evaluated by defining a natural language expression set ICP={*very low*, *low*, *medium*, *high*, *and very high*}. Linguistic matching uses distance (d) concept between a quantitative membership function and a natural language expression set. The most commonly used distance (d) measure in linguistic approximation is the Euclidean distance (e.g., Kangari and Riggs 1989; Lin et al. 2006). The Euclidean distance between FICI and natural language expression set (ICP) is defined in

$$d(\mathrm{FICI},\mathrm{ICP}_i) = \left\{ \sum_{x \in p} [f_{\mathrm{FICI}}(x) - f_{\mathrm{ICP}_i}(x)^2] \right\}^{1/2} \tag{6}$$

where d=Euclidean distance between FICI and natural language expression set (ICP_i); and $p=\{x_0,x_1,\ldots,x_m\}\subset[1,0]$ such that $0=x_0<x_1<x_m=1$. The Euclidean distance from (FICI) to each member of predefined natural-language set (ICP_i) can be computed by letting $p=\{0,0.05,0.10,0.15,0.20,0.25,0.30,0.35,0.40,045,0.50,0.55,0.60,0.65,0.70,0.75,0.80,0.85,0.90,0.95,$ and $1.0\}$. The natural language expression (i.e., linguistic term) with the minimum Euclidean distance represents the construction firm's intellectual capital performance. The accuracy of the language approximation process is very sensitive to the selection of the natural language expression set and its membership function. Therefore, the natural language expression set and its corresponding membership function should be jointly defined by the strategic leaders of the firm by considering the firm's long-term strategy.

Case Study: Measuring the Intellectual Capital of a Construction Firm

The case study approach was adopted in this study to illustrate the use of the proposed model for measuring the intellectual capital performance of construction firms, because this is a common research approach used in previous performance measurement modeling studies in the construction management domain (e.g., Kagioglou et al. 2001; Bassioni et al. 2005; Robinson et al. 2005). Turkish construction firm [*Alfa Construction Firm* (ACF)] located in Istanbul was chosen for the case study. ACF was established in 1974 and has more than 100 full time employees. Its turnover is over \$ 130 million. ACF undertakes general building and infrastructure projects.

The evaluation committee in this case study was composed of three top executives of ACF, including the chief executive officer. These individuals were considered to be the most knowledgeable persons regarding their firm's knowledge assets and long-term strategy. Four series of interviews were conducted with these top executives. The first series of interviews were in preliminary nature and focused on identifying the firm's intellectual stocks, interstock flows, and their relationship to the firm's long-term strategy. The second series of interviews focused on developing indicators for measuring intellectual stocks and interstock flows. A preliminary set of indicators was prepared based on a succinct review of previous research studies on intellectual capital and the analysis of the notes and transcripts from the first series of interviews. The initial set of indicators was modified based on the feedback and suggestions received from the evaluation committee. The third series of interviews focused on developing linguistics variables and their corresponding membership functions for measuring importance weights and performance ratings. The final series of interviews involved the administration of the intellectual capital evaluation form.

The evaluation form used in measuring ACF's intellectual performance consists of two parts. The first part of the evaluation form includes a series of questions that identify the importance of each criterion. In this part, committee members were asked to rate the importance of each main criterion (i.e., stocks, and interstock flows), each subcriterion and the indicators regarding their firm's long-term strategy by using linguistic variables that ranged from "*totally unimportant*," "*quite unimportant*," "*unimportant*," "*barely important*," "*moderately important*," "*very important*," to "*extremely important*." The second part of the evaluation form included a set of indicators for measuring ACF's current intellectual stocks and interstock flows. Table 1 presents the statements used for measuring ACF's intellectual stocks and interstock flows. In the second part of the evaluation form, committee members were instructed to rate their satisfaction of their firm's achievement on each indicator by using linguistic variables that ranged from "completely satisfied," "mostly satisfied," "somewhat satisfied," "somewhat unsatisfied," "mostly unsatisfied," to "completely unsatisfied."

Each evaluator's linguistic responses regarding the importance weight assigned to each criterion and the level of satisfaction with the achievement in each criterion were transformed into triangular fuzzy numbers. The triangular fuzzy numbers associated with the linguistic terms used to measure relative importance of each criterion were set as (0,0,0.2), (0,0.2,0.4), (0.2,0.35,0.5), (0.3,0.5,0.7), (0.5,0.65,0.8), (0.6,0.8,1), and (0.8,1.0,1.0). Similarly, the triangular fuzzy numbers associated with the linguistic terms used to measure the satisfaction from achievement in each criterion were set as (0,0,0.2), (0,0.2,0.4), (0.2,0.4,0.6), (0.4,0.6,0.8), (0.6,0.8,1.0), and (0.8,1.0,1.0). Fuzzy triangular numbers representing each evaluator's subjective judgments regarding the importance weights and the performance ratings of each criterion were then aggregated by using Eqs. (6) and (7), respectively. The rationale behind this process was to obtain the average fuzzy weights and average fuzzy performance ratings corresponding to each criterion. Table 2 presents the average fuzzy weights and the average fuzzy performance ratings of ACF.

FICI represents a construction firm's overall intellectual capital performance. Therefore, it requires a three-stage consolidation of the fuzzy weights and ratings of *Level 1*, *Level 2*, and *Level 3* criteria. The commercial optimization software LINGO 9.0 (LINDO Systems, Inc., Chicago, Illinois) was used in this process.

The first stage consolidated the average fuzzy importance weights (W_{ijk}) and the average fuzzy performance ratings (R_{ijk}) of Level 3 criteria by using Eq. (3). This consolidation process involved converting Eq. (3) into two linear programming models in the form of Eqs. (13*a*) and (13*b*) (See Appendix II) and solving them at two different α cuts ($\alpha=0.00$ and 1.00). Table 2 presents the calculated fuzzy-weighted average performance ratings (R_{ij}) for Level 2 criteria (C_{ij}).

The second stage consolidated the average fuzzy importance weights (W_{ij}) and the fuzzy-weighted average performance ratings (R_{ij}) of Level 2 (C_{ij}) criteria by using Eq. (4). Similarly, this consolidation process involved converting Eq. (4) into two linear programming models in the form of Eqs. (13*a*) and (13*b*) in Appendix II and solving them at two different α cuts ($\alpha=0.00$ and 1.00). The fuzzy-weighted average performance ratings (R_i) of *Level 1* criteria (C_i) are presented in Table 2.

The final stage calculated the FICI of ACF by converting Eq.

Table 1. Indicators for Evaluating Intellectual Stocks and Interstock Flows

$C_{1.1}$: Human capital—$C_{1.1.1}$: Strategic leadership of the management. $C_{1.1.2}$: Quality of the employees. $C_{1.1.3}$: Learning ability of the employees. $C_{1.1.4}$: Employees' creative ability. $C_{1.1.5}$: Identification with corporate values.

$C_{1.2}$: Structural capital—$C_{1.2.1}$: Building of corporate culture. $C_{1.2.2}$: Employees' identification with company vision. $C_{1.2.3}$: Clarity of relationship among authority, responsibility and benefit. $C_{1.2.4}$: Corporate operating efficiency. $C_{1.2.5}$: Mutual support and cooperation among employees.

$C_{1.3}$: Relational capital—$C_{1.2.1}$: Investing in client relationships. $C_{1.2.2}$: Satisfying client needs. $C_{1.2.3}$: Discovering client needs. $C_{1.2.4}$: Coordination level with external parties (i.e., construction material vendors, subcontractors). $C_{1.2.5}$: Creating mutual trust with external parties.

$C_{2.1}$: Flows from human capital to structural capital—$C_{2.2.1}$: Conversion of individual knowledge into organizational knowledge. $C_{2.2.2}$: Contribution of recent recruitments in improving efficiency of construction operations. $C_{2.2.3}$: Sharing of employees' individual experiences from previous construction projects through out the firm. $C_{2.2.4}$: Returns from man-hours spent on developing cost estimation database.

$C_{2.2}$: Flows from structural capital to relational capital—$C_{2.2.1}$: Quality management program's effectiveness in reducing of clients' complaints. $C_{2.2.2}$: Contribution of the information technology based project management system in enhancing coordination with external parties. $C_{2.2.3}$: Efficiency and effectiveness of project management system in meeting clients' expectations.

$C_{2.3}$ Flows from human capital to relational capital—$C_{2.3.1}$: Returns from man-hours spent on client relationships. $C_{2.3.2}$: Returns from man-hours spent on relationships with external parties. $C_{2.3.3}$: Contribution of employees' personal networks in winning new construction contracts. $C_{2.3.4}$: Employees' personal networks in obtaining favorable deals with external parties.

$C_{2.4}$: Flows from relational capital to structural capital—$C_{2.4.1}$: Organizational learning captured from external parties. $C_{2.4.2}$: Dissemination of client feedback throughout the firm. $C_{2.4.3}$: Quality improvements based on feedback from external parties.

$C_{2.5}$: Flows from structural capital to human capital—$C_{2.5.1}$: Contribution of systems and procedures of the firm in improving employees' skills and education. $C_{2.5.2}$: Efficiency of systems and procedures of the firm in enhancing employees' morale and welfare. $C_{2.5.3}$: Contribution of systems and procedures of the firm in enhancing employees' creative ability.

$C_{2.6}$: Flows from relational capital to human capital—$C_{2.6.1}$: Employees' professional skill and capability development through relationship with external parties. $C_{2.6.2}$: Contribution of relationships with external parties in enhancing employees' personal social networks. $C_{2.6.3}$: Contribution of client relationships in enhancing employees' creative ability.

(5), into linear programming models in the form of Eqs. (13*a*) and (13*b*) in Appendix II and solving at two different α cuts ($\alpha = 0.00$, and 1.0). The FICI of ACF is (0.50, 0.74, 0.91) (Table 2). For possibility level $\alpha=0$, the intellectual capital of ACF ranges from 0.50 to 0.91. This range points out that the intellectual capital of the ACF would not be higher than 0.91 and lower than 0.50. It highlights the degree of uncertainty regarding the intellectual capital performance of the firm. For the possibility level $\alpha = 1.00$, the intellectual capital performance of ACF is 0.74. This represents the most possible value of intellectual capital for ACF.

The final stage is translating the FICI of ACF back to a linguistic label as FICI is a fuzzy expression. The natural language expression set for the labeling ICP of ACF and its corresponding membership functions were developed after a thorough discussion with the executives of the construction firm. The developed natural language expression set is ICP={very poor (VP), poor (P), moderate (M), good (G), very Good (VG)}. The triangular fuzzy numbers that correspond to the membership functions of this natural language set are shown in Fig. 2. The Euclidean distance (d) from FICI to the each member of the ICP set was calculated by using Eq. (6). $d(\text{FICI},\text{VP})=1.680$, $d(\text{FICI},\text{P})=1.680$, $d(\text{FICI},\text{M})=1.533$, $d(\underline{\text{FICI},\text{G}})=0.245$, and $d(\text{FICI},\text{VG})=1.418$. The linguistic term "good" has the smallest Euclidean distance to FICI. Therefore the intellectual capital performance of ACF can be labeled as good. Fig. 2 provides a visual evidence to this result. In addition to this result, the findings also reveal potential improvement areas. The fuzzy weighted average performance ratings of intellectual stocks (R_1) and flows (R_2) of ACF are (0.55, 0.78, 0.93) and (0.48, 0.71, 0.90), respectively (Table 2). The α-cut ranking method [Eq. (9)] suggests that the fuzzy weighted average performance rating of intellectual flows (R_2) is lower than the fuzzy weighted average performance rating of intellectual stocks (R_1) for $\alpha=0.00$ and 1.00. Yet the average fuzzy weight of intellectual flows ($W_2=0.57,0.77,0.90$) is higher than the average fuzzy weight of intellectual stocks ($W_1 =0.37,0.55,0.73$) for $\alpha=0.00$ and 1.00 (Table 2). Further, applying the α-cut ranking method [Eq. (6)] to average fuzzy weights of intellectual stocks suggests that flows from structural capital to human capital has the highest average fuzzy importance weight ($W_{2.1}$) but it has the second poorest average fuzzy performance rating ($R_{2.1}$). It appears that ACF is experiencing difficulties in transforming human capital into structural capital. These findings jointly indicate that ACF should focus on improving its capability to transform its intellectual stocks into intellectual flows in particular transforming human capital into structural capital.

Conclusions and Implications

There is increasing recognition that managing knowledge assets is a key skill for Architectural/engineering/construction (A/E/C) firms in today's business environment. A/E/C firms should develop or adopt models, tools, and techniques that can enable them to manage their primary source of competitive advantage: knowledge assets. The research presented here proposes a performance measurement model called FICI in order to address these issues. It builds on intellectual capital performance modeling and fuzzy set theory. The proposed model presents some advantages in comparison with previous intellectual capital performance models, as well as other performance measurement models set forth in the construction management literature. First, FICI combines intellectual stocks and interstock flows to evaluate a construction firm's intellectual capital assets whereas previous research in construction management solely focused on intellectual stocks by ignoring the presence and importance of interstock flows. Second, FICI is based on fuzzy set theory, a rare approach in this field of research. Most of the information used in the evaluation process of intellectual capital (i.e., the importance weights of each criterion in firm's long-term strategy and a firm's achievement level on each criterion) is imprecise, vague, and uncertain. Fuzzy set theory is a flexible tool that can adequately handle uncertainty, imprecision and vagueness. Therefore, FICI provides the flexibility and robustness needed by construction business executives to better un-

Table 2. Average Fuzzy Importance Weights and Ratings and Fuzzy-Weighted Average Ratings

Criteria			Average fuzzy importance weights			Fuzzy-weighted average ratings		Average fuzzy ratings
C_i	C_{ij}	C_{ijk}	W_i	W_{ij}	W_{ijk}	R_i	R_{ij}	R_{ijk}
C_1			0.37, 0.55, 0.73			0.55, 0.78, 0.93		
	$C_{1.1}$			0.47, 0.65, 0.83			0.60, 0.84, 0.96	
		$C_{1.1.1}$			0.53, 0.70, 0.87			0.73, 0.93, 1.00
		$C_{1.1.2}$			0.43, 0.62, 0.73			0.60, 0.80, 0.93
		$C_{1.1.3}$			0.50, 0.70, 0.90			0.40, 0.60, 0.80
		$C_{1.1.4}$			0.43, 0.60, 0.77			0.67, 0.87, 1.00
		$C_{1.1.5}$			0.40, 0.60, 0.80			0.80, 1.00, 1.00
	$C_{1.2}$			0.63, 0.82, 0.93			0.50, 0.71, 0.88	
		$C_{1.2.1}$			0.30, 0.50, 0.70			0.47, 0.67, 0.87
		$C_{1.2.2}$			0.50, 0.65, 0.80			0.53, 0.73, 0.93
		$C_{1.2.3}$			0.57, 0.75, 0.93			0.60, 0.80, 0.93
		$C_{1.2.4}$			0.70, 0.88, 0.93			0.47, 0.67, 0.80
		$C_{1.2.5}$			0.53, 0.70, 0.87			0.47, 0.67, 0.80
	$C_{1.3}$			0.53, 0.72, 0.83			0.58, 0.81, 0.94	
		$C_{1.3.1}$			0.27, 0.45, 0.63			0.47, 0.67, 0.87
		$C_{1.3.2}$			0.43, 0.60, 0.77			0.67, 0.87, 0.93
		$C_{1.3.3}$			0.53, 0.72, 0.83			0.73, 0.93, 1.00
		$C_{1.3.4}$			0.33, 0.50, 0.67			0.53, 0.73, 0.93
		$C_{1.3.5}$			0.23, 0.40, 0.57			0.53, 0.73, 0.87
C_2			0.57, 0.77, 0.90			0.48, 0.71, 0.89		
	$C_{2.1}$			0.57, 0.75, 0.93			0.47, 0.68, 0.86	
		$C_{2.1.1}$			0.47, 0.65, 0.83			0.53, 0.73, 0.93
		$C_{2.1.2}$			0.53, 0.70, 0.87			0.53, 0.73, 0.87
		$C_{2.1.3}$			0.63, 0.82, 0.93			0.40, 0.60, 0.80
		$C_{2.1.4}$			0.57, 0.77, 0.90			0.47, 0.67, 0.80
	$C_{2.2}$			0.37, 0.55, 0.73			0.44, 0.66, 0.84	
		$C_{2.2.1}$			0.50, 0.70, 0.90			0.60, 0.80, 0.93
		$C_{2.2.2}$			0.60, 0.77, 0.87			0.33, 0.53, 0.73
		$C_{2.2.3}$			0.47, 0.65, 0.83			0.47, 0.67, 0.80
	$C_{2.3}$			0.47, 0.65, 0.83			0.52, 0.76, 0.92	
		$C_{2.3.1}$			0.27, 0.45, 0.63			0.53, 0.73, 0.93
		$C_{2.3.2}$			0.27, 0.45, 0.63			0.73, 0.93, 1.00
		$C_{2.3.3}$			0.40, 0.60, 0.80			0.40, 0.60, 0.73
		$C_{2.3.4}$			0.50, 0.65, 0.80			0.60, 0.80, 0.93
	$C_{2.4}$			0.33, 0.50, 0.67			0.49, 0.72, 0.88	
		$C_{2.4.1}$			0.57, 0.77, 0.90			0.47, 0.67, 0.87
		$C_{2.4.2}$			0.53, 0.72, 0.83			0.80, 1.00, 1.00
		$C_{2.4.3}$			0.63, 0.82, 0.93			0.33, 0.53, 0.73
	$C_{2.5}$			0.50, 0.65, 0.80			0.53, 0.74, 0.91	
		$C_{2.5.1}$			0.53, 0.70, 0.87			0.47, 0.67, 0.80
		$C_{2.5.2}$			0.57, 0.75, 0.93			0.53, 0.73, 0.87
		$C_{2.5.3}$			0.73, 0.93, 1.00			0.60, 0.80, 1.00
	$C_{2.6}$			0.50, 0.70, 0.90				
		$C_{2.6.1}$			0.53, 0.70, 0.87			0.60, 0.80, 0.93
		$C_{2.6.2}$			0.67, 0.87, 1.00			0.67, 0.87, 1.00
		$C_{2.6.3}$			0.50, 0.70, 0.90		0.45, 0.70, 0.89	0.20, 0.40, 0.60

derstand interrelations between intellectual stocks and flows. Third, FICI provides more information about the ability of a construction firm to achieve its strategic objectives than previous models that use crisp values. The intellectual capital performance expressed by triangular fuzzy numbers provides information regarding to its not only the most possible but also lowest and highest values in a range defined by $\alpha = 0.00 - 1.00$. Further, inputs (i.e., importance weights and performance ratings) and output (i.e., intellectual capital performance) of FICI are represented by linguistic variables. The use of linguistic variables in the evaluation process facilitates communication because interpreting linguistic variables is easier than interpreting numerical variables.

FICI can be used by A/E/C firms as an internal performance measurement tool to evaluate their knowledge assets and in turn

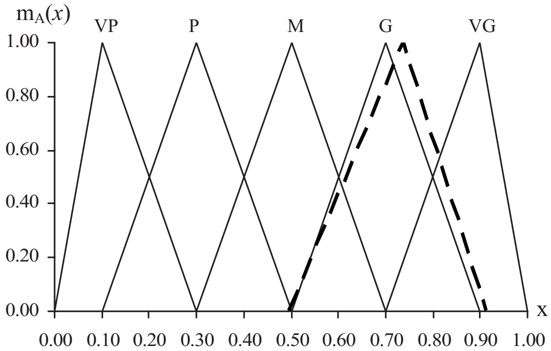

Fig. 2. Linguistic matching for intellectual capital performance

evaluate their ability to achieve their strategic objectives. FICI can be used in strategy formulation, implementation and control. The iterative process of identifying, rating and weighting intellectual capital criteria helps strategic leaders to understand which intellectual stocks and/or interstock flows are important and how intellectual stocks and/or interstocks flows are linked to their firm's long-term strategy. Therefore, FICI provides construction business executives with information that identifies their firm's strengths and weaknesses and allows them to neutralize threats and exploit opportunities presented by the current globalized and competitive environment. Further, FICI assists construction business executives in pinpointing those areas that need improvement in order to succeed in the future. Developing a computer program that can facilitate the implementation of FICI should be the focus of future research.

Appendix I. Basic Concepts of Fuzzy Set Theory

A fuzzy set is one which assigns grades of membership between 0 and 1 to objects within its universe of discourse (Zadeh 1965). If X is a universal set whose elements are $\{x\}$, then a fuzzy set A is defined by its membership function A: $X \in [0,1]$ which assigns to every x a degree of membership A in the interval [0,1].

A fuzzy number, on the other hand, is a convex normalized fuzzy set of the real line R whose membership function is piecewise continuous. It is a special fuzzy set $A=\{(x,\mu_A(x)), x \in R\}$, where x takes its values on the real line, R: $-\alpha < x < +\alpha$ and $\mu_F(x)$ is a continuous mapping from R to the closed interval [1,0]. A fuzzy number can be represented by any shape but the most commonly used shape is a triangle. A triangular fuzzy number is denoted by $A=(l,m,u)$ and has the following triangular membership function (Fig. 3):

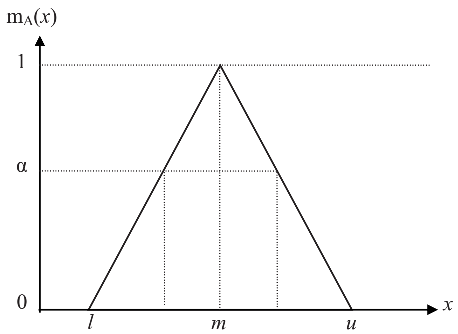

Fig. 3. Triangular membership function and the α cut of set for A

$$\mu_A(x) = \begin{cases} 0, & x \leqslant l \\ \dfrac{x-l}{m-l}, & l \leqslant x \leqslant m \\ \dfrac{l-x}{u-m}, & m \leqslant x \leqslant u \\ 0, & x > u \end{cases} \tag{7}$$

where m=most possible value of fuzzy number A, and l and u represent lower and upper bounds, respectively.

The α cut of a fuzzy number $A^\alpha=\{x \mid \mu_A(x) \geqslant \alpha\}$ $\alpha \in \{0,1\}$, is expressed as $(l^\alpha, m^\alpha, u^\alpha)$. The confidence interval of A^α α level can also be stated $A^\alpha[l^{(\alpha)}, u^{(\alpha)}]$. $l^{(\alpha)}$ and $u^{(\alpha)}$ represent lower and upper boundaries of confidence interval respectively (Fig. 3).

Arithmetic Operations on Triangular Fuzzy Numbers

Fuzzy arithmetic operations are based on two properties of fuzzy numbers (Klir and Yuan 1995): (1) each fuzzy number can be fully and uniquely represented by its family of α cuts and (2) α cuts of each fuzzy number are closed intervals of real numbers for all α [0,1]. It is these properties that enable researchers to define arithmetic operations on fuzzy numbers in terms of arithmetic operations on their α cuts. The basic arithmetic operations of two fuzzy triangular numbers $A=(l_1,m_1,u_1)$ and $B=(l_2,m_2,u_2)$ based on closed interval arithmetic are defined as follows (Klir and Yuan 1995):

$$A^\alpha \oplus B^\alpha = [l_1^{(\alpha)} + l_2^{(\alpha)}, u_1^{(\alpha)} + u_2^{(\alpha)}] \tag{8a}$$

$$A^\alpha \ominus B^\alpha = [l_1^{(\alpha)} - u_2^{(\alpha)}, u_1^{(\alpha)} - l_2^{(\alpha)}] \tag{8b}$$

$$A^\alpha \otimes B^\alpha = [l_1^{(\alpha)} * l_2^{(\alpha)}, u_1^{(\alpha)} * u_2^{(\alpha)}] \tag{8c}$$

$$A^\alpha \oslash B^\alpha = [l_1^{(\alpha)}/u_2^{(\alpha)}, u_1^{(\alpha)}/l_2^{(\alpha)}] \tag{8d}$$

where A^α and B^α represent the α cuts of the fuzzy numbers A and B, respectively, and ⊕, ⊖, ⊗, and ⊘ denote addition, subtraction, multiplication, and division operators for two intervals of confidence, respectively.

The basic method for ranking fuzzy numbers is the α-cut method. The ranking of fuzzy numbers should be based on a set of α cuts rather than a single α cut

$$A \leqslant B \quad \text{if } u_1^{(\alpha)} \leqslant u_2^{(\alpha)} \tag{9}$$

Appendix II. Fuzzy-Weighted Average

The algorithm proposed by Kao and Liu (2001) can be defined as follows: Denote the α cuts of the fuzzy importance weights W_i and fuzzy performance ratings R_i as

$$(W_i)\alpha = \{w_i \in W_i | f_{W_i}(w_i) \geqslant \alpha\} \tag{10a}$$

$$(R_i)\alpha = \{r_i \in R_i | f_{R_i}(w_i) \geqslant \alpha\} \tag{10b}$$

Using Zadeh's (1965) extension principle, the membership function of f_{FICI} of Fuzzy Intellectual Capital Index can be derived from the following equation:

$$f_{\mathrm{FICI}}(y) = \mathrm{sup.min.}\left\{ f_{W_i}(w_i), f_{R_i}(r_i), i = 1, \ldots, n \middle| \mathrm{FICI} = \sum_{i=1}^{n} w_i r_i \bigg/ \sum_{i=1}^{n} w_i \right\} \quad (11)$$

The lower and upper bounds of F-ICP at a specific α cut can be solved as

$$(\mathrm{FICI})_\alpha^L = \mathrm{min.FICI} = \sum_{i=1}^{n} w_i r_i \bigg/ \sum_{i=1}^{n} w_i$$

$$\mathrm{s.t.}(W_i)_\alpha^L \leqslant w_i \leqslant (W_i)_\alpha^U, \quad i = 1, \ldots, n \quad (12a)$$

$$(R_i)_\alpha^L \leqslant r_i \leqslant (R_i)_\alpha^U, \quad i = 1, \ldots, n$$

$$(\mathrm{FICI})_\alpha^U = \mathrm{max.FICI} = \sum_{i=1}^{n} w_i r_i \bigg/ \sum_{i=1}^{n} w_i$$

$$\mathrm{s.t.}(W_i)_\alpha^L \leqslant w_i \leqslant (W_i)_\alpha^U, \quad i = 1, \ldots, n$$

$$(R_i)_\alpha^L \leqslant r_i \leqslant (R_i)_\alpha^U, \quad i = 1, \ldots, n \quad (12b)$$

The minimum of FICI occurs at $(R_i)_\alpha^L$ and the maximum of FICI $(R_i)_\alpha^U$. Thus, the variable r_i in the objective function of can be replaced by $(R_i)_\alpha^L$ and $(R_i)_\alpha^U$, respectively, and the constraints $(R_i)_\alpha^L \leqslant r_i \leqslant (R_i)_\alpha^U$, i=1, …, n, can be eliminated. Using the Charnes and Cooper (1962) transformation method by letting $t = 1/\sum_{i=1}^{n} w_i$ and $v_i = tw_i$, Eqs. (12*a*) and (12*b*) can be transformed to the conventional linear program of the following form:

$$(\mathrm{FICI})_\alpha^L = \mathrm{min.FICI} = \sum_{i=1}^{n} v_i (R_i)_\alpha^L$$

$$\mathrm{s.t.}\ t(w_i)_\alpha^L \leqslant v_i \leqslant t(w_i)_\alpha^U, \quad i = 1, \ldots, n \quad (13a)$$

$$\sum_{i=1}^{n} v_i = 1$$

$$t, v_i \geqslant 0$$

$$(\mathrm{FICI})_\alpha^U = \mathrm{max.FICI} = \sum_{i=1}^{n} v_i (R_i)_\alpha^U$$

$$\mathrm{s.t.}\ t(w_i)_\alpha^L \leqslant v_i \leqslant t(w_i)_\alpha^U, \quad i = 1, \ldots, n \quad (13b)$$

$$\sum_{i=1}^{n} v_i = 1$$

$$t, v_i \geqslant 0$$

By enumerating different values α values, the membership function of FICI can be constructed.

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