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# Construction Safety Monitoring Based on The Project's Characteristic with Fuzzy Logic Approach

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**Abstract.** Construction workers accident is the highest number compared with other industries and falls are the main cause of fatal and serious injuries in high rise projects. Generally, construction workers accidents are caused by unsafe act and unsafe condition that can occur separately or together, thus a safety monitoring system based on influencing factors is needed to achieve zero accident in construction industry. The dynamic characteristic in construction causes high mobility for workers while doing the task, so it requires a continuously monitoring system to detect unsafe condition and to protect workers from potential hazards. In accordance with the unique nature of project, fuzzy logic approach is one of the appropriate methods for workers safety monitoring on site. In this study, the focus of discussion is based on the characteristic of construction projects in analyzing "potential hazard" and the "protection planning" to be used in accident prevention. The data have been collected from literature review, expert opinion and institution of safety and health. This data used to determine hazard identification. Then, an application model is created using Delphi programming. The process in fuzzy is divided into fuzzification, inference and defuzzification, according to the data collection. Then, the input and final output data are given back to the expert for assessment as a validation of application model. The result of the study showed that the potential hazard of construction workers accident could be analysed based on characteristic of project and protection system on site and fuzzy logic approach can be used for construction workers accident analysis. Based on case study and the feedback assessment from expert, it showed that the application model can be used as one of the safety monitoring tools.

## INTRODUCTION

The occupational accident in construction is the highest number compared with other industries in Indonesia. Based on the data from *BPJS Ketenagakerjaan*, the total number of occupational accident in minor category, it is rising until 5% each year and the major accident category has higher increasing trend between 5% - 10% in each year [4]. Based on the previous literatures, it is stated that some accidents of construction workers is caused by some factors, such as: unsafe act, unsafe condition, management, and time factors [6, 7, 8, 12, 22].

In Indonesia, 20 occupational accidents per 100.000 workers, for 31.9%, happen in construction sector and are the highest with the details of: falls (26%), collision (12%), and strucked (9%) [29]. In America and almost all other countries, construction workers are quite possible to get work accident. On the other hand, based on the data from *CPWR, The Center for Construction Research and Training U.S* that is supported by *National Institute for Occupational Safety and Health (NIOSH),* the prediction number of construction workers is rising 33% in the last decade (between 2010 – 2020) [31].

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Project's physical characteristic as one of the unsafe conditions causes of fall from the height [2, 3, 9, 10, 13, 25, 28]. Project's characteristic that causes of fall is identified as hazard area [17, 30, 32]. The typical of hazard in construction project in context of fieldwork is working too close with unprotected edge and incident that can cause slipped or fall [20]. Many researches were conducted related to fall accidents, project's characteristic and hazard's type that causes accident and analyse information technology based development system [5, 11, 22, 27, 35]. Whereas, the application of fuzzy logic method and its development has been used in many industries, such as research related to work accident prevention. This approach method is used because it is simple and can be used to cover the weakness of qualitative approach when subjectivity, vague, and ambiguous comment and ranking of experts are appearing, so that it can get better accuracy [9, 16, 18, 33]. Based on the problem, that is why continously monitoring system to detect unsafe condition and protect workers from potential hazard using fuzzy logic approach is needed.

## Hazardous Area in Construction

Hazardous area is identified as area of hazard risk bounded by warning area. There are 3 dimentional models of hazard area, that are: point hazard, line hazard and area hazard [19]. Based on the analysis of accident caused by fall, there is 70% accident happened in the elevation of < 21.35 m (70 ft). While the horizontal distance between workers and hazard that must be determined is 3 meters for fall hazard from the height [19]. The work field with more than 2 meters height must be given protection planning form fall hazard [1, 14]. So, in this study, we used the average number of fall from height ≤ 20 meter. Based on hazard's type on site, it is divided into two types: static hazard and mobile hazard. Which is included in static hazard such as unprotected edges, roof, and floor openings, while mobile hazard such as equipment [19]. In this research, the analysis was only conducted to static hazard excluded temporary structure in the application of slab structure that is referring to the research of [23] by adopting dimention of hazard area as the research finding of [19].

## Work Accident's Prevention and Control

Prevention action of fall from height can be done by minimizing the number of hazard potential and conducting protection to worker's condition through work performance monitoring [21]. Based on the research conducted by [26], it was found that the result of identification from the availability of fall protection types are guardrail system, safety net system, personal fall arrest system, safety monitor, warning line and slide guard. *S*election and combination of protection used, depending on potential hazard on site. It is necessary to optimize the application of workers accident prevention.

## METHODS

The dynamic character of construction project causes high mobility to workers in performing the activities, so construction requires a continuously monitoring system to detect unsafe condition and to protect workers from potential hazards. In accordance with the nature conditions of project, fuzzy logic approach is one of the appropriate methods which can be used for safety monitoring of workers on site. The analysis framework is shown in Fig. 1.

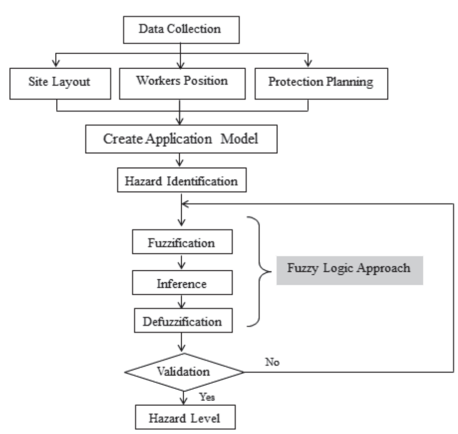



**FIGURE 1.** The analysis framework

## Data Collection

Data was conducted based on literature review (previous study in safety and health), secondary data (planning design and protection planning will be applied) and interview with the experts who has experienced in construction project expertist more than 5 years, academician related to the study of work safety and health and institution related with safety and health. The interview was conducted to obtain numerical variable data related to potential hazard based on project's characteristic when workers perform their job at high elevation.

## Site Layout Identification

Identification of project's characteristic based on the planning design that is in a form of coordinate (x, y) and identification of hazard location based on building characteristic in a form of hazard area coordinate (x, y). Hazard area is identified as line hazard for unprotected side and hole/ floor opening.

## Fuzzy Logic Analysis

Fuzzy logic was introduced by Lofti Zadeh in1965. This approach gives a basis to generate powerful, commonly used as problem solving techniques, especially on decision making [16]. In fuzzy logic, decision making is done by using inference system. There several method in fuzzy inference system such as Mamdani and Sugeno. This research used Mamdani method that is mostly applied because the structure is simple. Fuzzification is the first step in fuzzy logic. It is a modification of set theory where each of its member has membership level between 0 – 1. If U is *universe* object and x is U member, a *fuzzy set* A in U is defined as a membership function $\mu_A(x)$, that determine every object in U to be a real value in interval [1, 0]. The value of $\mu_A(x)$ explains membership level x in A:

$$A = \{(X, \mu_A(X)) \mid X \varepsilon X\} \tag{1}$$

The value of μ that has been obtained from the first step will be applied in fuzzy rule base. Fuzzy rule base is a set of rules based on knowledge based in the form of implication function between input and output with association rule approach. Some rules used fuzzy logic algorithm is explained as following:

$$\text{IF antecedent THEN consequent} \tag{2}$$

In a system with free variable (at consequent) x1, …. , xn and numbers of m bound variables (at antecedent) y1, … , ym. For example R is a basis of some fuzzy rules:

$$\begin{aligned} &\text{IF Pr } (x1, ..., xn) \text{ THEN Qr } (y1, ..., ym) \\ &\vdots \\ &\text{IF Pr } (x1, ..., xn) \text{ THEN Qr } (y1, ..., ym) \end{aligned} \tag{3}$$

Where P1, …, Pr shows fuzzy predicate for free variable and Q1, …, Qr shows fuzzy predicate for bound variable. The last step is defuzzification, which is changing the linguistic variable from fuzzy output into crisp value. There some methods of defuzzification process such as centroid method, weighted average method and max method.

### *Fuzzification*

Based on [7], triangular fuzzy number (TFN) are often utilized to provide more precise description and obtain more accurate results [16]. A membership function of fuzzy set is called triangle fuzzy set when it has 3 parameters, they are: a, b, c ϵ R with a < b < c, explained with S (x, a, b, c) using rules:

$$\mu(X) = \begin{cases} 0, x \le a \text{ or } x \ge c \\ (x-a)/(b-a), a \le x \le b \\ (b-x)/(c-b), b \le x \le c \end{cases} \tag{4}$$

In this research, some input variables are used to determine the hazard level as output. Input variable consisted of hazard type and accident prevention plan. Variable input based on hazard are height of fall and position of worker from hazard (distance from hazard). The linguistic variable for height of fall variable is based on injury level caused by fall accident, while distance from hazard is position of worker from hazard [14, 15, 19]. Fuzzy input for "height of fall" are divided into minor, moderate, serious, severe and lethal. For "distance from hazard", we found immediate, nearby, medium and far as fuzzy input. Based on accident prevention plan, it is identified the using of guardrail system, safety net system, fall arrest system, hole covering and warning line system as variables. The linguistic variable in this part are "not used", "used (with unstandardized)" and "standard (used standardized)". The protection used is being rated as the effect to the worker safety with the scoring from the experts. We divided the linguistic variables into some categories based on fuzzy range and fuzzy number. This value assessed by expert opinion. Output variable is analyzed based on the level of risk suffered by the workers. Based on the research of [15], risk assessment is a multiplication function between distance from hazard dan injury level (as consequence of falls from height) plus the effectiveness of protection used to minimize accident risk. From the range value based on literature review then we found the fuzzy number based on expert judgment. This fuzzy number is shown in the combination of up linear, triangle, and down linear representation (Table 1).

### *Inference*

There are seven bound variables (antecendent) which are the height of fall, distance from hazard, the using of guardrail system, the using of safety net system, the using of fall arrest system, the using of hole covering, and the using of warning line system. Whereas the free variable (consequent) is the level of hazard. Based on the review of literature and observation with the experts, it is obtained that the combination of fall's protection can give efficiency and optimalization to the workers' safety; generally, it can use the combination of two items of safety protection based on the condition of working field.

**TABLE 1.** Fuzzy Set

| Function | Variable | Linguistic Variable | Range | Fuzzy Number |
|---|---|---|---|---|
| Input | Height of Fall | Minor | [0 20] | [0 2] |
| | | Moderate | | [1.4 5] |
| | | Serious | | [3.5 10] |
| | | Severe | | [8.1 13.6] |
| | | Lethal | | [10.9 20] |
| | Distance from Hazard | Immediate | [0 3] | [0 0.5] |
| | | Nearby | | [0.4 1.3] |
| | | Medium | | [1 2.1] |
| | | Far | | [2.1 3] |
| | Guardrail system | Not Used | [0 10] | [0 1.8] |
| | | Used | | [1.5 5.1] |
| | | Standard | | 5.1 10] |
| | Safety Net System | Not Used | [0 10] | [0.3 2.3] |
| | | Used | | [2 5.5] |
| | | Standard | | [5.3 10] |
| | Fall Arrest System | Not Used | [0 10] | [0 1.9] |
| | | Used | | [1.4 4.9] |
| | | Standard | | [4.6 10] |
| | Hole Covering | Not Used | [0 10] | [0 1.6] |
| | | Used | | [1.3 5] |
| | | Standard | | [4.5 10] |
| | Warning Line System | Not Used | [0 10] | [0 1.8] |
| | | Used | | [1.3 5] |
| | | Standard | | [4.5 10] |
| Output | Level of Hazard | Low | [0 20] | [0 6] |
| | | Medium | | [5 12] |
| | | High | | [9 16] |
| | | Very High | | [15 20] |

The fuzzy inference system is using Mamdani method with implication function using AND operator obtained by using MIN function. According to Siller, the function of MIN is the function to find the smallest membership value from two or more operand [24]. Generally, it can be drawn as following equation:

$$\mu A \cap B = \min\left(\mu A\left[x\right], \mu B\left[y\right]\right) \tag{5}$$

Analysis of rule composition uses MAX function by taking maximum value of rule, then using it to modify fuzzy area and applying it to output. According to Siller, generally, the calculation of rule composition can be drawn with the equation of:

$$\mu sf\left(xi\right) = \max\left(\mu sf\left(xi\right), \mu kf\left(xi\right)\right) \tag{6}$$

Where µsf (xi) is the value of fuzzy membership solution until i rule, and µkf (xi) is the value of i rule of consistent fuzzy membership. The fuzzy rule base is generated by the expert opinion. Based on hazard zone and protection systen, we found 180 rules for analysis in fuzzy inference system. The rules ilustrated in Table 2.

**TABLE 2.** Identified fuzzy rule base

| No. | Height of Fall | Distance from Hazard | Protection System 1 | Protection System 2 | Level of Hazard |
|---|---|---|---|---|---|
| 1. | Lethal | Immediate | Not Used | Not Used | Very High |
| 2. | Lethal | Immediate | Not Used | Not Used | Very High |
| 3. | Lethal | Immediate | Not Used | Not Used | Very High |
| 4. | Lethal | Immediate | Used | Used | Very High |
| 5. | Lethal | Immediate | Used | Used | Very High |
| 6. | Lethal | Immediate | Used | Used | Very High |
| 7. | Lethal | Immediate | Standard | Standard | Very High |
| 8. | Lethal | Immediate | Standard | Standard | Very High |
| 9. | Lethal | Immediate | Standard | Standard | Very High |
| 10. | Lethal | Nearby | Not Used | Not Used | Very High |
| . | . | . | . | . | . |
| . | . | . | . | . | . |
| . | . | . | . | . | . |
| 180. | Minor | Far | Standard | Standard | Low |

*Defuzzification*

In this research, defuzzification used centroid method as generally used in fuzzy Mamdani. Centroid method takes central point (Z*) of fuzzy area as crisp solution through following equation:

$$z^* = \frac{\int_a^b \mu A\left(z\right).z\,dz}{\int_a^b \mu A\left(z\right)dz} \tag{7}$$

The example value of Z* and the linguistic variable of hazard level is shown in output program.

## RESULT AND DISCUSSION

### Case Study

In this research, supporting tool is used for systematic calculation for fuzzy logic analysis using Delphi programming. it has a good interface and user friendly. The reason why we build our own application model is to make it easier in analysis when integrated with another sub system in the future work. In this application model, fuzzy logic analysis is used to represent hazard level caused by physical project's characteristic and protection system. From this application, we can simulate the hazard level of worker in construction site as the final output.

The main display of application model can be illustrated in Fig. 2. We used a high-rise building construction project in Malang, Indonesia, for case study.

The first step in this input program is project's characteristic identified based on the planning design in a form of coordinate (x, y). By inputting these coordinates, the project layout will be drawn. Then we can fill the opening/ hole on the layout according to the design. The results of identification will automatically show hazard lines on the building. Then, an initial worker's position was choose at the project location such as Z point in Fig. 4. This data used to indicate whether worker was in the hazard area or safe zone and will automatically become the data variable of "distance from hazard" for simulation in application model. All of these identification are shown in Fig. 3.

Then, the hazard zone will be identified around the hole or opening or unprotected side and illustrated as line diagram in Fig. 5. Furthermore, the fuzzy number and membership function were inputted to the application according to table 1. All rules that have been identified are directly stored in the application database (Fig. 5).

The final step is running the program using the example of data variables from project case. We can choose the value of "height of fall" variable and combination of safety protection used on site. Especially, for "distance from hazard" variable just need to fill Z point as workers position and will automatically show the distance value and category of distance from hazard. We simulate the hazard level by filling the option menu in the empty box on each variable. The final result is shown in Fig. 6.


**FIGURE 2.** Main display of application model

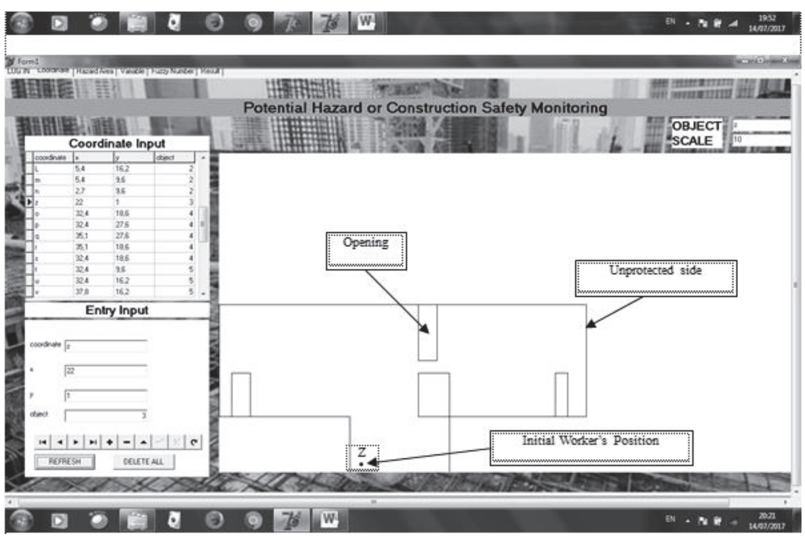



**FIGURE 3.** Setting layout and hazard identification

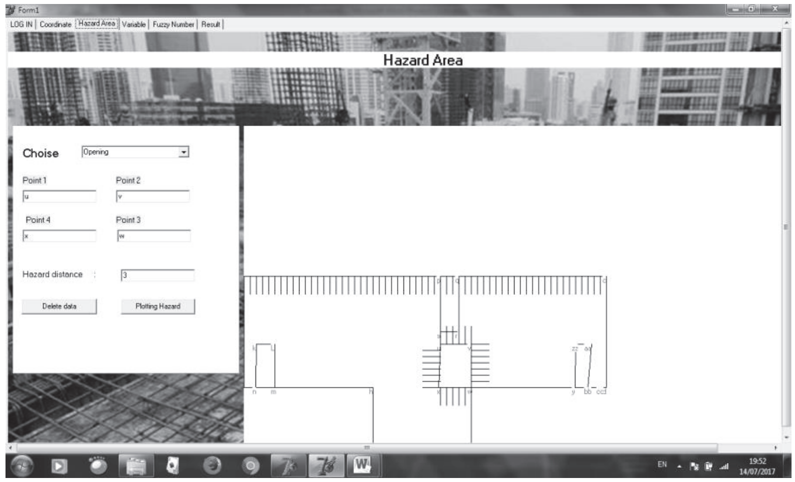
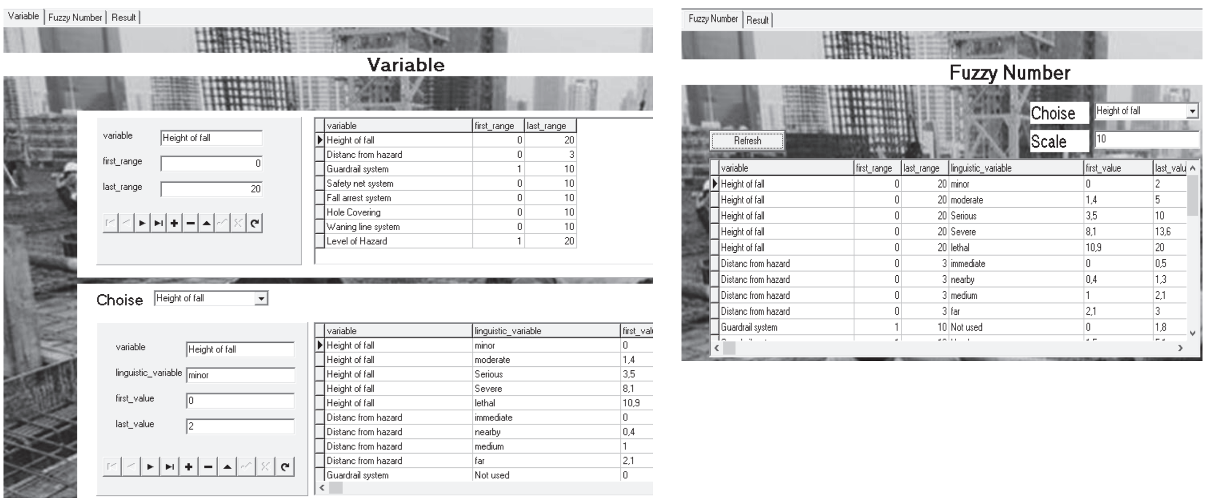



**FIGURE 4.** Hazardous area




(a) (b)

**FIGURE 5.** Fuzzy Set; (a) Input menu of variables, (b) Summary of variables.

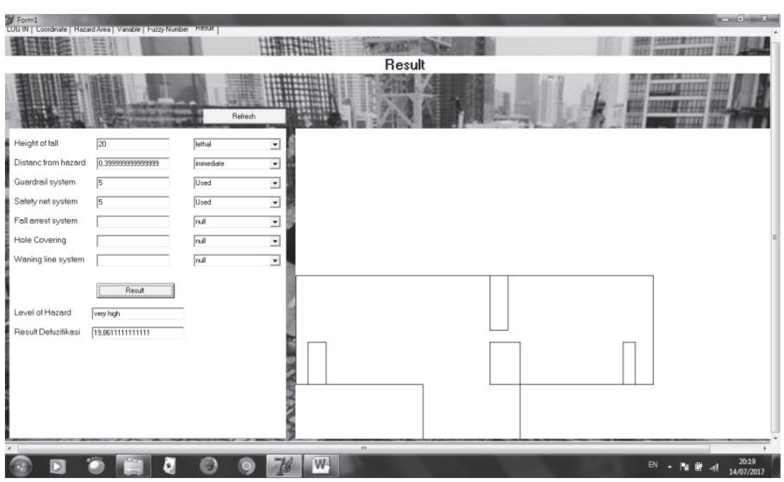



**FIGURE 6.** Output program

## Discussion

From some tests conducted to workers' position when they are in high elevation with safety protection, the finding showed the hazard level that can occur to the workers in construction site. For example when initial workers position (Z) was identified in coordinate of (22.0; 1.0) in 20 m elevation from the ground. The position showed that the hazard area is "Unprotected side" with "Immediate" criteria for distance from the hazard category. The elevation means that workers position is in "lethal" criteria for height of fall based on injury level. The Assumption of protection planning are "Used" guardrail system and "Used" fall arrest system on site. By clicking the result button, we found the linguistic variable of the output and the value of defuzzification process. The result of a potential hazard according to the sample case is "Very High" which means the worker is in very danger condition when working in this position (Fig. 6). After we conduct the trial many times with some other data on the application model, it can be placed the result tabulation of running program (Fig. 7).

**TABLE 3.** The trial data tabulation on the model

| Coordinate | Distance from hazard (m) | | Height of Fall (m) | | Guardrail System | | Fall Arrest System | | Level of Hazard | |
|---|---|---|---|---|---|---|---|---|---|---|
| (22.0 ; 1.0) | 0.39 | Immediate | 20 | Lethal | 5 | Used | 5 | Used | 19.2 | Very High |
| (29.4 ; 15) | 3 | Far | 3 | Moderate | 2 | Used | 4 | Used | 11 | High |
| (15.6 ; 10.0) | 0.4 | Immediate-Nearby | 17 | Lethal | 3 | Used | 9 | Standard | 11 | High |
| (45.0 ; 27.0) | 0.6 | Nearby | 1 | Minor | 8 | Standard | 7 | Standard | 4.9 | Low |
| (37.0 ; 0.4) | 0.4 | Immediate-Nearby | 7 | Serious | 2 | Used | 2 | Used | 8.5 | Medium |
| (33.0 ; 6.6) | 3 | Far | 10 | Serious-Severe | 4 | Used | 6 | Standard | 5.5 | Medium |
| (13.5 ; 15.0) | 8.1 | Clear Area | | | | | | | | Safe Zone |
| (40.8 ; 14.0) | 3 | Far | 5 | Moderate-Serious | 7 | Standard | 9 | Standard | 5.1 | Medium |
| (33.0 ; 17.0) | 0.8 | Nearby | 10 | Serious-Severe | 10 | Standard | 3 | Used | 11 | High |
| (31.0 ; 24.0) | 1.4 | Medium | 15 | Lethal | 4 | Used | 6 | Standard | 11.4 | High |
| (35.0 ; 21.0) | 0.1 | Immediate | 12 | Severe-Lethal | 7 | Standard | 9 | Standard | 14.9 | High |
| (18.0 ; 27.5) | 0.1 | Immediate | 20 | Lethal | 4 | Used | 2 | Standard | 18.4 | Very High |
| (7.5 ; 15.0) | 2.1 | Medium-Far | 18 | Lethal | 1 | Not Used | 4 | Used | 9 | High |
| (43.0 ; 9.61) | 0.009 | Immediate | 3 | Moderate | 10 | Standard | 10 | Standard | 8.5 | Medium |
| (57.0 ; 13.0) | 0.29 | Immediate | 16 | Lethal | 9 | Standard | 7 | Standard | 14.7 | High |
| (58.5 ; 20.5) | 0.89 | Nearby | 7 | Serious | 2 | Used | 1 | Not Used | 9.7 | High |
| (21.9 ; 4.0) | 0.29 | Immediate | 10 | Serious-Severe | 3 | Used | 3 | Used | 15 | Very High |

As illustrated in Fig. 6, the hazard area can be in the intersection area such as "Immediate" and "Nearby" based on the membership function identification for the same workers position. The application model will analyze the data based on all identified fuzzy rules and then selects only one output according to the fuzzy inference system. This tabulation data is given back to experts to assess whether the results have been close to the real conditions on site. The feedback from the assessment indicates the approval of the experts. When the model has been valid, so we can use the model to track the worker's position related to the hazard level and can be used for warning and decision of worker's safety monitoring. With this model, can also be simulated the risk level of worker accident which is still tolerable based on site condition.

## CONCLUSION

According to the model, it can be concluded that potential hazard in falling from height caused by several factors include physical project's characteristic and the use of fall protection system in project. Based on the finding, it is known that fuzzy approach is able to analyze the hazard level for workers position in site, therefore created model can be used for safety monitoring in construction. From the interview with expert related to the output model, concluded that the model provides good accuracy based on the approval of the expert.

However, this research has some weaknesses because it requires more practical testing to get accurate result when combined into an integrated safety monitoring system in further research. The future research can enhance (1) the research methodology uses triangular fuzzy number to represent linguistic approach, therefore future research can try to use another type of fuzzy number, so it can be compared of fuzzy number that gives a good precision in analysis, (2) hybrid analysis method can be conducted as using fuzzy fault tree or fuzzy bayesian network for future research, (3) the simulation model is improved using more other variables.

## REFERENCES


1. Menakertranskop, *Peraturan Menakertranskop No. Per.01/MEN/1980 tentang Keselamatan dan Kesehatan Kerja dalam Penebangan dan Pengangkatan Kayu* (Departemen Menakertranskop Republik Indonesia, Jakarta, 1978).
2. M. Abderrahim, E. Garcia, R. Dies, and C. Balaguer, Automation in Construction, **14** (4), 460-466 (2005).
3. J. M. Adam, F. J. Pallares, and P. A. Calderon, Journal of Safety Research, **40**, 293-299 (2009).
4. BPJS, *"Jumlah Kecelakaan Kerja di Indonesia Masih Tinggi"*, http://www.bpjsketenagakerjaan.go.id, January 11, 2016, (2016).
5. A. Carbonari, B. Naticchia, A. Giretti, and M. D. Grassi, 26th International Symposium on Automation and Robotics in Construction (ISARC 2009), Austin TX, 2009, Vol. 26, p. 47-54.
6. A. Charehzehi and A. Ahankoob, International Journal of Advances in Engineering & Technology, **5** (1), 303-312 (2012).
7. C.-W. Cheng, C.-C. Lin, and S.-S. Leu, Safety Science, **48**, 436-444 (2010).
8. Y. M. Goh and N. F. Sa'adon, Journal of Construction Engineering Management, **141** (16), 04015003 (2015).
9. M. Gunduz, T. Birgonul, and M. Ozdemis, Journal of Construction Engineering Management, 04016112 (2016).
10. M. R. Hallowell, Professional Safety, **55** (12), 18 (2010).
11. S. G. Herrero, M. A. Mariscal, J. R. L. Garcia, and A. Cofino, edited by L. Podofillini, B. Sudret, B. Stojadinovic, E. Zio and W. Kroger, Taylor & Francis Group, pp. 1951 (2009).
12. S. S. Hosseinian and Z. J. Torghabeh, International Journal of Advances in Engineering & Technology, **4** (2), 53-66 (2012).
13. D. Hsu, Y. M. Sun, K. Chuang, Y. Juang, and F. Chang, Safety Science, **46**, 833-843 (2008).
14. X. Huang and J. Hinze, J., Journal of Construction Engineering and Management, **129** (3), 262-271 (2003).
15. S. Isaac and T. Edrei, Automation in Construction, **63**, 66-78 (2016).
16. M. Javadi, G. Saeedi, and K. Shahriar, Journal of Applied Sciences, **17** (3), 103-115 (2017).
17. H. Li, M. Lu, G. Chan, and M. Skitmore, Automation in Construction **49**, 163-174 (2015).
18. H. T. Liu and Y. I. Tsai, Safety Science, **50**, 1067-1078 (2012).
19. X. Luo, H. Li, T. Huang, and T. Rose, Safety Science **84**, 216-234 (2016).
20. P. Mitropoulos, G. A. Howell, and T. S. Abdelhamid, Construction Research Congress 2005, pp. 1-10.
21. E. A. Nadhim, C. Hon, B. Xia, I. Stewart, and D. Fang, International Journal of Environmental Research and Public Health, **13**, 1-20 (2016).
22. D. A. Patel and K. N. Jha, Journal Construction Engineering Management, **14** (1), 04014066 (2015).
23. J. Qi, R. R. A. Issa, S. Olbina, and J. Hinze, Journal of Computing in Civil Engineering, **28** (5), (2014).
24. Rodiah and R. Widodo, *Seminar Nasional Teknologi Informasi dan Komunikasi Terapan* (SEMANTIK), p. 471 (2015).
25. H. Russell, B. Maitre, and W. Dorothy, The Economic and Social Research Institute (2015).
26. J. Sa, D. C. Seo, and S. D. Choi, Journal of Safety Research, **40,** 1-6 (2009).
27. R. Sacks, O. Rozenfeld, Y. Rozenfeld, Journal of Construction Engineering and Management, **135** (8), 726-736 (2009).
28. N. Sooksil and V. Benjaoran, Association of Research in Construction Management, Portsmouth, *Procs 30th Annual ARCOM Conference*, pp. 371-379 (2014).
29. L. Sulistyowati, "*Angka Kecelakaan Pekerja Konstruksi 31.9%",* http://www.republika.co.id/berita/nasional/umum/15/06/29/nqplkta-angka-kecelakaan-pekerja-konstruksi-319-persen*,* June 29, 2015, (2016).
30. J. Teizer and T. Cheng, Automation in Construction, **60**, 58-73 (2015).

31. A. J. Tixier, M. R. Hallowell, B. Rajagopalan, and D. Bowman, Automation in Construction, **62**, 45-56 (2016).
32. D. Wang, F. Dai, and X. Ning, Journal of Construction Engineering and Management, 141 (6), 04015008 (2015).
33. W. Yanfu and X. Min, International Symposium On Safety Science and Technology 2012, pp. 131-138 (2012).
34. W. Yi, A. P. Chan, X. Wang, and W. Jun, Automation in Construction, **62**, 101-113 (2016).