Predicting and Evaluating Construction Trades Foremen Performance: Fuzzy Logic Approach

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Abstract: This paper illustrates a fuzzy logic model for use in predicting and evaluating the performance of construction trades foremen. The model assists in measuring the effectiveness of a foreman, monitoring improvements in effectiveness over time, and identifying areas where a foreman requires training or mentoring to improve his/her performance. This paper also discusses the factors that affect the performance of a foreman in each area of responsibility. The structure of the model and the use of fuzzy logic are described. The model is validated using data collected from an actual construction company, illustrating its high level of linguistic accuracy. This model is relevant to researchers and makes a contribution to performance evaluation by developing a methodology for evaluating and predicting the performance of construction trades foremen. The model provides a complete approach for handling uncertainty inherent in performance evaluation by using fuzzy logic. The use of fuzzy logic in the model allows users to express themselves linguistically and to make assessments that are subjective in nature. It is relevant to construction industry practitioners since it provides them with a useful technique for evaluating the performance of foremen and identifying the factors that affect their performance on a daily basis. Last, the model offers the advantage of benchmarking foreman performance, allowing organizations to develop plans to improve the performance of their foremen over time.

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Introduction

Construction trades foremen have a significant impact on the performance and quality of a construction project and are a crucial link between management and the workforce. Foremen participate in planning the work, defining the work sequence, communicating with crew members, and motivating crew members. The foremen's performance and how they manage their crew to perform daily tasks have a direct impact on the cost and schedule of a construction project. To ensure that construction trades foremen are qualified in all aspects of their position, the process of selection should be changed from an informal one to a prescribed methodology recognized by the construction industry.

Foremen must be productive to be successful and to help with this task, aspects of productivity related to the uniqueness of the company and/or work environment, and factors that affect performance need to be identified. Most of the factors identified can be improved through training programs; however, the relationship between these factors and the foreman's tasks must be understood to create a cohesive performance evaluation methodology.

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Even with clear identification of the methodology for evaluating foreman performance, imprecision and vagueness can occur in the evaluation process. The challenge in measuring the performance of any individual in a construction organization is in identifying and determining the relationship between the variables that are suitable for evaluating performance. Once the variables are identified, the next step is to quantify the contribution of each of these variables on the performance measures. Quantitative methods of measuring performance, such as correlation factors and cost and schedule measures for work performed under the supervision of a particular individual, have obvious limitations because they neglect subjective factors such as worker motivation and morale, communication skills, and work ethic. Consequently, new methodologies need to be explored to provide a more holistic approach to evaluating the performance of construction trades foremen.

The numerous factors involved in the process of performance evaluation, the linguistic nature of assessments, and the nonlinear relationship that exists between the factors involved and the overall performance makes fuzzy logic perfectly suited to evaluating and predicting the performance of foremen, as described in this paper. This paper is relevant to researchers and makes a contribution to performance evaluation by developing a methodology for evaluating and predicting the performance of construction trades foremen. The developed fuzzy logic model provides a complete approach for handling uncertainly inherent in performance evaluation. The use of fuzzy logic in the model allows users to express themselves linguistically and to make assessments that are subjective in nature. It is relevant to construction industry practitioners since it provides them with a useful technique for evaluating the performance of foremen and identifying the factors that affect their performance on a daily basis. Lastly, the model offers the

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advantage of benchmarking foreman performance, allowing organizations to develop plans to improve the performance of their foremen over time.

Fuzzy Logic and Previous Research on Foremen Performance Evaluation

Although improving performance is vital to increasing productivity in the construction industry, the evaluation of construction trades foremen has been a limited area of research. The Construction Industry Institute's research on supervisory development for the construction industry assessed the personal characteristics, behaviors, knowledge, skills, education, and training of supervisors in the construction industry, in an effort to improve the performance of supervisors and define supervisory development programs (Rogge et al. 1996). Various studies have documented foremen tasks, responsibilities, behaviors, characteristics, and influence on their peers and crew members (Warr and Bird 1967; Hinze and Kuechenmeister 1981; Lemna et al. 1986; Maloney and McFillen 1987; Uwakweh 2005), creating a foundation for the development of foreman performance evaluation models.

The construction industry has contributed to the development of programs for foreman training and evaluation. Bantrel Constructors developed a Supervisory Selection Feedback Tool, based on a 360° review of foremen by supervisors, peers, crew members, and self-assessment. Better SuperVision, developed by Construction Labour Relations Alberta and the Alberta Building Trades Council, provides a training program for unionized construction supervisors, including an on-the-job competency assessment. The Construction Owners Association of Alberta (COAA) has sponsored a Skills Development Tool for Construction Trades Foremen that links subjective evaluations obtained from a 360° review to more objective measures of performance, such as productivity, cost, schedule, quality, and safety measures (Fayek and Poveda 2008).

Fuzzy logic has been used extensively in construction engineering and management. However, it has not been used to the expected extent in evaluating the performance of the construction workforce. Regression models have been used to model and predict the performance of professionals such as architects and engineers (Ling 2002). Competency-based multidimensional conceptual models have been proposed to predict the performance of project managers (Dainty et al. 2005; Ahadzie et al. 2008). Other studies have correlated project managers' behavior with the final project outcomes (Dulaimi and Langford 1999; Ling 2004; Cheng 2007). Neurofuzzy models have been developed to predict the performance of engineers and design professionals (Georgy et al. 2005). The impact of quality engineers on construction projects has been evaluated using fuzzy neural networks (Georgy and Chang 2005). A fuzzy logic approach to measure performance of services and employees based on client satisfaction was presented by Ammar and Wright (1995). The model described in this paper adds to such previous efforts by using fuzzy logic to evaluate and predict the performance of construction trades foremen.

Factors Affecting the Performance of a Foreman

Performance is such a complex process that no single factor can be used to predict or evaluate it. A series of factors must be taken into consideration before a certain methodology can be applied. First, the foreman's performance evaluation should involve assessments from different perspectives (i.e., supervisors and peers, crew members, and the foreman himself/herself). Second, performance evaluation is a dynamic process that incorporates a number of different areas, responsibilities, knowledge, skills and attitude, and qualifications. Accordingly, a single measure, such as qualifications (i.e., training, education level, and experience), cannot be used alone to evaluate a foreman's performance. Third, a foreman's performance evaluation may vary depending on the project characteristics. Different project locations may impact the behavior of employees and their interaction; also, different climates, owners' characteristics, and company policies will have a considerable impact on foreman performance.

In an effort to formalize the qualifications of foremen in the industrial construction sector, the Construction Owners Association of Alberta (www.coaa.ab.ca), through its Workforce Development Supervisory Training and Qualifications Subcommittee, developed a formal position description for industrial construction trades foremen. This position description divides the task and duties of foremen into six areas of responsibilities: safety, quality assurance/quality control (QA/QC), leadership and supervision, employee relations, planning and scheduling, and administration, and is used as a basis for the foremen performance evaluation model described in this paper. This position description has been supplemented with previous research, as described earlier in the paper, to create a set of factors against which foremen are evaluated in the model (Fayek and Poveda 2008). These factors, shown in Table 1, have been classified by area of responsibility and internally regrouped according to similarity between them, to create the set of input variables for the fuzzy logic model.

Data Collection and Model Development

The data for validating and testing the foreman performance evaluation model were collected in the fall of 2007 in the fabrication shop and module yard of a leading industrial construction contractor in Edmonton, Alberta (Fayek et al. 2008). The data were collected through self-completed questionnaires covering the six areas of foreman responsibility. The questionnaires used a 7-point semantic differential scale, shown in Fig. 1, to assess the performance of the foreman against the set of tasks shown in Table 1. Due to a high level of trust between employees and the company, and a culture of continuous improvement in the company, the study obtained 100% participation. Seventeen foremen, 140 crew members, five superintendents, eight general foremen, three QA/QC managers, two safety managers, and four materials management personnel participated in the data collection process.

The questionnaires were self-completed in three group assessments: supervisors and peers, foremen (self-assessment), and crew members, thus yielding a 360° review. The supervisors and peers group included the general foreman, superintendents, QA/QC personnel, materials management personnel, safety personnel, and fellow foremen with whom the foreman under evaluation interacted. Personnel participating in the study had been interacting with the foremen for a reasonable period of time, and the foremen themselves had been foremen with the company for a significant period of time prior to the assessment. Participants were aware of the foremen's duties and responsibilities. The foremen knew the company policies and practices and had an established relationship with their crew members.

A statistical model for foreman performance evaluation was initially developed as part of the Skills Development Tool for Construction Trades Foremen developed for the Construction

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Table 1. Factors Affecting the Foreman's Performance

Input variable	Factors
	Safety category
Technical knowledge	Understanding of health safety and environment good practices and procedures
	Knowledge of worker's compensation board and insurance provisions
Company policies	Supporting of the company safety program
	Emphasis of safe work practices
	Effective communication of safety policies and procedures
	Enforcement of the company drug and alcohol policy
Safety procedures	Completion of initial safety and hazard assessments
	Participation in safety/incidents investigations and reviews
	Completion of incidents and other safety reports
Safety development for crew	Conduction of meetings (i.e., safety tool box meetings)
	Development of safe work plans for crew members
	Answers technical safety questions from crew members
	Identification and arrangement of crew safety training
	Planning and scheduling category
Meeting weekly targets/productivity	Works toward meeting weekly schedule/production targets
	Works toward meeting weekly productivity targets (e.g., performance factors)
	Ability to review/adjust specific workplace activities and task schedules to meet established production schedules
	Ability to identify and attempt to resolve road blocks to productivity
Workface/detailed planning	Ability to translate work requirements into a plan for individual tasks, and assign them to crew members (delegate)
	Capacity to plan manpower requirements
	Ability to plan scaffold requirements
	Ability to plan ahead work to minimize delays in schedule
	Ability to identify and verify that all tools and materials are available and complete
Communication to crew members/other crews	Ability to resolve, or else report, schedule problems or conflicts with other crews or contractors
	Ability to communicate the plan, schedule, and scope of work to crew members
	Ability to work with crew members to overcome work challenges
Planning abilities	Understanding and application of project schedules
	Ability to identify needs and deficiencies in the plan/schedule and communicate them to the right person
	Participation in preparing weekly and look-ahead schedules
	Administration category
Documentation	Ability to keep and update logs or diaries as required
	Capacity to maintain accurate time cards
	Ability to report workface production and work progress
	Ability to complete quality reports
	Ability to complete the statistics required by the company
Communication Skills	Ability to complete reports in a clear and easy to understand manner
	Capacity to recommend personnel actions (e.g., hiring, promotions, discipline)
	Computers skills, if required
Logistics	Ability to request supplies on time
	Ability to obtain permits on time
	Ability to distribute checks and effectively handle problems with checks
	QA/QC category
Inspection and resolution of QA/QC problems	Understating of company's quality assurance and quality control (QA/QC) expectations
	Effectively resolves technical and QA/QC issues
QA/QC specifications	Ensures that crew members work according to job specifications and blueprints
	Ensures that crew members work according to QA/QC company's specifications
	Ensures that the correct use of tools and equipment are used
	Inspection of the complete work and initiate corrective actions if needed

J. Constr. Eng. Manage., 2009, 135(9): 920-929

Table 1. (*Continued.*)

Input variable	Factors
	Leadership and supervision category
Oral and written skills	Oral communication skills
	Written communication skills
Knowledge of crew and scope of work	Knowledge of trade's scope of work
	Knowledge of other trades' scope of work
	Skills at reading and applying blueprints and specifications
	Ability to match other's capabilities and interests with task assignments
	Ability to explain to his/her crew their responsibility and duties
	Ability of assess the capabilities and interest of crew members
Responsibility at work and work ethic	Punctuality and presence at work
	Ability to promote pride and workmanship among employees
	Responsibility and reliability at work
	Good work ethic, integrity, and honesty
	Ability to set an example of behavior and work standards to help ensure crew morale and productivity.
Decision making abilities	Ability to make good decisions on time
	Ability to adapt to change and be flexible
	Ability to anticipate and avoid problems
Teamwork	Ability to work in a group or as part of a team
	Ability to promote teamwork and harmony between all construction crews and trades
	Ability to ensure that crew members are oriented to the job
	Ability to coordinate on the job training for apprentices and facilitate mentoring of apprentices by journeymen
	Employee relations category
Crew issues	Ability to identify training needs for the crew and facilitate delivery of the training and mentoring programs
	Recognizes, addresses, and resolves issues/problems within crew members or between crews
	Ability to coordinate and communicate with other trades
	Respect for crew members
	Consults with and includes crew members in discussions on how to carry out the work
Disciplinary action	Document performance problems of crew members
	Ability to investigate and document incidents with crew members accurately and thoroughly
	Ability to apply company's corrective action policy
Company policies	Ensures a respectful and inclusive employee relations work environment
	Understands, communicates, and ensures compliance with the company employee relation policies
	Ensure that project relations manager or designate is included in all major potential controversial or questionable employee relations matters.
	Ability to apply project procedures, worksite policies, and collective agreement requirements

Owners Association of Alberta (Fayek and Poveda 2008). The Skills Development Tool uses the data collected from the 360° review described above to assess each foreman using statistical measures (e.g., medians and means) in each of the six categories of responsibility. Additionally, project-related and foreman-related performance data were collected to conduct correlations between these statistical measures of performance based on subjective evaluations, and objective performance measures, such as productivity, cost, schedule, quality, and safety performance measures. The Skills Development Tool thus addresses a gap in previous efforts that of linking subjective evaluations obtained from a 360° review to more objective measures of performance. The foreman performance evaluation fuzzy logic model described in this paper uses the data collected and the statistical results from the Skills Development Tool to validate its accuracy.

The results obtained from both the Skills Development Tool and the foreman performance evaluation fuzzy logic model can be used to (1) predict and evaluate the foreman's performance (i.e., skills level) in each area of responsibility; (2) compare the foreman's performance evaluation given by different groups' assessments and identify gaps between them; (3) measure the

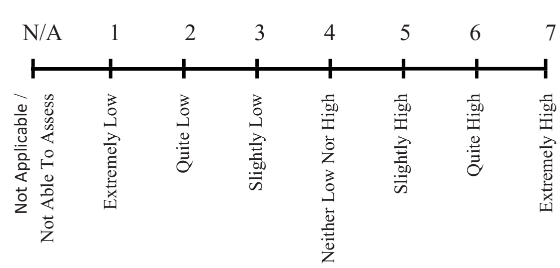

Fig. 1. Seven-point linguistic scale for performance evaluation

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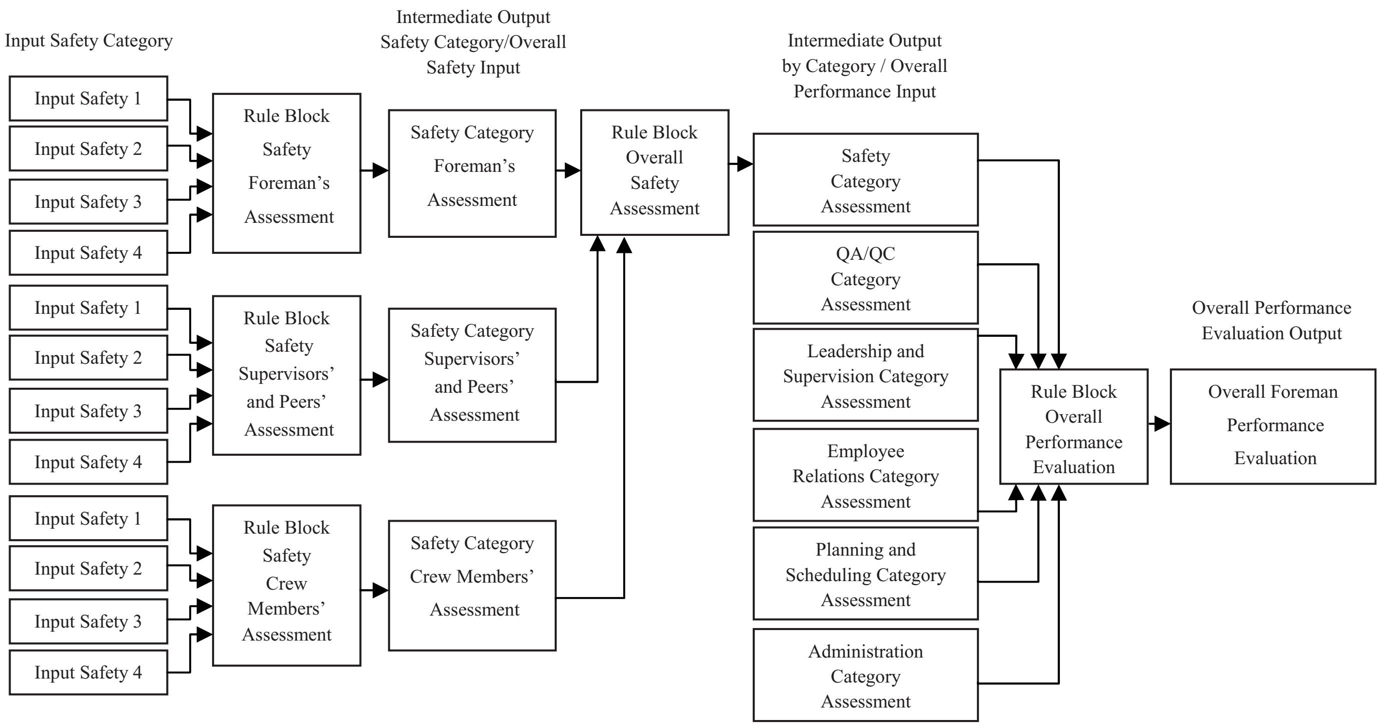

Fig. 2. Structure of the fuzzy expert system—safety category

effectiveness of a foreman among his/her crew members, supervisors, and peers in each area of responsibility; (4) provide foremen with feedback on their skills and measure improvements over time; (5) identify training and mentoring required for a foreman to improve his/her skills in each area of responsibility; (6) measure the impact of training or mentoring on the skills of a foreman; (7) provide foremen with an opportunity to gain recognition for their skills; and (8) help the company to identify site-wide or project-wide issues that may be affecting the ability of foremen to carry out their responsibilities.

Fuzzy Logic Model to Predict and Evaluate Foreman Performance: Structure and Description

Fuzzy logic is a modeling technique designed to deal with natural language and reasoning that is approximate rather than precise (Zadeh 1965). Fuzzy expert systems combine fuzzy logic for linguistic expression with expert systems reasoning, to reason with a large number of variables to reach a conclusion. A fuzzy expert system is a fuzzy rule-based system that incorporates fuzzy logic concepts with if-then rules to mimic the expert way of thinking. Both, the premise (if part) and the conclusion (then part) of each rule can be expressed in linguistic terms, which are represented by membership functions. The logic of the system is mainly governed by the choice of fuzzy reasoning mechanisms (Jang 1993): (1) input variables are compared with the membership functions in the premise part of a rule to determine the "level of truth" of each linguistic term in the rule (fuzzification); (2) the firing strength of each rule is calculated by combining the membership values in the premise part, most commonly by the minimum or product (t-norm) operator; (3) depending on the firing strength, the qualified rule consequent is generated most commonly by a t-norm operator; and (4) the qualified consequent is aggregated (using an s-norm operator, such as maximum or algebraic sum) to produce an output set, which can be reduced to a crisp value (through defuzzification).

The foreman performance evaluation model described in this paper consists of a fuzzy expert system with 63 input variables, 25 output variables (24 intermediate outputs and one final output), 24 intermediate variables, 25 rule blocks, 11,577 if-then rules, and 450 membership functions. Each category of assessment in the model (i.e., safety, QA/QC, leadership and supervision, employee relations, planning and scheduling, and administration) consists of input variables, intermediate inputs/outputs, and output, as shown in Fig. 2. Input variables are defined by the factors affecting the foreman's performance, as listed in Table 1. At the early stage of model development, approximately 77 input factors were considered in developing the model. However, it was found that using a large number of input factors is impractical due to the exponential growth of rules and consequent generation of a very large rule base. These 77 factors were regrouped and classified by category as shown in Table 1. Intermediate output/input variables are defined as in-between evaluations in the model. The user can obtain the foreman's evaluation by group assessment (e.g., foreman, supervisors and peers, and crew members) in each category. The model then uses the evaluation from each group assessment as input to obtain the evaluation for each category of assessment (i.e., safety, QA/QC, leadership and supervision, employee relations, planning and scheduling, and administration). The final output variable is defined as the overall foreman performance evaluation and is determined using the evaluation in each category of assessment as input, as shown in Fig. 2.

The creation of membership functions, curves that define how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1, was dependent on the availability of data. Membership functions can be determined using different techniques. They can be divided into two categories, based on the means of representation: (1) discrete representation; and (2) continuous functional form representation

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(Dissanayake and Fayek 2007). Examples of discrete representation techniques are direct assignment, pairwise comparison, and exemplification techniques. Heuristically based methods and statistically-based or cluster-based methods that used sample historical numerical data are examples of techniques for continuous functional form representation.

Due to a limited set of data, a heuristic method was used to generate the membership functions for the input and output variables in the model presented in this paper. Input and intermediate variables used trapezoidal membership functions to represent poor and outstanding linguistic descriptors. Triangular membership functions were used to represent acceptable linguistic descriptors. The final output variables, which used poor, acceptable, and good linguistic descriptors, were represented by triangular membership functions, and very poor and outstanding were represented by trapezoidal membership functions. Trapezoidal and triangular shapes were selected to represent the membership functions for the fuzzy input and output variables in the model for three reasons: (1) Simplicity and efficiency with respect to computation; (2) ease of application and understanding from construction personnel's perspective; and (3) commonly used in fuzzy logic modeling. A crisp membership function was used to represent the not applicable (N/A) values, eliminating any involvement in the results after the defuzzification process. The overlapping between adjacent membership functions is such that the crossover points have membership values equal to 0.5, facilitating the gradual and uniform transition between variables in the model. Table 2 shows the linguistic descriptors for each input, intermediate output/input, and final output variables in the model. Fig. 3 shows sample membership functions for an input variable, technical knowledge, and the final output variables, overall foreman performance evaluation.

The if-then rules relate the input variables to the output or intermediate variables. The membership functions of the input variables represent the antecedents or premises of the rules, and the membership functions of the output or intermediate variables represent the consequents or conclusions. The if-then rules provide the logical reasoning framework for determining the output, based on values of input factors. For example, assuming that technical knowledge and supervisory experience are input factors and administration category assessment is the output factor, a fuzzy if-then rule can be expressed as follows:

- If technical knowledge is poor and supervisory experience is outstanding, then administration category assessment is acceptable.

Each variable is represented by a set of membership functions representing linguistic states of the variable (e.g., poor, acceptable, outstanding). In this example, the "and" (t-norm) operator assumes that the input factors exert equal but independent effect on the output factor. Each rule base in the fuzzy logic model was developed by iteratively combining the input factors in a logical manner, and considering each input factor as independent and equally weighted.

Model Validation and Sensitivity Analysis

The accuracy of the model was determined by comparing the crisp (defuzzified) output of the final layer (i.e., predicted overall foreman performance evaluation) with the mean performance evaluation of the same foreman, based on the previously described Skills Development Tool for Construction Trades Foremen (i.e., statistical model). The mean performance evaluation is calculated based on the mean assessment of all three groups of respondents and all six categories of responsibility combined, assuming an equal weighting of each. The percentage error for a given foreman (i.e., data point) in the fuzzy logic model was calculated using

$$\text{Percentage error} = \frac{[\text{Fuzzy Logic Model Output} - \text{Mean Output}]}{\text{Mean Output}} \times 100 \quad (1)$$

where Fuzzy Logic Output = value generated by fuzzy logic model after defuzzification and Mean Output = value generated by statistical model.

The criterion used for a numerical match for each data point was calculated as less than or equal to 7.1 %. This criterion is based on the premise that the values obtained using the fuzzy logic model should not vary by more than ± 0.5 of an evaluation point as calculated using the statistical model, as shown in Table 3. For example, if a foreman obtains an evaluation of 5.0 on the 7-point linguistic scale using the statistical model, values accepted using the fuzzy logic model would be between 4.50 and 5.49. The percentage difference between the statistical and fuzzy logic model would be 10% (percentage difference between 5.0 and 4.50) and 9.8% (percentage difference between 5.0 and 5.49). The same principle applies to each of the 7-points in the linguistic scale, as shown in Table 3. Although some points in the scale allow a higher percentage difference, the lowest value, 7.1%, is used as the criterion for evaluating the accuracy of the fuzzy logic model against the statistical model.

A base case fuzzy expert system was created with the following characteristics: triangular and trapezoidal membership function shapes, minimum t-norm operator (corresponding with linguistic AND) for combining the input variable, product t-norm operator for implication of the combined input to the output in each rule, maximum s-norm operator in the aggregation of the rules, and the center of maximum (CoM Method) as the defuzzification method, which computes a crisp output as a weighted average of the term membership maxima, weighted by the inference results. The results obtained using the base case model are shown in Table 4. Seventeen data points were available, where each data point represents one foreman evaluation averaged over the three group assessments (e.g., foreman, supervisors and peers, and crew members). The values shown in Table 4 represent the average error of the fuzzy expert system, calculated using Eq. (1), for each category of assessment and for the overall foreman performance evaluation, averaged over the seventeen data points.

A sensitivity analysis was conducted by varying the parameters of the base case model to examine the impact on the accuracy of the model. During the sensitivity analysis, four different parameters were modified: (1) membership function shapes; (2) input aggregation methods for combining input variables, and implication methods; (3) result rule aggregation methods; and (4) defuzzification methods. Three different analyses were made using different membership functions shapes: (1) all membership functions using triangular shapes (Sensitivity Analysis I); (2) all membership functions using trapezoidal shapes (Sensitivity Analysis II); and (3) all membership functions using S-shapes (Sensitivity Analysis III). The input aggregation and implication methods were tested in two scenarios: (1) using Max-Product as input aggregation and implication methods (Max represents the linguistic OR to combine the input variables, and Product represents the implication operator), and Max as result aggregation,

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Table 2. Input, Intermediate Output/Input, and Final Output Variables

Input variable	Linguistic descriptors	Numerical scale
Technical knowledge	N/A, poor, acceptable, outstanding	1–7 ratings
Company policies	N/A, poor, acceptable, outstanding	1–7 ratings
Safety procedures	N/A, poor, acceptable, outstanding	1–7 ratings
Safety development for crew	N/A, poor, acceptable, outstanding	1–7 ratings
Inspection and resolution of QA/QC problems	N/A, poor, acceptable, outstanding	1–7 ratings
QA/QC specifications	N/A, poor, acceptable, outstanding	1–7 ratings
Oral and written communications skills	N/A, poor, acceptable, outstanding	1–7 ratings
Knowledge of crew and scope of work	N/A, poor, acceptable, outstanding	1–7 ratings
Responsibility at work and work ethic	N/A, poor, acceptable, outstanding	1–7 ratings
Decision making abilities	N/A, poor, acceptable, outstanding	1–7 ratings
Teamwork	N/A, poor, acceptable, outstanding	1–7 ratings
Crew issues	N/A, poor, acceptable, outstanding	1–7 ratings
Disciplinary action	N/A, poor, acceptable, outstanding	1–7 ratings
Company policies	N/A, poor, acceptable, outstanding	1–7 ratings
Meeting weekly targets/productivity	N/A, poor, acceptable, outstanding	1–7 ratings
Communication to crew members/other crews	N/A, poor, acceptable, outstanding	1–7 ratings
Planning abilities	N/A, poor, acceptable, outstanding	1–7 ratings
Workface/detailed planning	N/A, poor, acceptable, outstanding	1–7 ratings
Documentation	N/A, poor, acceptable, outstanding	1–7 ratings
Communication skills	N/A, poor, acceptable, outstanding	1–7 ratings
Logistics	N/A, poor, acceptable, outstanding	1–7 ratings
Intermediate output/input variables	**Linguistic descriptors**	**Numerical scale**
Safety category—foreman’s assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Safety category—supervisors’ and peers’ assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Safety category—crew members’ assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Safety category assessment	N/A, poor, acceptable, outstanding	1–7 ratings
QA/QC category—foreman’s assessment	N/A, poor, acceptable, outstanding	1–7 ratings
QA/QC category—supervisors’ and peers’ assessment	N/A, poor, acceptable, outstanding	1–7 ratings
QA/QC category—crew members’ assessment	N/A, poor, acceptable, outstanding	1–7 ratings
QA/QC category assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Leadership and supervision category—foreman’s assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Leadership and supervision category—supervisors’ and peers’ assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Leadership and supervision category—crew members’ assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Leadership and supervision category assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Employee relations category—foreman’s assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Employee relations category—supervisors’ and peers’ assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Employee relations category—crew members’ assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Employee relations category assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Planning and scheduling category—foreman’s assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Planning and scheduling category—supervisors’ and peers’ assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Planning and scheduling category—crew members’ assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Planning and scheduling category assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Administration category—foreman’s assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Administration category—supervisors’ and peers’ assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Administration category—crew members’ assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Administration category assessment	N/A, poor, acceptable, outstanding	1–7 ratings
Final output variable	**Linguistic descriptors**	**Numerical scale**
Overall foreman performance evaluation	N/A, very poor, poor, acceptable, good, outstanding	1–7 ratings

which takes the maximum value of each output set (from each rule) for a given output variable (Sensitivity Analysis IV); and (2) using Min-Product and as input aggregation and implication methods (Min represents the linguistic AND to combine the input variables, and Product represent the implication operation), and bounded SUM (BSUM) operator as result aggregation, which sums each rule’s output set using a bound of 1.0 (Sensitivity Analysis V). The defuzzification methods tested were the (1) mean of maximum (MoM method), which computes a system output on the basis of the term with the highest resulting degree of support; if the maximum is not unique, the mean of the maximizing interval is computed (Sensitivity Analysis VI); (2) Fast

J. Constr. Eng. Manage., 2009, 135(9): 920-929

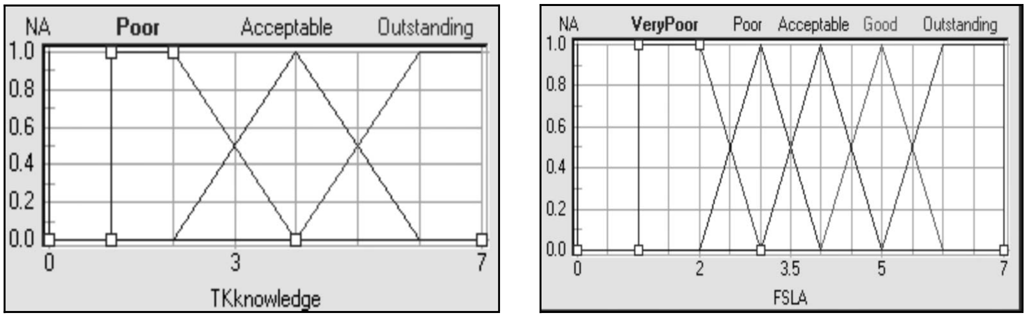

Fig. 3. Sample membership functions for input and output variables

Center of Area defuzzification method (i.e., Fast CoA Method), which computes the individual areas under the membership functions during compilation to avoid numerical integration during run time. This approach neglects the overlapping of the areas, hence it is only an approximation of the "real" center of area defuzzification method (Sensitivity Analysis VII); and, (3) Hyper-defuzzification Center of Maximum defuzzification method (Hyper CoM), which is used for fuzzy applications for which not only positive experience in the form of recommendations is of importance, but also negative experience in the form of warnings and prohibitions (Sensitivity Analysis VIII).

Table 3. Percentage Difference Allowed for Each Scale Point

Scale point	Higher/lower value fuzzy logic model output		Maximum percentage difference allowed by criterion (%)
1	Higher value	1.49	49.0
2	Lower value	1.50	25.0
	Higher value	2.49	24.5
3	Lower value	2.50	16.7
	Higher value	3.49	16.3
4	Lower value	3.50	12.5
	Higher value	4.49	12.3
5	Lower value	4.50	10.0
	Higher value	5.49	9.8
6	Lower value	5.50	8.3
	Higher value	6.49	8.2
7	Lower value	6.50	7.1

Table 4 shows the results of model testing for each model configuration used in the sensitivity analysis. Sensitivity Analysis VII provides the best accuracy, resulting in an improvement of 27.85% in accuracy over the base case model. The parameters of the model configuration for Sensitivity Analysis VII are: (1) triangular membership functions to represent acceptable linguistic descriptors, and trapezoidal membership functions to represent poor and outstanding linguistic descriptors in input and intermediate variables. The final output variables used triangular membership functions to represent poor, acceptable, and good linguistic descriptors, and trapezoidal membership functions to represent very poor and outstanding linguistic descriptors; (2) min as input aggregation method for combining input variables, representing the linguistic AND; (3) product implication method; (4) max as result (rule) aggregation method; and (5) fast center of area (i.e., Fast CoA Method) as defuzzification method.

Contributions and Uses of the Model

The fuzzy logic model presented in this paper provides a number of contributions to academic research and for the construction industry. Academically, the main contribution of this research is in developing a methodology for evaluating the performance of construction trades foremen based on subjective evaluations, using fuzzy logic and fuzzy expert systems. This paper demonstrates the appropriateness of the application of fuzzy logic in predicting and evaluating performance, despite facing difficulties such as limited data and uncertainty resulting from the subjective nature of performance evaluation. The use of fuzzy logic provides an alternative approach to assessing performance using linguistic terms (i.e., very poor, poor, acceptable, good, and outstanding)

Table 4. Sensitivity Analysis Comparison Results—Percentage Error by Category

	Safety (%)	QA/QC (%)	Leadership and supervision (%)	Employee relations (%)	Planning and scheduling (%)	Administration (%)	Overall performance (%)
Base case	6.40	8.17	5.53	7.90	8.15	6.34	4.68
Sensitivity Analysis I	9.77	11.98	7.50	8.71	10.41	8.12	6.15
Sensitivity Analysis II	6.19	8.05	5.44	7.37	7.00	5.99	4.52
Sensitivity Analysis III	13.06	15.54	13.05	15.92	15.78	12.81	12.04
Sensitivity Analysis IV	35.53	40.45	37.27	30.76	35.10	44.63	43.37
Sensitivity Analysis V	5.36	7.36	5.42	5.39	6.97	3.89	4.51
Sensitivity Analysis VI	17.98	18.73	20.41	21.06	18.35	22.21	20.16
Sensitivity Analysis VII	3.64	5.06	5.15	5.12	6.43	3.69	4.27
Sensitivity Analysis VIII	6.31	8.22	5.49	7.87	8.20	6.46	4.42

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instead of numeric evaluations. Furthermore, the structure of the model allows the user to obtain results in three different levels: by group assessment (foreman, supervisors and peers, and crew members), by category (safety, QA/QC, leadership and supervision, employee relations, planning and scheduling, and administration), and by overall performance. The model can be adapted easily to suit different organizations by modifying the input variables considered as foremen's tasks shown in Table 1.

Industrial contributions include the development of a model that provides insight into the factors that affect a foreman's performance. The developed fuzzy expert system provides a tool for performance evaluation and prediction, both of which are difficult to quantify and measure in the present conditions and with the existing tools in the construction industry. The fuzzy expert system is useful to project management personnel in evaluating performance of employees (e.g., foremen), identifying areas of training needed and the impact of such training, and recognizing foremen for possible promotions and bonuses. The model allows the users to express themselves linguistically to evaluate the performance of their personnel, which suits the way they normally express themselves. If the model is implemented by a number of organizations over time, the collective results can be used to identify industry-wide gaps in foremen's skills and to develop training programs to address these gaps. The fuzzy expert system provides the advantage of being able to trace back through the rules to identify which factors (i.e., foreman's tasks) and rules have the most significant impact on the overall results (i.e., foreman performance evaluation). Since each company and/or project has unique characteristics, it was necessary to design a model that could generalize overall performance by group assessment, by evaluation category, and by foreman (e.g., overall performance evaluation). Furthermore, the model can also distinguish between assessments of different foremen by better capturing and evaluating their individual characteristics. These two features (generalization and distinction between assessments) can be accomplished by adjusting the particular characteristics of the fuzzy rules (e.g., rule weightings) and membership functions to capture foreman-specific and company specific characteristics.

Conclusions and Future Development

This paper illustrates how fuzzy logic and fuzzy expert systems can be used to build performance evaluation models based on realistic data. A large number of factors affecting the foreman's performance were identified and incorporated in the model. The factors were divided into six categories to build the performance evaluation model. A process of converting numerical data into linguistic terms was also developed. The membership functions and fuzzy rule bases were developed based on logical reasoning, without the availability of large data sets.

This research provides a basis for future work in predicting and evaluating the performance of construction trades foreman and construction supervisors in general, given the numerous factors affecting the performance of the construction workforce. Data collection should incorporate a larger number of projects and/or companies to obtain a larger data set, which would allow researchers to explore other techniques such as clustering and neurofuzzy training to develop the membership functions and train the rules in the model. The accuracy of the model is based on a comparison with a statistical-based model (i.e., mean evaluation). A larger data set would provide more confidence in basing the assessment of accuracy against a mean value.

Two areas related to the input variables should be explored: (1) The relative weightings of input variables; and (2) the way the input variables they are grouped in the model. Each input variable was assumed to be equally weighted, i.e., each foreman task was assumed to have equal relevance on the foreman's performance. Additionally, each group of respondents was assumed to have equal significance in evaluating the performance of the foreman. Future research should determine which tasks are most significant in determining a foreman's performance and impact on a project, and which groups of respondents are best able to assess a foreman's performance (and against which tasks). More research needs to be done on the variables involved in the foreman's performance evaluation. These variables were regrouped according to a set of criteria. Further research on these criteria, variables, and categories to evaluate foreman performance should be conducted.

Lastly, objective performance data should be incorporated as input variables to the model. For example, a foreman's safety record for his/her crew could be used as an input variable in the safety category, together with the subjective evaluations from the 360° review. Another alternative is building a parallel system to the existing fuzzy expert system that uses objective performance measures as input variables. Results from each system could be interpreted individually so that comparisons between subjective and objective measures could be made, or results from each system could be integrated to obtain an overall foreman performance evaluation. The model presented in this paper provides a basis for future research on both construction workforce performance evaluation and the use of fuzzy logic in conducting such evaluations.

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