Overview of the Application of "Fuzzy Techniques" in Construction Management Research

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Abstract: During the last decade, "fuzzy techniques" have been increasingly applied to the research area of construction management discipline. To date, however, no paper has attempted to summarize and present a critique of the existing "fuzzy" literature. This paper, therefore, aims to comprehensively review the fuzzy literature that has been published in eight selected top quality journals from 1996 to 2005, these being J*ournal of Construction Engineering and Management,* ASCE; *Journal of Management in Engineering,* ASCE; *Construction Management and Economics; Engineering, Construction and Architectural Management; International Journal of Project Management; Building Research and Information; Building and Environment; and Benchmarking: An International Journal.* It has been found that fuzzy research, as applied in construction management discipline in the past decade, can be divided into two broad fields, encompassing: (1) fuzzy set/fuzzy logic; and (2) hybrid fuzzy techniques, with the applications in four main categories, including: (1) decision making; (2) performance; (3) evaluation/assessment; and (4) modeling. The comprehensive review provided in this paper offers new directions for fuzzy research and its application in construction management. Based on a comprehensive literature review on the applications of fuzzy set/fuzzy logic, and hybrid fuzzy techniques in construction management research, an increasing trend of applying these techniques in construction management research is observed. Therefore, it is suggested that future research studies related to fuzzy techniques can be continuously applied to these four major categories. Fuzzy membership functions and linguistic variables in particular can be used to suit applications to solving problems encountered in the construction industry based on the nature of construction, which are widely regarded as complicated, full of uncertainties, and contingent on changing environments. Moreover, hybrid fuzzy techniques, such as neurofuzzy and fuzzy neural networks, can be more widely applied because they can better tackle some problems in construction that fuzzy set/fuzzy logic alone may not best suit. For example, neural networks are strong in pattern recognition and automatic learning while fuzzy set and fuzzy logic are strong in modeling certain uncertainties. Their combination can assist in developing models with uncertainty under some forms of pattern. Finally, an increasing trend of applying fuzzy techniques in the building science and environmental disciplines is also observed; it is believed that the application of fuzzy techniques will go beyond the construction management area into these disciplines as well.

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Introduction

The application of "fuzzy techniques" has been gaining popularity to the research area of construction management over the past decade. Fuzzy techniques, as defined in this paper, refer to all fuzzy concepts, which include fuzzy set, fuzzy logic, and hybrid fuzzy techniques (those that combining fuzzy set/fuzzy logic with other techniques), such as fuzzy neural network, neurofuzzy, fuzzy reasoning, fuzzy expert system, fuzzy analysis, and fuzzy clustering. To date, nevertheless, no paper has attempted to summarize and present a critique of the existing "fuzzy" literature. The aim of this paper is to provide an overview of the application of fuzzy techniques in construction management research that has been published in eight selected top quality journals (Chau 1997). In fact, fuzzy is widely accepted as a branch of modern mathematics when compared with traditional mathematics although its history has just over 40 years (Zimmermann 2001). Its origin can be tracked back when Zadeh (1965) wrote a seminal paper in 1965 in which he introduced fuzzy sets (sets with unsharp boundaries). These sets are in general in better agreement with the human mind because they work with shades of gray but not just black or white. Fuzzy sets are typically able to represent linguistic terms, for instance, warm, hot, high, and low. Table 1 records the most important events of the historical development of fuzzy techniques from 1965 to 1994. After 1994, fuzzy techniques are continuously applied to the research area of construction management.

The new millennium 2000 starts with over 30,000 publications in the area of "computational intelligence" or "soft computing" (Zimmermann 2001). These are terms which have been coined during the first half of the 1990s, when fuzzy set, neural networks and evolutionary computing joined forces because they felt that there were strong synergies between these areas. Zimmermann

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Table 1. Historical Development and Application of Fuzzy Theories from 1965 to 1994

Year	Main event
1965	Prof. L.A. Zadeh of U.C. Berkeley first published a paper on fuzzy sets in the *Information and Control Journal*. He was the first academic who addressed the fuzzy concepts concretely and mathematically.
1972	1. Prof. L.A. Zadeh proposed fuzzy control theory and approximation reasoning. 2. Prof. Chi Yeah Shou Long and Prof. Kwun Yeah Tao Fu of Yi Tung Kone University set up "Fuzzy System Association" in Japan.
1974	1. Prof. E.H. Mamdani of London University succeeded in applying Fuzzy Control Theory in steamed machine. He had successfully completed the first remote controller by using IF-THEN rule base and fuzzy theory, which was much better than the traditional PID remote controller. 2. The Fuzzy Set and Its Applications Conference was jointly organized by Japan and the United States. This was the first time to introduce the fuzzy theories to academics.
1977	Fuzzy theory was introduced in mainland China.
1980	The F.L. Smith Co. in Holland applied fuzzy theory to the automatic operation of cement making. This was the first commercialized product applying fuzzy theory.
1981	1. China established "China Fuzzy Mathematics and System Association." The members were mainly mathematicians who were specialized in conducting research in the fuzzy mathematics theories. By doing so, fuzzy theory was strengthened in the scope of mathematics. 2. China published *"Journal of Fuzzy Mathematics,"* the second journal on fuzzy theory. In 1987, it was renamed to *"Fuzzy System and Mathematics."* Since then, China took a leading role in fuzzy mathematics theories.
1982	Prof. C.L. Tang of Wah Chong Polytechnic proposed grey theory and grey hazy sets. He proved fuzzy set was a special instance of grey hazy sets. Since then, grey theory became vital and it was successfully applied to weather prediction, system modeling, decision making, and so on.
1984	The International Fuzzy Systems Association was set up and Prof. H.J. Zimmermann of Technical University of Berlin was elected to be the chairman. At the same time, four branches were set up in North America, Japan, Europe, and China.
1985	The first Fuzzy IFSA World Congress was held in Spain. There were a total of 290 researchers from 29 countries attending the congress. It is of interest to note that the conference papers were mainly related to theoretical foundations, but not practical applications.
1986	1. Japan set up "Japan Society of Fuzzy Theory and System (SOFT)." 2. Fuji electrical engineering, Fuji Facom and Tokyo Industry University had applied fuzzy control theory to manage the import of clear water system and they had got a very good result.
1987	1. The second Fuzzy IFSA World Congress was held in Tokyo. There were a total of 380 researchers from 25 countries attending the congress. There were a total of 250 conference papers and many of them were related to practical applications. 2. Japan first applied Fuzzy Control to successfully accomplish automatic driving systems.
1988	The first Neural Networks and Fuzzy Logic Applied Technical Conference were held in NASA.
1989	1. The third Fuzzy IFSA World Congress was held in Seattle, and there were numerous conference papers on practical applications. 2. The Laboratory for International Fuzzy Engineering Research was set up, which was mainly composed of industry practitioners, government officials, and academics. 3. The "China's Governmental Natural Science Funding Committee" funded 1,350 thousand RMB dollars to set up 35 tertiary schools and research organizations so as to investigate a research project entitled 'Fuzzy Message Management and Mechanical Intelligence,' which was led by Professor P.Z. Wang. 4. The China Productivity Centre set up a Fuzzy Group to introduce fuzzy techniques and advocate the fuzzy theories.
1991	The fourth Fuzzy IFSA World Congress was held in Belgium.
1993	1. An academic journal entitled *"IEEE Transaction on Fuzzy Systems"* was first published. 2. The fifth Fuzzy IFSA World Congress was held in South Korea. The themes of conference papers included control system, image processing, machine video, medical diagnosis, share prediction, synthetic assessment, management technology, and system research. 3. The First Asia Fuzzy Symposium was held in Singapore. 4. The first Fuzzy Theory and its Applications Conference was jointly organized by Tsing Wah University and Jiao Tong University.
1994	1. The Republic of China Fuzzy Association was set up. 2. The second Fuzzy Theory and its Applications Conference was held in Taiwan, which was jointly organized by Taiwan University and Taiwan Industrial Technical University. 3. The sixth Fuzzy IFSA World Congress was held in the United States. 4. "Fuzzy theories" were further developed prosperously.

Note: Source: Translated from Lin and Pang (1994); permission has been obtained for both print and online use from the authors.

(2001) further stated that evolutionary computing has its strength in optimization while neural nets are particularly strong in pattern recognition and automatic learning. Fuzzy set/fuzzy logic has its strength in modeling, interfacing humans with computers and modeling certain uncertainties. The Unite States, Japan, and mainland China are probably the most important nations to develop fuzzy theories and fuzzy technology. Lin and Pang (1994) asserted that although fuzzy techniques were originated in the United States, their developments and applications are both less intensive and extensive than in Japan, where fuzzy control is widely recognized and applied. In many consumer products like washing machines and cameras, fuzzy controllers are used in

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order to obtain higher machine IQ and user-friendly products. Its use is also extended to other fields, including control of subway systems, image stabilization of video cameras, and autonomous control of helicopters. However, unlike Japan and the United States, fuzzy set and fuzzy logic are further developed by mathematicians in mainland China. The major achievements include the developments of: (1) molecule lattice theory; (2) fuzzy normed linear space; (3) fuzzy topolopy; (4) fuzzy measure and fuzzy integral; (5) fuzzy sets and fallowing shadow of random sets theory; (6) factor space theory; and (7) truth-valued-flows inference (Lin and Pang 1994).

"Fuzzy" Definitions

Fuzzy means blurred, indistinct in shape or outline, frayed or fluffy (Oxford University 1993). In modern mathematical society, fuzzy is defined as a branch of modern mathematics that was formulated by Zadeh (1965) to model vagueness intrinsic in human cognitive process and to solve ill-defined and complicated problems because of ambiguous, incomplete, vague, and imprecise information that characterize the real-world system. It is appropriate for uncertain or approximate reasoning that involves human intuitive thinking (Zimmermann 2001) because much of our natural language is fuzzy in nature, for example, it was "very hot" yesterday; 100 is "much larger" than 10; I "like" watching TV; you drive "too fast," please keep it "slower;" and he is not too "old."

It is generally accepted that two fundamental fuzzy concepts are: (1) fuzzy set; and (2) fuzzy logic. Fuzzy set uses linguistic variables and membership functions with varying grades to model uncertainty inherent in natural language (Zimmermann 2001). Fuzzy relation can be defined as more or less vague relationships between some fixed numbers of objects, and it can formally be treated like fuzzy sets (Bandemer and Gottwald 1995). Fuzzy logic is a superset of Boolean conventional logic that has been expanded to handle the concept of partial truth and true values between "completely true" and "completely false" (Zimmermann 2001). Fuzzy control can be defined as the application of fuzzy logic (Lin and Pang 1994). In general, the design and setting of fuzzy controllers consist of defining three parameters, including: (1) defining the domain for the input and output of linguistic variables for each fuzzy controller; (2) defining the set and the type of membership function for each linguistic value-input of every fuzzy controller. The relations between inputs and outputs of linguistic values have to be provided in the form of fuzzy rules, which represent logical inference; and (3) defining the fuzzy logic operators for each IF-THEN sentence, as a base for final inference (Lah et al. 2005).

Two Fundamental "Fuzzy Concepts" Applications in Construction Management Research

Two fundamental "fuzzy concepts," including fuzzy set and fuzzy logic, are extensively applied in construction management research. It should be noted that fuzzy set is the basis of fuzzy logic and they are highly associated with each other in that fuzzy logic is a reasoning system that uses fuzzy sets. In fact, both fuzzy set and fuzzy logic are intended to deal with a different type of uncertainty than probability theory, that of vagueness and imprecision. Since these two concepts are increasingly applied to construction management discipline, they are described in the following subsections in greater detail, and their applications in construction management research will be further discussed after the section "Fuzzy Research in the Past."

Fuzzy Set

As mentioned before, fuzzy set theory (FST) is a branch of modern mathematics that was formulated by Zadeh (1965) to model vagueness intrinsic in human cognitive process. Since then, it has been used to tackle ill-defined and complex problems due to incomplete and imprecise information that characterize the real-world systems (Baloi and Price 2003). In fact, Zadeh stated that when the complexity of a system increases, the ability for human beings to make precise but significant statements about their behavior diminishes. This will continue to happen until a threshold is reached beyond which precision and significance becomes mutually exclusive—the principle of incompatibility. Therefore, it follows that modeling complex or ill-defined systems cannot be made precisely. However, FST was not intended to replace probability theory, but rather to provide solutions to problems that lack mathematical rigor inherent to probability theory (Baloi and Price 2003). FST is an extension of the classical Boolean or binary logic. The main problem with binary approach is that it fails to convey information effectively, that is, the states between full and nonmembership are ignored but they are very vital. Meanwhile, most real-world systems are extremely complicated and ill defined.

In contrast to binary or dual logic, the essence of fuzziness is that the transition from a membership to nonmembership state of an element of a set is gradual rather than abrupt (Baloi and Price 2003). Thus, FST allows a generalization of the classical set concept to model complex and ill-defined systems. The main concepts associated with FST as applied to decision systems are: (1) membership functions; (2) linguistic variable; (3) natural language computation; (4) linguistic approximation; (5) fuzzy set arithmetic operations; (6) set operations; and (7) fuzzy weighted average (Zimmermann 2001; Bandemer and Gottwald 1995; Baloi and Price 2003; Jamshidi 1997; Grima 2000; Piegat 2001; Ng et al. 2002; Seo et al. 2004; Zheng and Ng 2005). It is observed that linguistic variable and membership functions are much more widely applied in construction management discipline. And the membership functions applied are always triangular and trapezoidal shapes (Fayek and Oduba 2005).

Fuzzy Logic

Fuzzy logic is a superset of Boolean-conventional logic that has been extended to handle the concept of partial truth and truth values between completely true and "completed false" (Zadeh 1965; Lin and Pang 1994; Lah et al. 2005). Fuzzy logic should be seen as a data analysis methodology to generalize any specific theory from "crisp" to "continuous." Fuzzy modeling opens the possibility for straightforward translation of the statements in natural language—verbal formulation of the observed problem—into a fuzzy system. Its functioning is based on mathematical tools. The basic operations of the set theory are intersection, union, and complement extended for the purpose of fuzzy logic.

Research Methodology

The research method used for this paper was to launch a comprehensive review of the related literature from 1996 to 2005.

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Table 2. Summary of Literature Review on the Applications of Fuzzy Set/Fuzzy Logic and Hybrid Fuzzy Techniques in Construction Management Research over the Last Decade

	Decision making	Performance	Evaluation/ assessment	Modeling	Total
Fuzzy set	9	6	4	4	23
Fuzzy logic	1	2	5	0	8
Hybrid fuzzy techniques	5	6	4	6	21
Total	15	14	13	10	52

The selection of literature was mainly based on the top quality journals in construction management and other related fields, which include: (1) *Journal of Construction Engineering and Management, ASCE*; (2) *Journal of Management in Engineering, ASCE*; (3) *Construction Management and Economics*; (4) *Engineering, Construction and Architectural Management*; (5) *International Journal of Project Management*; (6) *Building Research and Information*; (7) *Building and Environment*; and (8) *Benchmarking: An International Journal*. In fact, with reference to a research study on journal ranking in construction management conducted by Chau (1997), the first six journals were assessed by respondents to have very high rankings among 22 relevant journal assessed. And the last two journals are widely perceived by academics to be first tier journals in construction related areas. Keywords for "searching" were "fuzzy set," "fuzzy logic," "fuzzy control," and other hybrid fuzzy techniques. These terms were well known of having been used in writing papers on fuzzy techniques. The procedures for retrieving the fuzzy papers are as follows:

- The titles of the articles were scanned with the keywords. Altogether, there were 59 articles that contained one of the keywords in their articles' titles, which are either "genuine fuzzy" papers or closely related papers.
- Seven articles were taken out as they were not in the context of construction management.

Metaanalysis is a statistical technique for combining the research findings from independent studies. The essential character of metaanalysis is that it is the statistical analysis of the summary findings of many empirical studies (Glass et al. 1981). It can be understood as a form of survey research in which research reports, rather than people, are surveyed. A coding form is developed, a sample or population of research reports is gathered, and each research study is "interviewed" by a coder who reads it carefully and codes the suitable information about its characteristics and quantitative findings (Lipsey and Wilson 2001). Since the aim of this research study is to summarize and present a critique of the existing fuzzy literature so as to investigate which major categories fuzzy techniques are strong to analyze and provide a path for future research studies on some areas, content analysis, instead of metaanalysis, was deployed in this research study because it was not aimed at conducting statistical analysis by combining the research findings from a number of independent empirical research studies.

By using the content analysis method in this research study, four major categories of applications have been grouped under two broad fields. The two broad fields are: (1) fuzzy set/fuzzy logic; and (2) hybrid fuzzy techniques. The four major categories are: (1) decision making; (2) performance; (3) evaluation/assessment; and (4) modeling. The four major classifications of the area of application is mainly based on analyzing the contents of paper (with particular reference to paper title, abstract, and keywords) using the content analysis technique. The results show that 15 papers can be classified under "decision making;" 14 papers under "performance;" 13 papers under "evaluation/assessment;" and 10 papers under "modeling." Content analysis is frequently adopted to determine the major facets of a set of data, by simply counting the number of times an activity happens, or a topic is depicted (Fellows and Liu 2008). The first step to conduct content analysis is to identify the materials to be analyzed. The second step is to determine the form of content analysis to be used, which includes qualitative, quantitative, or structural. The choice is dependent on the nature of the research project. The choice of categories will also depend upon the issues to be addressed in the research if they are known. In qualitative content analysis, emphasis is on determining the meaning of the data (i.e., grouping data into categories). Quantitative content analysis extends the approach of the qualitative form to generate numerical values of the categorized data (frequencies, ratings, ranking, etc.) which may be subjected to statistical analyses. Comparisons can be made and hierarchies of categories can be examined (Fellows and Liu 2008).

"Fuzzy" Research in the Past

Table 2 shows that fuzzy research in construction management during the past decade can be divided into two broad fields, encompassing (1) Fuzzy set/fuzzy logic (since most applications involve some form of the logic theory) and (2) hybrid fuzzy techniques (those that combine fuzzy logic with other techniques, such as fuzzy neural network, neurofuzzy, fuzzy reasoning, fuzzy expert systems, fuzzy analysis, and fuzzy clustering), with the applications in four main categories, including (1) decision making; (2) performance; (3) evaluation/assessment; and (4) modeling.

"Fuzzy Set/Fuzzy Logic" Applications in Construction Management Research

Table 3 shows that 31 journal papers have applied fuzzy set/fuzzy logic in construction management research and their areas of application. Grouping these applications into related headings, they can be classified into four categories, namely, (1) decision making; (2) performance; (3) evaluation/assessment; and (4) modeling.

Fuzzy Set Applications in Decision-Making

Singh and Tong (2005) stated that contractor selection in a multicriteria environment is largely dependent upon the uncertainty inherent in the nature of construction projects and subjective judgment of decision makers. For this reason, they used a systematic procedure, based on FST, to evaluate the capability of a con-

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Table 3. Applications of Fuzzy Set/Fuzzy Logic in Construction Management Research

Number	Journal name	Writer(s)	Theory/concept	Field/application	Relevance/classification
1	JCEM	Singh, D., and Tiong, R.L.K. (2005)	Fuzzy sets	Contractor selection	Decision making; performance evaluation
2	JCEM	Seo, S., Aramaki, T., Hwang, Y., and Hanaki, K. (2004)	FST	Environmental sustainable buildings	Decision making; assessment
3	JCEM	Tam, C.M., Tong, T.K.L., Leung, A.W.T., and Chiu, G.W.C. (2002b)	Fuzzy sets	Site preparation	Decision making
4	JCEM	Fayek, A. (1998)	FST	Competitive bidding strategy	Decision making; assessment
5	CME	Wang, R.C., and Liang, T.F. (2004)	Fuzzy sets theory	Project management decisions	Decision making
6	CME	Zhang, H., and Tam, C.M. (2003)	Fuzzy sets	Dynamic resource allocation	Decision making
7	CME	Li, H., and Shen, Q. (2002)	FST	Sustainable housing	Decision making
8	CME	Ng, S.T., Luu, D.T., Chen, SE, and Lam, K.C. (2002)	FST	Procurement selection criteria	Decision making
9	IJPM	Wang, W., Hawwash, K.I.M., and Perry, J.G. (1996)	FST	Contract type selector	Decision making
10	IJPM	Lin, C.T., and Chen, Y.T. (2004)	Fuzzy logic	Bid/no-bid decision making	Decision making
11	JCEM	Zheng, D.X.M., and Ng, S.T. (2005)	Fuzzy sets theory	Project management; risk management; productivity	Time and cost performance
12	JCEM	Bonnal, P., Gourc, D., and Lacoste, G. (2004)	Fuzzy sets	Project scheduling	Time performance
13	JCEM	Lorterapong, P., and Moselhi, O. (1996)	Fuzzy sets theory	Project network analysis	Time performance
14	CME	Kishk, M. (2003)	FST	Whole-life costing	Cost performance
15	ECAM	Zhang, H., Li, H., and Tam, C.M. (2004)	FST; fuzzy logic	Activity duration	Time performance
16	IJPM	Baloi, D., and Price, A.D.F. (2003)	FST	Risk management	Performance
17	JCEM	Oliveros, A.V.O., and Fayek, A.R. (2005)	Fuzzy logic	Project management; activity delay analysis	Time performance
18	JCEM	Knight, K., and Fayek, A.R. (2002)	Fuzzy logic	Cost control; project management	Cost performance; decision making
19	CME	Okoroh, M.I., and Torrance, V.B. (1999)	FST ; fuzzy logic	Subcontractor selection	Modeling
20	IJPM	Wei, C.C., and Wang, M.J.J. (2004)	FST	Selection of ERP system	Modeling
21	IJPM	Tseng, T.L., Huang, C.C., Chu, H.W., and Gung, R.R. (2004)	Fuzzy sets theory	Multi-functional project team formation	Modeling
22	IJPM	Leu, S.S., Chen, A.T., and Yang, C.H. (2001)	FST	Construction time-cost trade-off	Modeling
23	JCEM	Choi, H.H., Cho, H.N., and Seo, J.W. (2004)	Fuzzy sets	Risk assessment	Assessment
24	JME	Sánchez, M., Prats, F., Agell, N., and Ormazabal, G. (2005)	Fuzzy sets	Value management	Evaluation; decision making
25	ECAM	Kumar, V.S.S., Hanna, A.S., and Adams, T. (2000)	FST	Assessment of working capital requirement	Assessment
26	IJPM	Holt, G.D. (1998)	FST	Contractor selection	Evaluation
27	JCEM	Zayed, T.M., and Halpin, D.W. (2004)	Fuzzy logic	Productivity	Quantitative assessment (performance)
28	JCEM	Chao, L.C., and Skibniewski, M. (1998)	Fuzzy logic	Construction technology	Evaluation
29	CME	Tah, J.H.M., and Carr, V. (2000)	Fuzzy logic	Construction project risk assessment	Assessment
30	ECAM	Shang, H., Anumba, C.J., Bouchlaghem, D.M., and Miles, J.C. (2005)	Fuzzy logic	Intelligent risk assessment system	Assessment
31	BIJ	Ma, H., Deng, Z., and Solvang, W.D. (2004)	Fuzzy logic	Distributor benchmarking	Benchmarking/ assessment

Note: JCEM=*Journal of Construction Engineering and Management*, ASCE; CME=*Construction Management and Economics*; IJPM=*International Journal of Project Management*; JME=*Journal of Management in Engineering*, ASCE; ECAM=*Engineering, Construction and Architectural Management*; and BIJ=*Benchmarking: An International Journal*.

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tractor to deliver the project as per the owner's requirements. The notion of Shapley value was used to determine the global value or relative importance of each criterion in accomplishing the overall objective of the decision-making process. Seo et al. (2004) attempted several alternatives to obtain the sustainable residential buildings based on the acceptable level of environmental impact and socioeconomic characteristics of residential building. However, these criteria are in conflict with each other. Therefore, it is very difficult to assess the sustainable residential buildings. To solve this problem, Seo et al. (2004) adopted a methodology, which is based on FST, to assess a residential building that is intended to assist the decision making for the building planners or industrial practitioners.

Site layout planning can affect productivity and is crucial to project success (Tam et al. 2002a). Nevertheless, since construction is heterogeneous in the nature of its organizations, project designs, and time constraints. Site layout planning for each project becomes unique (Tam et al. 2002a). Therefore, site layout planning is a typical multiobjective problem because it is affected by many uncertainties and variations. In order to facilitate the decision-making process for these problems, Tam et al. (2002a) proposed a nonstructural fuzzy decision support system (NS-FDSS), which was based on FST. This system integrates both expert's judgment and computer decision modeling, thus making it suitable for the appraisal of complex construction problems. Fayek (1998) developed a competitive bidding strategy model by using FST to help a company achieve its objectives in bidding. He stated that the use of FST allows assessments to be made in qualitative and approximate terms, which suit the subjective nature of the margin-size decision. He concluded that the competitive bidding strategy model can improve the quality of the decision-making process used in setting a margin and can help contractors gain a competitive edge in bidding. Wang and Liang (2004) pointed out that project managers have to handle conflicting goals that govern the use of the resources within organizations in the real world. These conflicting goals are required to be optimized by the project managers in the framework of fuzzy aspiration levels. Wang and Liang (2004) then proposed the multiple fuzzy goals programming model based on fuzzy sets in order to help project managers minimize project total costs, total completion time, and total crashing costs. They believed that the proposed model can provide a systematic decision-making framework, thus enabling a decision maker to interactively modify the fuzzy data and model parameters until a satisfactory solution is generated.

Timely resource allocation is vital to avoid unnecessary waiting time of resources and delay of activities for construction activities. Zhang and Tam (2003) opined that timely resource allocation is a dynamic decision-making process dependent on real-time information during a construction process. Having considered operational and stochastic characteristics of construction operations and the fuzziness of multiple-decision objectives for an appropriate allocation policy, Zhang and Tam (2003) developed a fuzzy dynamic resource allocation based on fuzzy set/fuzzy logic and the fuzzy decision-making approach. They explained that this model can finally help improve construction productivity by making the best use of resource allocation. Li and Shen (2002) introduced a conceptual approach in developing a decision support tool for sustainable housing, and they illustrated an empirical decision support model for sustainable housing indicators using FST.

Ng et al. (2002) pointed out that many procurement selection models fail to address the fuzziness of selection criteria used for procurement selection. To tackle this problem, they used a modified horizontal approach to establish the fuzzy membership function of procurement selection criteria through an empirical study conducted in Australia. Wang et al. (1996) investigated the possibility of developing a knowledge-based system to assist in choosing an appropriate contract strategy for a specific project. Fuzzy sets have been used for knowledge representation and manipulation and dBASE has been used to manage the database.

Fuzzy Logic Applications in Decision Making

Lin and Chen (2004) studied bid/no-bid decision making and stated that they were associated with uncertainty and complexity. They adopted a fuzzy logic approach because subjective considerations, such as nature, competition, value of the bid opportunity, resource capabilities, and the reputation of the company are relevant to the bid/no-bid decision. By using this approach, assessments were described subjectively in linguistic terms while screening criteria were weighted by their corresponding level of importance using fuzzy logic and fuzzy values. A practical example proved that this method could provide the analyst with more convincing and reliable results and cost saving for a company.

Fuzzy Set Applications in Performance

Zheng and Ng (2005) opined that the duration and cost of each construction activity could change dynamically as a result of many uncertain variables, such as productivity, resource availability, and weather. Project managers have to take these uncertainties into account so as to provide an optimal balance of time and cost, based on their own knowledge and experience. For this reason, FST was applied to model the managers' behavior in predicting time and cost pertinent to a specific option within a construction activity. Zheng and Ng (2005) believed that by incorporating the concept of fuzzy sets, managers and planners can represent the range of possible time-cost values and their associated degree of belief. They claimed that this model can support decision makers in analyzing their time-cost optimization decision in a more flexible and realistic manner. Bonnal et al. (2004) pointed out that stochastic project-scheduling approaches are used by many project schedulers. However, the axiom associated with the theory of probabilities is always incompatible with decision-making situations. They analyzed that fuzzy project-scheduling approaches are most suited to fuzzy situations, and they proposed a framework, which was based on fuzzy sets, to address the resource-constrained fuzzy project-scheduling problem. Lorterapong and Moselhi (1996) presented a new network scheduling method based on FST to estimate the durations of construction activities. The proposed method incorporated a number of new techniques that facilitate: (1) the representation of imprecise activity durations; (2) the calculation of scheduling parameters; and (3) the interpretation of the fuzzy results generated.

Zhang et al. (2004) observed that it is always problematic to define uncertain information input for construction-oriented discrete-event simulation. Therefore, they proposed incorporating FST with discrete-event simulation to handle the vagueness, imprecision, and subjectivity in the estimation of activity duration, particularly when insufficient or no sample data are available. Based on an improved activity scanning simulation algorithm, a fuzzy distance ranking measure was used in fuzzy simulation time advancement and event selection for simulation experimentation. Baloi and Price (2003) discussed the core issues of global risk factors' modeling, assessment, and management. Their prelimi-

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nary indications showed that FST is a viable technology for modeling, assessing, and managing global risk factors that affect construction cost performance and therefore a fuzzy decision framework for risk management can be successfully developed. Kishk (2004) developed a practical procedure to handle statistically significant data and expert evaluations within the same whole-life costing model calculation. The proposed model was implemented into a computational algorithm using probability distribution function or fuzzy numbers in a manner consistent with the nature of the information in hand.

Fuzzy Logic Applications in Performance

Oliveros and Fayek (2005) developed a fuzzy logic model that integrates daily site reporting of activity progress and delays, with a schedule updating and forecasting system for construction project monitoring and control. This model can help with the analysis of the effects of delays on a project's completion date because the use of fuzzy logic allows linguistic and subjective assessments to be made, and thereby suiting the actual practices commonly used in the construction industry.

Knight and Fayek (2002) used fuzzy logic to predict potential cost overruns on engineering design projects. By doing so, it assists in assessing the amount of possible risk on a project and the likelihood of making a profit on the job. In particular, the research used fuzzy logic to model the relationships between the characteristics of a project and the potential risk events that may occur, and the associated cost overruns caused by combinations of the project characteristics and risk events.

Fuzzy Set Applications in Evaluation/Assessment

Choi et al. (2004) presented a risk assessment methodology for underground construction projects, in which they developed a formalized procedure and associated tools to evaluate and manage the risks involved in underground construction. The main tool of the proposed risk assessment methodology is the risk analysis software and this software is built upon an uncertainty model based on fuzzy set. In more detail, the fuzzy-based uncertainty model was designed to consider the uncertainty range that represented the degree of uncertainties involved in both probabilistic parameter estimates and subjective judgments.

Holt (1998) pointed out that the need for judicious construction contractor selection is increasing. For this reason, he reviewed a number of contractor evaluation and selection modeling methods. The methods include: (1) bespoke approaches; (2) multiattribute analysis; (3) multiattribute utility theory; (4) cluster analysis; (5) multiple regression; (6) FST; and (7) multivariate discriminant analysis. The merits and demerits as well as previous and future applications of each methodology were discussed.

Kumar et al. (2000) asserted that the assessment of working capital requirement in construction projects was subjective and based on uncertainty. There is an inherent difficulty in the classical approach to assess the effect of qualitative factors for the evaluation of working capital requirement. Kumar et al. (2000) developed a methodology to incorporate linguistic variables into workable mathematical propositions for the assessment of working capital using FST after considering the uncertainty associated with many of the project resource variables. Sánchez et al. (2005) developed a fuzzy set-based approach for representing and synthesizing information about the various kinds of variables involved in the evaluation of a project's value in the context of construction in civil engineering. This methodology for summarizing and normalizing values aims at contributing to decision-making analysis in the context of multiple-criteria evaluation and group decision making.

Fuzzy Logic Applications in Evaluation/Assessment

Zayed and Halpin (2004) viewed that in the piling process, both qualitative and quantitative factors have to be considered so as to estimate productivity efficiently. To assess the effect of subjective factors on bored pile construction productivity, Zayed and Halpin (2004) developed a productivity index model mainly based on fuzzy logic to represent the subjective effect in refining productivity assessment using simulation and deterministic techniques. Chao and Skibniewski (1998) presented a fuzzy-logic-based, risk-incorporating approach to evaluate new construction technology. Experimental results indicate that the approach can produce a consistent evaluation of the available options, based on a set of user-defined linguistic rules that state the priorities in a given project scenario.

Tah and Carr (2000) used a hierarchical risk breakdown structure representation to develop a formal model for qualitative risk assessment. To do so, a common language for describing risks was first presented, which included terms for quantifying likelihoods and impacts in order to achieve consistent quantification. The relationships between risk factors, risks, and their consequences are represented on cause and effect diagrams through the application of fuzzy logic, and the concepts of fuzzy association and fuzzy composition. Shang et al. (2005) developed an innovative risk assessment approach for distributing project teams. The approach was based on a client and server architecture and used fuzzy logic and web-based technology. It was found that the use of a web-based risk assessment system for distributing project team members had major benefits in terms of use of linguistic terms to express risk assessment, ease of communication, ease of maintenance, and greater consistency.

Ma et al. (2004) mentioned that when an enterprise intends to design its distribution chain, it first needs to assess all possible distributors, and then select the eligible ones to form the design model. In fact, this assessing process can be done by distributor benchmarking by the following three steps. The first step is to identify all factors needed for benchmarking a distributor by a systematic analysis. The second step is to develop an internet-based information acquisition module to get all needed information from possible distributors. The third step is to develop an inference module, based on the combination of fuzzy logic and array-based logic, to benchmark a distributor.

Fuzzy Set Applications in Modeling

Okoroh and Torrance (1999) developed a subcontractor selection and appointment model for analyzing the subcontractor's risk elements in construction refurbishment projects. The model is based on the use of FST with the fuzzy set representing the overall weighted average rating of refurbishment contractors' criterion for the selection of subcontractors. It was believed that the implementation of the model in linguistic terms enables the user to interact with the system in a very friendly manner using natural language expressions.

Wei and Wang (2004) developed a comprehensive framework, which combined objective data obtained both from external professional report and subjective data derived from internal interviews with vendors, to select an appropriate Enterprise Resource Planning (ERP) project. By doing so, a hierarchical attribute

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structure was suggested to evaluate the ERP projects systematically. In addition, FST was adopted to aggregate the linguistic evaluation descriptions and weights.

Tseng et al. (2004) defined "a multifunctional team" in the e-world as a group of people from various functional departments or different areas of work responsibility to work together and exchange information through networks. In fact, multifunctional teams are becoming more and more important because organizations often require group cooperation across functional lines and the members may not be in the same location. However, the literature did not provide any analytical solutions for forming multifunctional teams under uncertain information environment. In order to handle the underlying complexities of the multifunctional teams' formation process, Tseng et al. (2004) developed a methodology based on FST and grey decision theory for the multifunctional team formation. FST was applied to deal with problems involving ambiguities, which were normally confronted in multifunctional teams' formation practice and formed groups, when there was no clear boundary for relationship between customers' requirements and project characteristics. Grey decision theory was used to select desired team members through abstract information. It was concluded that the application of the fuzzy and gray approaches demonstrated its capability of forming a good multifunctional team and it was promising to deal with insufficient information at the team forming stage (Tseng et al. 2004). It is understandable that construction activity duration is uncertain due to variations in the outside environment, such as weather, site congestion and productivity level. Because of different resource utilization, construction activity duration might need to be adjusted and the project direct cost could also be changed accordingly. Leu et al. (2001) proposed a new optimal construction time-cost trade-off model in which the effects of both uncertain activity duration and time-cost trade-off were taken into consideration. FST was adopted to model the uncertainties of activity durations. A searching technique using genetic algorithm (GA) was used to search for the optimal construction project time-cost trade-off profiles under different risk levels. This method provided an insight into the optimal balance of time and cost under various risk levels as defined by decision makers.

It should be emphasized that the proposed classification systems are by no means mutually exclusive. Some papers can be grouped in more than one category. For example, the Okoroh and Torrance (1999) paper could also be grouped under the decision making section. However, the writers opined that the focus of this paper is more on model development; therefore, it was put under the grouping of modeling.

"Hybrid Fuzzy Techniques" Applications in Construction Management Research

Table 4 shows that 21 journal papers have applied hybrid fuzzy techniques in construction management research. Their applications can be classified into the same four categories, namely, (1) decision making; (2) performance; (3) evaluation/assessment; and (4) modeling.

Hybrid Fuzzy Techniques in Decision Making

Lam et al. (2005) conducted a study on construction site layout planning and discovered that the actual closeness of relationships between site facilities ultimately governed the site layout. They had applied two modern mathematical approaches, GA and fuzzy logic, to minimize the uncertainty and vagueness of the collected data and improve the quality of the information. Lam et al. (2001b) developed a methodical system for construction project management decision making by using a combination of fuzzy multiple-objective decision-making theory and the fuzzy reasoning technique in order to solve most real-world decision-making problems that combine both qualitative and quantitative concepts. The model developed can be applied to construction project management problems by suggesting an optimal path of corporate cash flow that results in the minimum use of resources. Wong et al. (2000) explained that by incorporating fuzzy analysis into multiattribute utility theory, project selection problems can be dealt with when some project attributes are subject to random variations. The aggregate utility function for an individual project is derived as a fuzzy number (or interval) which, in turn, yields probabilistic information for stochastic dominance tests. A unique feature of the approach is that it dispenses with the task of selecting probability distributions for aggregate utility function.

Boussabaine and Elhag (1999) stated that fuzzy models are particularly suited to making decisions involving new technologies where uncertainties inherent in the complex situations. Based on an assumption that cash flow at particular valuation stages of a project is ambiguous, they used an innovative fuzzy cash flow analysis to analyze the cash flow curve of projects at any progress period to make sure that it is reasonable. Lam and Runeson (1999) established a decision model for a contracting firm. The model provided a methodical system for construction financial decision making and a way of solving a financial decision problem under qualitative and fuzzy circumstances. The model can be applied to the management of corporate cash flow, thereby facilitating the minimal use of resources. The information provided by the model also allows the planner to eliminate excess use or idleness of resources during the scheduling of a project.

Hybrid Fuzzy Techniques in Performance

Fayek and Oduba (2005) applied fuzzy logic and fuzzy expert systems to predict the labor productivity of two common industrial construction activities, that is, rigging pipe and welding pipe, given the realistic constraints of subjective assessments, multiple contributing factors, and limitations on data sets. Liu and Ling (2005) considered that it is difficult to estimate a contractor's markup because the construction environment is changeable and uncertain. In a study, they constructed a fuzzy logic-based artificial neural network (ANN) model to assist contractors in making markup decision. By integrating the fuzzy logic inference system, this model provides users with a clear explanation to justify the rationality of the estimated markup output. Marzouk and Moselhi (2004) adopted a two-step fuzzy clustering method to estimate haulers' travel time, and the method provided a generic tool that could be incorporated in models dedicated for estimating earthmoving production. The developed method used linear regression and fuzzy subtractive clustering in which seven factors affecting haulers' travel time were first identified and their significance were then quantified using linear regression. Portas and AbouRizk (1997) developed an approach by using a three-layered network with a fuzzy output structure to estimate construction productivity for concrete formwork tasks. It was found that this structure provided the most suitable model since much of the input was subjective. Boussabaine (2001a,b) developed an understanding of neurofuzzy concept modeling techniques and demonstrated the power and versatility of neurofuzzy methods when applied to the determination of construction project duration.

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Table 4. Applications of Hybrid Fuzzy Techniques in Construction Management Research

Number	Journal name	Writer(s)	Theory/concept	Field/application	Relevance/classification
1	CME	Lam, K.C., Tang, C.M., and Lee, W.C. (2005)	GA with fuzzy logic	Construction site layout planning	Decision making
2	CME	Lam, K.C., So, A.T.P., Ng, T., Yuen, R.K.K., Lo, S.M., Cheung, S.O., and Yang, H. (2001b)	Fuzzy reasoning	Construction project management	Decision making
3	CME	Wong, E.T.T., Norman, G., and Flanagan, R. (2000)	Fuzzy analysis	Project selection	Decision making
4	CME	Boussabaine, A.H., and Elhag, T. (1999)	Fuzzy techniques	Cash flow analysis	Decision making
5	CME	Lam, K.C., and Runeson, G. (1999)	Fuzzy concepts	Financial decisions	Decision making
6	JCEM	Fayek, A.R., and Oduba, A. (2005)	Fuzzy expert systems with fuzzy logic	Construction labor productivity	Productivity performance
7	JCEM	Liu, M., and Ling, Y.Y. (2005)	Fuzzy neural network	Contractor's markup estimation	Cost performance
8	JCEM	Marzouk, M., and Moselhi, O. (2004)	Fuzzy clustering	Travel time	Time performance
9	JCEM	Portas, J., and AbouRizk, S. (1997)	Neural network	Estimation of construction productivity	Productivity performance
10	ECAM	Boussabaine, A.H. (2001a)	Neurofuzzy	Construction projects' duration	Time performance
11	ECAM	Boussabaine, A.H. (2001b)	Neurofuzzy	Construction projects' duration	Time performance
12	CME	Lam, K.C., Hu, T., Ng, T., Skitmore, M., and Cheung, S.O. (2001a)	Fuzzy neural network	Contractor prequalification	Evaluation
13	IJPM	Dzeng, R.J., Wen, K.S. (2005)	Fuzzy delphi method	Project teaming strategies	Evaluation
14	IJPM	Tam, C.M., Tong, T.K.L., Chiu, G.C.W., and Fung, I.W.H. (2002a)	Nonstructural fuzzy decision	Safety management	Evaluation
15	IJPM	Kuchta, D. (2001)	Fuzzy numbers	Project risk assessment	Assessment
16	JCEM	Cheng, M.Y., and Ko, C.H. (2003)	Fuzzy neural network	Construction management	Modeling
17	ECAM	Tong, T.K.L., and Tam, C.M. (2003)	Fuzzy sets with GA	Multi-skilled labor allocation	Modeling
18	IJPM	Hsieh, T.Y., Lu, S.T., and Tzeng, G.H. (2004)	Fuzzy analytic hierarchy process	Planning and design tenders selection	Modeling
19	B&E	Liu, M., and Ling, Y.Y. (2003)	Fuzzy neural network	Contractors' markup	Modeling
20	BRI	Li, H. (1997)	Angular fuzzy sets	KBES	Success factor/ modeling
21	BIJ	Bouchereau, V., and Rowlands, H. (2000)	GA with fuzzy logic	Quality function deployment	Modeling

Note: JCEM=*Journal of Construction Engineering and Management*, ASCE; CME=*Construction Management and Economics*; ECAM=*Engineering, Construction and Architectural Management*; IJPM=*International Journal of Project Management*; B&E=*Building and Environment*; BRI=*Building Research and Information*; and BIJ=*Benchmarking: An International Journal*.

Hybrid Fuzzy Techniques in Evaluation/Assessment

Dzeng and Wen (2005) proposed an analytical model for the teaming strategies of owners on the inclusion of additional contractors. The proposed model was based on the resource-based theory and the fuzzy Delphi method. It allows the owner to identify critical resources required by the project, to assess the contractors' capacities, and to identify the resource gaps. Tam et al. (2002a) conducted a study to evaluate the safety management systems and prioritized a number of safety improvement measures with the consideration of different decision criteria. To do so, NSFDSS was applied to facilitate the decision-making process for these multiobjective problems. It was found that the modified FDSS is appropriate for the appraisal of complicated construction problem, which allows assessment based on a pair-wise comparison of alternatives using semantic operators, even under the condition that insufficient precise information is available.

Lam et al. (2001a) developed a fuzzy neural network (FNN) model, which amalgamated both the fuzzy set and neural network theories, to improve the objectiveness of contractor prequalification. Through the FNN model, the fuzzy rules as used by the prequalifiers could be identified and the corresponding membership functions could be transformed. Kuchta (2001) proposed a new approach to the criticality of an activity and of the whole project by using the fuzzy critical path method method. This approach considers both the decision maker attitude and the project network structure. The criticality measure obtained may serve as a measure of risk or of the supervision effort needed and can assist to make the decision on whether to accept or reject the project.

Hybrid Fuzzy Techniques in Modeling

Hsieh et al. (2004) adopted a fuzzy multicriteria analysis approach to select planning and design alternatives in public office buildings. The innovative fuzzy analytic hierarchy process method was used to determine the weightings for evaluation criteria among decision makers. On the other hand, the subjectivity and vagueness in the alternative selection process was dealt with by using fuzzy numbers for linguistic terms. By incorporating the decision makers' attitude toward preference, a crisp overall performance value was obtained for each alternative based on the concept of fuzzy multiple criteria decision making. Multiskilled labor allocation within a defined time frame falls into the class of nonpolynomial hard problems, and solutions can only be derived

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through repeated trials and errors (Tong and Tam 2003). A fuzzy GAs optimization model, which is based on fuzzy sets and GAs, was developed by Tong and Tam (2003) to provide an efficient method to arrive at a "near-optimal" solution.

It is widely accepted that problems associated with the construction industry are complex, full of uncertainty, and vary with environment. Cheng and Ko (2003) stated that fuzzy logic, neural networks, and GAs have been successfully applied in construction management to solve different types of problems over the past decade. Having considered the characteristics and merits of each method, Cheng and Ko (2003) combined the three methods to develop the evolutionary fuzzy neural inference model. It was concluded that this model could be used as a multifarious intelligent decision support system for decision making to solve manifold construction management problems. Liu and Ling (2003) developed the FNN model to help contractors estimate markup percentage to be included in their tenders. This model provides users with a clear explanation to justify the rationality of the estimated markup output. By using this model, it is believed that the difficulties in markup estimation due to its heuristic nature can be overcome.

Quality function deployment is a management tool that provides a visual connective process to help teams focus on the needs of the customers throughout the total development cycle of a product or process (Bouchereau and Rowlands 2000). It provides a means for translating customer needs into appropriate technical requirements for each stage of a product/process-development life cycle. It helps develop more customer-oriented higher-quality products. Although there are numerous benefits of using quality function deployment, it is not a simple tool to use. Bouchereau and Rowlands (2000) analyzed that fuzzy logic, ANNs, and the Taguchi method can be combined with quality function deployment to resolve some of its weaknesses, and proposed a synergy between quality function deployment and the three methods and techniques reviewed. Li (1997) investigated vital issues and factors related to the success of a knowledge-based expert system (KBES) development. He used angular fuzzy sets to quantitatively determine values of the surrogate items and values less than one were regarded as weak items. Deployment of corrective action is then required to enhance the weak items. It was proposed that the identified factors and their surrogate items should bring the attention of KBES developers to a number of vital issues that are crucial to a successful KBES implementation.

Implications for the Future Research Directions

After conducting a comprehensive literature review on the applications of fuzzy set/fuzzy logic and hybrid fuzzy techniques in construction management research, some research areas have been identified for further study. First, it is recommended that fuzzy set/fuzzy logic can be incessantly adopted in the previously mentioned four major categories because they can assist in developing models to make decisions and to evaluate the performance in a wide range of areas when analyzing construction problems, which are often viewed as complicated, uncertain, and ill defined. Fuzzy membership functions and linguistic variables, two of the major concepts associated with fuzzy set/fuzzy logic (others including natural language computation, linguistic approximation, fuzzy set arithmetic operations, set operations, and fuzzy weighted average) (Zimmermann 2001; Bandemer and Gottwald 1995; Baloi and Price 2003; Jamshidi 1997; Grima 2000; Piegat 2001; Ng et al. 2002; Seo et al. 2004; Zheng and Ng 2005) can be especially adopted to suit applications to solve construction problems with reference to the aforesaid nature of construction. In fact, fuzzy membership functions enable one to perform quantitative calculations in fuzzy decision making (Bharathi-Devi and Sarma 1985) while the concept of linguistic variables serves the purpose of providing a means of approximate characterization of phenomena that are too complex or too ill defined to be amendable to description in conventional quantitative terms (Cross and Sudkamp 2002; Niskanen 2004). In addition, it has been observed that hybrid fuzzy techniques, such as neurofuzzy and fuzzy neural networks (Boussabaine 2001a,b; Lam et al. 2001a; Cheng and Ko 2003; Liu and Ling 2003, 2005), are increasingly applied in construction management research and they can be more widely adopted in this field because they can better solve some construction problems that fuzzy set/fuzzy logic alone may not best fit. For example, neural networks are strong in pattern recognition and automatic learning while fuzzy set and fuzzy logic are strong in modeling certain uncertainties. Their combination can help to develop models with uncertainty under some forms of pattern. For instance, neurofuzzy systems are able to represent qualitative, vague, and imprecise concepts and to combine the ability of knowledge representation with the learning power of neural networks (Boussabaine 2001a). These attributes permit neurofuzzy models to be used in modeling complicated systems and decision processes when the pattern of indeterminacy is the result of inherent variability or vagueness rather than randomness. In fact, neurofuzzy models can assist in developing reliable construction decision support models with ambiguous and imprecise events or facts by representing them in linguistic terms (Boussabaine 2001a). Besides, the fuzzy techniques can be applied more extensively to construction technology and information technology disciplines. Examples on areas of investigation included: (1) building thermal dynamic response (Skrjanc et al. 2001); (2) sulfate expansion (Inan et al. 2007); (3) user acceptance and adaptation (Guillemin and Molteni 2002); (4) car-parking guidance (Leephakpreeda 2007); (5) thermal conductivity (Singh et al. 2007); (6) heating control (Gouda et al. 2006); and (7) thermal and illumination control (Lah et al. 2005).

Conclusions

This paper has conducted a comprehensive literature review on the application of fuzzy techniques in construction management discipline. Although fuzzy techniques have been increasingly applied in the research area of construction management during the last decade, no paper has attempted to draw up a holistic commentary of the existing fuzzy literature. To fill up this research gap, this paper provides a comprehensive review on the fuzzy literature that has been published in eight selected top quality journals from 1996 to 2005. It has been found that fuzzy research, as adopted in the construction management discipline over the past decade, can be divided into two broad fields, encompassing: (1) fuzzy set/fuzzy logic; and (2) hybrid fuzzy techniques, with their applications in four main categories, including: (1) decision; (2) performance; (3) evaluation/assessment; and (4) modeling. The applications of fuzzy techniques on these categories are very effective and practical because they can help to develop models to make decisions and to evaluate the performance in a wide range of areas when analyzing problems encountered in the construction industry, which are widely regarded as complex, full of uncertainties, and contingent on changing environments. Having conducted a comprehensive overview on the applications of fuzzy tech-

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niques in construction management research, it puts forward new directions for fuzzy research and its application in construction management research. It is suggested that future research studies on fuzzy set/fuzzy logic can constantly be applied on the four major categories mentioned previously. Fuzzy membership functions and linguistic variables can be particularly employed to suit applications to tackling construction problems facing the aforesaid nature of construction. In addition, hybrid fuzzy techniques, such as neurofuzzy and fuzzy neural network, can be more broadly adopted because they can better solve some construction problems that fuzzy set/fuzzy logic alone may not best suit. For example, neural networks are strong in pattern recognition and automatic learning while fuzzy set and fuzzy logic are strong in modeling certain uncertainties. Their mixture can assist in developing models with uncertainty under some forms of pattern. For instance, neurofuzzy systems can represent qualitative, vague, and imprecise concepts and combine the ability of knowledge representation with the learning power of neural networks (Boussabaine 2001a). These attributes enable neurofuzzy models to be used in modeling complex systems and decision processes when the pattern of indeterminacy is the result of inherent variability or vagueness rather than randomness. Finally, an increasing trend of applying fuzzy techniques in the building science and environmental disciplines is also observed (Skrjanc et al. 2001; Guillemin and Molteni 2002; Lah et al. 2005; Gouda et al. 2006; Inan et al. 2007; Leephakpreeda 2007; Singh et al. 2007); it is believed that the application of fuzzy techniques will go beyond the construction management area into these disciplines as well.

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