CONTINUOUS CONSTRUCTABILITY KNOWLEDGE ACQUISITION WITH FUZZY KNOWLEDGE-BASED FAILURE MODE AND EFFECTS ANALYSIS

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Abstract: Constructability analysis and the resulting adjustments in facility design have a significant potential in improving cost effectiveness of construction projects. However, traditional constructability knowledge acquisition techniques are the key barrier to successful constructability improvement. A new approach to automated constructability lessons-learned documentation and constructability analysis is presented, building upon elements of constructability analysis and improvement programs and ISO Document Systems techniques developed. The paper describes an original solution to continuous constructability knowledge acquisition based on such an approach, combining Failure Mode and Effects Analysis (FMEA) with fuzzy knowledge-based systems. The framework and implementation process of this solution is presented in detail and illustrated on an example construction project. It is concluded that FMEA combined with fuzzy knowledge-based systems provides systematic approach for acquiring structured and reusable constructability knowledge useful for automated constructability analysis.

Keywords: Constructability; FMEA; ISO; Fuzzy Knowledge-Based Systems.

1. INTRODUCTION

Constructability has been defined as "the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives" [1]. Past researches had identified 1:10 to 1:20 returns on constructability programs [2]. However, barriers were found to implementing the traditional constructability programs [3]. In the past decade, several automatic systems for constructability knowledge acquisition and constructability analysis were developed to improve traditional constructability programs, such as multi-media knowledge base [4], machine learning techniques [5], and neuro-fuzzy systems [6]. However, the essential limitations of the traditional constructability programs and systems were not improved. The key reason was the lack of effective methods for acquiring constructability knowledge gained from previous projects and for performing quantitative constructability analysis [7].

There are five major functions in a typical constructability program or system: (1) detecting potential constructability problem; (2) analyzing the criticality of the detected problem; (3) proposing improvement solutions; (4) implementing constructability improvement and evaluating resulting benefits; and (5) back-feeding to constructability lessons-learned. Among the above five elements, building and maintaining of the constructability knowledge base, or the so-called "lessons-learned file", is the most crucial and difficult work for a successful constructability program or system. A traditional approach uses an "Idea Log" and some other forms for collecting constructability improvement ideas [1]. O'Connor et al. [4] suggested several formal methods for soliciting constructability improvement ideas, such as: (1) voluntary survey; (2) questionnaires; (3) on-site interviews; (4) pre-construction meetings; and (5) final project reports. However, due to the unsteady sources and inconsistent format of the constructability data acquired, the constructability improvement functions of the traditional constructability programs are severely limited [7].

This paper describes a new approach to an automated constructability analysis and lessons-learned documentation, built upon elements of traditional constructability programs [1] and ISO document systems techniques [6][7]. An original method of a continuous constructability knowledge acquisition is developed based on this approach, combining Failure Mode and Effects Analysis (FMEA) [8] with fuzzy knowledge-based systems. The primary objective is to provide an effective and effcient approach to steady and continuous acquisition of constructability knowledge.

2. SOURCES FOR CONTINUOUS CONSTRUCTABILITY ACQUISITION

In the traditional approach, constructability knowledge acquisition is performed manually. The constructability improvement ideas are recorded into pre-designed forms such as the Idea Log (see Figure 1). These requirements result in an intensive human effort and in maintaining a large set of constructability documents. In addition, proprietary rights of the various participants in a project have made the collection of constructability knowledge extremely difficult.

Project ____

Item No.	Date	Description	Initiator Name	Initiating Company	Estimated Savings	Effort-Hour Savings	A-Approved R-Rejected

Figure 1. CII Constructability Tool 14: Idea Log

The advent of global economy and the internationalization of construction projects have forced the enterprises in the developing countries to adjust to global standards. As a result, the ISO Certifications is becoming more popular with contractors in Taiwan and elsewhere. Up to 1998, more than 60% of the major Class-A General Contractors in Taiwan have been certified or have been pursuing certifications with authorized organizations in the ISO 9000 series [8]. By comparing the constructability roadmap [1] with ISO/CD2 9001:2000 [9], one can see the similarity between the ISO system established vs. compliance procedures and constructability programs, such as:

(1) the quality control documents can be accommodated for the purpose of constructability acquisition;
(2) the "quality manual" (5.6.5) is similar to the function of a "constructability manual";
(3) the "control of records" (5.6.7) performs similar functions to "management of constructability forms";
(4) the "measurement and monitoring" (8.2) performs the same functions as the "constructability program monitor and effectiveness evaluation";
(5) the "nonconformity review and disposition" (8.3.2) functions are similar to the "constructability problem detection";
(6) the "analysis of data for improvement" (8.4) is similar to the "constructability analysis";
(7) the "corrective action" (8.5.2) and "preventive action" are similar to the "constructability improvement and problem prevention";

Thus, it is possible to tailor the ISO document system, if maintained regularly by the constructors, to provide a steady source of data for constructability knowledge acquisition. However, the ISO document system does not provide the facility for quantitative constructability analysis that is the key for automated constructability analysis and improvement [10].

3. CONSTRUCTABILITY FAILURE MODE AND EFFECTS ANALYSIS

3.1 Constructability failure mode and effects anaysis

In order to perform quantitative constructability analysis within the ISO document system, Yu proposed a Failure Mode and Effects Analysis (FMEA) approach to calculate the criticality of the constructability problems detected with the help of an established ISO system [7]. The FMEA is an established method for preventive quality assurance. It involves the investigation and assessment of the causes and effects of all possible failures in a system during its earliest development phases [11]. Traditionally, the FMEA is conducted by specialists from various departments of a business organization (e.g., design, procurement, and production) in one or more meetings. A team of experts analyzes each safety-critical subsystem and component. For each failure mode, all potential causes and effects are investigated. Then, the team records which actions have already been taken, and which actions still need to be performed in order to prevent or identify the failure mode. After identifying the failure mode, the team assesses the severity, the likelihood of occurrence, and the difficulty of detection of each failure mode. The above assessments are ranked from 1 to 10. The product of those numbers gives the risk priority number (RPN). The engineer then uses the RPN to select the parts or processes with higher priorities to be improved. When RPN exceeds a predefined threshold, actions must be taken to avoid the potential failure mode of the component or process, otherwise the product will be rejected. The RPN, as well as the systematic procedure of FMEA, provide a useful tool for the quantitative constructability analysis. An example FMEA form and procedure for constructability analysis were proposed by Yu [7]. For convenience, we named it hereafter the "constructability FMEA" or CFMEA, to differentiate it from the traditional FMEA form.

3.2 Procedure for CFMEA

The proposed CFMEA procedure, combing the traditional FMEA and a constructability program, is as follows: (1) establishing the CFMEA team; (2) training the team members; (3) defining the construction system, constructability objectives, sub-objectives, and their performance measures; (4) preparing a flow diagram of the construction system; (5) analyzing all possible constructability problems of the system and identifying them on the diagram; (6) estimating the severity, occurrence, and RPN of each problem; (7) performing criticality analysis for detected problems; (8) proposing improvement methods; (9) estimating improvement benefits; and (10) documenting all findings.

4. FUZZY CFMEA

4.1 Criticality assessment in CFMEA

In the CFMEA analysis, there are two traditional approaches to the criticality assessment: (1) determining the risk priority number (RPN); (2) calculating the item's criticality value. The former approach adopts linguistic terms to rank the probability of the occurrence of the failure mode, the severity of the corresponding failure effect, and the likelihood of the failure being detected based on a numeric scale from 1 to 10. These numbers are then multiplied to determine the RPN. A high RPN implies a high priority for the product component to be improved. In the latter method, one first categorizes the severity of the failure mode effect and then calculates the criticality ranking, which represents the expected value of a failure to occur.

4.2 Need for Fuzzy CFMEA

Either of the two traditional approaches for criticality assessment is confronting a problem of expressing the relevent parameters and interpreting the calculation results [13]. For example, in the RPN calculation, a failure mode with a very high severity, a low rate of occurrence, and a very high detectability (say 9, 2, 2 respectively) may result in a very low RPN (36). In another case, a failure mode with moderate parameters (say 5, 4, 5) will yield a much higher RPN (100). Even though the first case should be considered for improvement first, the calculation result gives a much higher priority to the second case. In order to overcome the shortcoming of the criticality assessment of the traditional FMEA, researchers have proposed the fuzzy risk priority numbers to replace the traditional 1 to 10 numeric scales. Bowles and Peláez proposed a fuzzy logic prioritization for FMEA RPN assessment [13]. In this paper, we adopt the prioritization of RPN based on Bowles and Peláez's method as we proceed with the constructability analysis.

4.3 Generation of fuzzy decision rules

The generation of fuzzy decision rules for CFMEA involves two tasks: (1) determination of the fuzzy membership function for each linguistic term; (2) determination of the association between the parameter antecedents and the criticality consequences. In the proposed method, the first task is determined by a criteria set up originally by Livonia [12]; while the second task is performed via a *two-step criticality classification*. Tables 1, 2, and 3 show the criteria for fuzzy evaluation of occurrence, severity, and detectability, as modified based on Bowles and Peláez's [13]. The *two-step criticality classification* consists of: (1) preliminary classification—first, list criticality parameters (i.e., *occurrence*, *severity*, and *detectability*) in a table (see Figure 2), then by dividing the table into five separate areas (where the darker shadow means the more critical class), one is able to determine the consequence of the fuzzy decision rules (see example in Table 4); (2) relaxation to fuzzy sets — the preliminary classification obtained in step (1) is relaxed to allow overlaps between two adjacent criticality classes and thus results in fuzzy sets for criticality classification. With the fuzzy membership functions of the linguistic terms for the criticality parameters and associated criticality classifications, the fuzzy decision rules for CFMEA are generated. The resulting fuzzy rules will be used for criticality analysis of the constructability problems.

Table1 Fuzzy evaluation criteria for *occurrence*

Rank	Fuzzy term	Meaning	Probability
1	Very low	Failure is unlikely	$<1/10^6$
2	Low	Relatively few failures	1/20,000
3			1/4,000
4	Moderate	Occasional failures	1/1,000
5			1/400
6			1/80
7	High	Repeated failures	1/40
8			1/20
9	Very high	Failure is almost inevitable	1/8
10			>1/2

Table2 Fuzzy evaluation criteria for *severity*

Rank	Fuzzy term	Meaning

1	Very low	Unnoticeable minor failure.
2	Low	Failure causes slight deterioration.
3		
4	Moderate	Failure causes some user dissatisfaction.
5		
6		
7	High	High degree of user dissatisfaction.
8		
9	Very high	Severe failure might cause unsafe or noncompliance with government regulations.
10		

Table3 Fuzzy evaluation criteria for *detectability*

Rank	Fuzzy term	Meaning
1	Very high	Always be able to detect the failure.
2		
3	High	Likely to detect the failure
4		
5	Moderate	May detect the failure.
6		
7	Low	Unlikely to detect the failure.
8		
9	Very low	May not detect failure.
10	Non-detection	Cannot detect the failure.

Criticality	Detectability									
Occurence x Severity	1	2	3	4	5	6	7	8	9	10
1	1	2	3	4	5	6	7	8	9	10
2	2	4	6	8	10	12	14	16	18	20
3	3	6	9	12	15	18	21	24	27	30
4	4	8	12	16	20	24	28	32	36	40
5	5	10	15	20	25	30	35	40	45	50
6	6	12	18	24	30	36	42	48	54	60
7	7	14	21	28	35	42	49	56	63	70
8	8	16	24	32	40	48	56	64	72	80
9	9	18	27	36	45	54	63	72	81	90
10	10	20	30	40	50	60	70	80	90	100
12	12	24	36	48	60	72	84	96	108	120
14	14	28	42	56	70	84	98	112	126	140
15	15	30	45	60	75	90	105	120	135	150
16	16	32	48	64	80	96	112	128	144	160
18	18	36	54	72	90	108	126	144	162	180
20	20	40	60	80	100	120	140	160	180	200
21	21	42	63	84	105	126	147	168	189	210
24	24	48	72	96	120	144	168	192	216	240
25	25	50	75	100	125	150	175	200	225	250
27	27	54	81	108	135	162	189	216	243	270
28	28	56	84	112	140	168	196	224	252	280
30	30	60	90	120	150	180	210	240	270	300
32	32	64	96	128	160	192	224	256	288	320
35	35	70	105	140	175	210	245	280	315	350
36	36	72	108	144	180	216	252	288	324	360
40	40	80	120	160	200	240	280	320	360	400
42	42	84	126	168	210	252	294	336	378	420
45	45	90	135	180	225	270	315	360	405	450
48	48	96	144	192	240	288	336	384	432	480
49	49	98	147	196	245	294	343	392	441	490
50	50	100	150	200	250	300	350	400	450	500
54	54	108	162	216	270	324	378	432	486	540
56	56	112	168	224	280	336	392	448	504	560
60	60	120	180	240	300	360	420	480	540	600
63	63	126	189	252	315	378	441	504	567	630
64	64	128	192	256	320	384	448	512	576	640
70	70	140	210	280	350	420	490	560	630	700
72	72	144	216	288	360	432	504	576	648	720
80	80	160	240	320	400	480	560	640	720	800
81	81	162	243	324	405	486	567	648	729	810
90	90	180	270	360	450	540	630	720	810	900
100	100	200	300	400	500	600	700	800	900	1000

Figure 2. Criticality classification

Table 4 Example criticality classifications

Criticality	Criterion for criticality classification
Very low	0<RPN≦2
Low	2<RPN≦18
Medium	18<RPN≦180
High	180<RPN≦512
Very high	512<RPN≦1000

5. DEMONSTRATION

In order to demonstrate the feasibility of the concept proposed in this paper, an example of concrete formwork constructability analysis is presented to illustrate the step-by-step procedure of the Fuzzy CFMEA. The example project is a part of the Mailiao Formosa Plastic Group No. 6 Naphtha Cracker Project. The construction site encompassed 2,652 hectares in the Yunlin Offshore Industrial District in Yulin County of Taiwan. The main project was constructed during 1994~1998.

5.1 Acquisition of constructability data

The constructability program of the example has been incorporated within an ISO Quality Assurance Program with the following accomondations: (1) Organization for Constructability Improvement – incorporated in the responsibility of the management (4.01); (2) Constructability Analysis – incorporated in the contract review (4.03) and fabrication management (4.09); (3) Constructability Improvement Evaluation Procedure – incorporated in the procurement (4.06) and statistical techniques (4.20); (4) Lessons Learned File – incorporated in the contract review (4.03), fabrication management (4.09), rejected items management (4.13), correction and prevention procedure (4.14) and quality record management (4.16).

5.2 Assessment of membership functions

The fuzzy membership functions for the liguistic terms of the CFMEA parameters are assessed using the criteria set up in Tables 1~3. The resulting fuzzy membership functions are shown in Figures 3~5. The triangular membership functions are adopted for the assessments. These membership functions will be used in Fuzzy CFMEA for dertermining the criticality of the potential constructability problems.

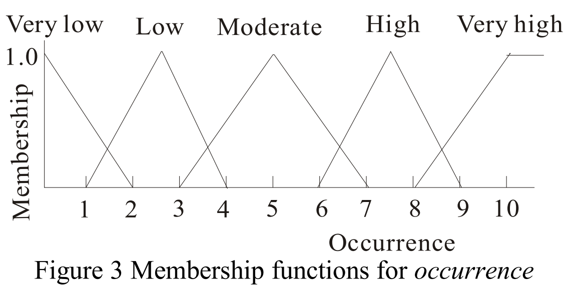

Figure 3 Membership functions for *occurrence*

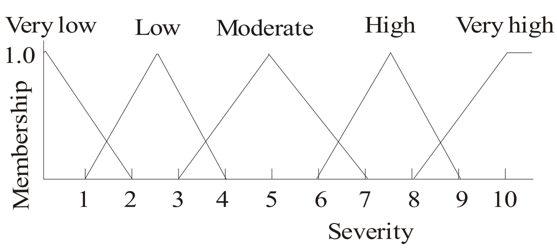

Figure 4 Membership functions for *severity*

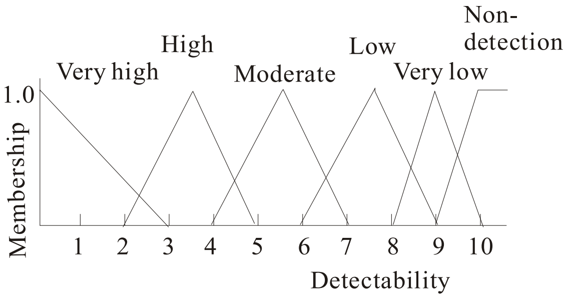

Figure 5 Membership functions for *detectability*

5.3 Determiniation of fuzzy decision rules

The association between premises and consequences of the fuzzy decision rules for Fuzzy CFMEA is based on the criticality classifications shown in Figure 2. Totally, 750 fuzzy decision rules are derived from the above rule determiniation method. Following are three examples of such rules:

Rule #1: If **occurence** is *Very high* (9) and **severity** is *High* (8) and **detectability** is *Moderate* (5), then **constructability** is *Low* (360).

Rule #2: If **occurence** is *High* (8) and **severity** is *High* (8) and **detectability** is *Very low* (9), then **constructability** is *Very low* (576).

Rule #3: If **occurence** is *Low* (3) and **severity** is *Low* (3) and **detectability** is *Very high* (1), then **constructability** is *High* (45).

5.4 Fuzzy CFMEA

The procedure of the Fuzzy CFMEA is similar to the one used in fuzzy expert systems and fuzzy control systems. The following shows the process of the Fuzzy CFMEA for the "Back shoring" item in a checklist of the concrete formwork construction within the ISO document system. Following is a scenario for the analysis: (1) the statistics shows there were 4 irregular records found in total 28 regular checks; (2) the severity from the past records was high (a failure of back shoring usually caused failure of formwork); (3) the detectability of back shoring from past records was 2 times out of the 4 failure records.

(1) Fuzzification using crisp rankings

By the definition in Tables 1~3, the values of CFMEA parameters for the example are: (1) occurence = 9 (very high); (2) severity = 7 (high); and (3) detectability = 5 (moderate). The fist step is to fuzzify the crisp rankings of the parameter values. The results of this fuzzification are fuzzy terms with membership values. In this example, the fuzzy membership values for occurence, severity, and detectability are 0.5, 0.67, and 0.67, repectively.

(2) Fuzzy rule matching

The next step of the Fuzzy CFMEA is to find the applicable fuzzy decision rules and calculate the firing strength of each applicable rule. By looking up the rule base, rule # 1 is found to be applicable. The result of the rule matching is that "**constructability** is *Low*" with a membership value of 0.5. The membership value of the consequence is calculated using a *fuzzy AND* operator. Similar to other fuzzy decision making problems, the *Min* operater is adopted in this paper for *fuzzy AND* calculation.

(3) Defuzzification

The last step of the Fuzzy CFMEA is to derive a crisp constructability classification value from all of the applicable fuzzy rules. There are also several approaches for defuzzification, such as Center of Gravity and Weighted Mean of Maximum (WMoM). In this paper, the WMoM approach is used. The calculation for defuzzification in the WMoM method is described by the Equation (1):

$$Z = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i} \quad (1)$$

where n is the value of the constructability criticality classification; x_i is the support value at which the i^{th} membership function reaches its maximum value; w_i is the degree of truth of the i^{th} membership function obtained in step (2); and Z is the result of defuzzification.

The result for this example comes out to be that the "**constructability** is *Low*" with criticality value of 7.1. Action should be taken to improve the formwork constructability. Otherwise, potential cost overruns and schedule delays may occur during construction.

5.5 Summary of demonstration

The illustration example demonstrates the procedure of the Fuzzy CFMEA for constructability analysis. It is shown that the Fuzzy CFMEA is able to perform quantatative constructability analysis. When intergrated with an ISO document system and a fuzzy decision support system, the Fuzzy CFMEA is not only an efficient tool for constructability analysis but also the link between the detected constructability problem and the improvement solution. Since the potential constructability problem is identified through a regular checking routine of the ISO standard operating procedure (SOP), historical corrective records can be used as the lessons-learned file in traditional constructability programs. Thus, the Fuzzy CFMEA provides a possible solution for continuous constructability improvement of construction firms. Moreover, the quantitative analysis capability of the Fuzzy CFMEA approach allows measuring, estimating, and evaluating the constructability improvement of the proposed solution. Thus, improve the key drawback of the traditional constructability programs in implementing automated constructability analysis and improvement. Therefore, the proposed Fuzzy CFMEA is more suitable for developing a automated constructability analysis and improvement system as compared with the previous approaches.

6. CONCLUSIONS

This paper presented a new method for quantitative constructability analysis and knowledge acquisition. The proposed approach combines the ISO document system and a fuzzy constructability failure mode and effects analysis (CFMEA) procedure to provide a knowledge-based system for constructability analysis and improvement. The ISO document system is used as a media for collecting constructabiliity lessons-learned. The Fuzzy CFMEA is adopted for quantitative constructability analysis. The modified FMEA, CFMEA, shows a promising solution to link the detected constructability problems with the possible solutions through design improvement. It is concluded that the integration of the ISO document system and the Fuzzy CFMEA provides a promissing solution for automated and continuous constructability improvement which is desirable but not found in the traditional constructability programs.

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