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OPTIMIZING SEARCH AND RESCUE PERSONNEL ALLOCATION IN DISASTER EMERGENCY RESPONSE USING FUZZY LOGIC

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ABSTRACT

Several models have been developed to facilitate decision-making in disaster management, especially in relation to emergency resource allocations. These models are required in order for search and rescue personnel to operate efficiently. However, in Indonesia, in general, technology has not been used to help make decisions during the response phase; rather, these decisions are still made subjectively. This paper presents a decision-making model that helps search and rescue teams determine the number of personnel to deploy. Therefore, it streamlines the allocation of personnel in a search area, and it determines the number of personnel that are needed based on the area, population density, equipment, and the number of high buildings. Then, those variables are processed using a fuzzy expert system and a decision tree. The data and knowledge acquired as a reference were obtained from disaster management experts as well as experienced practitioners in the field of Search and Rescue.

Keywords: Decision tree; Disaster management; Fuzzy expert system; Search and rescue

1. INTRODUCTION

Indonesia is situated at the intersection of three major tectonic plates—the Indo-Australian, Eurasian, and Pacific plates—that collide. Thus, this region experiences many earthquakes, and tsunamis that occur due to tectonic activities. An earthquake is a natural disaster, the occurrence of which is unpredictable even though some variables can indicate if one will happen. However, until now, these indications have not yet achieved a high accuracy rate, so regions with a high disaster risk need to devise other methods for managing an earthquake, considering that it is a disaster that can exact a severe toll in terms of its impact on the economy, human lives, and physical damage. Based on risk assessment data reported by the National Disaster Management Agency BNPB (BNPB, 2016), the social losses that Indonesia has to bear because of earthquakes include: 86,247,258 lives, IDR 406,689,834 in physical structure losses, and IDR 182,185,171 in economic losses. Hence, Indonesia needs to have an effective natural disaster management policy to reduce these risks.

Disaster management is a series of activities implemented prior to, during, and following the occurrence of a disaster. There are five disaster phases in the disaster management cycle:

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planning, mitigation, response, recovery, and evaluation (Herrmann, 2007). The response phase is the execution phase of the planning; it addresses the need to reduce the losses caused by the disaster. Therefore, all stakeholders must contribute to increasing the efficiency of the disaster response.

In Indonesia, the BNPB, a non-ministerial government agency, is responsible for conducting disaster management, including the response phase that covers the pre-disaster phase, the disaster phase, and the post-disaster phase. To fulfil its duty, BNPB is supported by a search and rescue (SAR) team and volunteers. Based on BNPB's 2017 performance report, BNPB needs 24 hours post-incident to respond to a disaster. Moreover, the time needed to disseminate information to the public regarding the disaster occurrence is about 3 hours. Based on the 2016 performance report released by SAR, the survivor percentage was 79.86%; thus, there is room for improvement. The response time and survivor percentage are affected by the capability of the rescue team and the availability of information regarding the victims.

Several decision-making models are used in disaster management, especially in regard to emergency resource allocations. They are required in order for SAR personnel to operate efficiently. However, in Indonesia, technology has not been used to help make decisions in the response phase. Furthermore, fuzzy logic and mathematical models have not been used in disaster management. The 2015 National SAR Agency (BASARNAS) performance report regarding the percentage of the number of survivors and victims found during SAR operations, were 83.21% and 96.61%, respectively (BNPB, 2016). The result indicates that the response efforts made to save victims can be improved. Moreover, because the number of rescuers is limited, it is essential that personnel allocation be optimized. While previous studies have investigated similar issues, none have made use of fuzzy logic. In fact, it is one of the most suitable methods used for decision making in relation to disaster problems (Öztaysi et al., 2013).

1.1. Disaster Management

According to the 2007 Indonesian Law Number 24, disaster management is a dynamic, continuous, and integrated process to improve the quality of the actions related to disaster observation and analysis. It also encompasses prevention, mitigation, preparedness, early warning, emergency response, recovery, and post-disaster reconstruction.

The cycle of disaster management (Figure 1) can be described in various ways, using different terms; however, the continuity of the interlinked activities carried out throughout the cycle is the most important factor. Hence, this cycle is not intended to be a string of activities that begins and ends every time a disaster occurs (Carter, 2008).

Figure 1 Disaster management cycle

According to the 2008 Regulation of the Head of National Disaster Management Agency Number 4 concerning the Instruction Guide for Disaster Management Planning, there are three phases in the implementation of disaster management: the pre-disaster phase, the emergency response phase, and the post-disaster phase. For the areas that have the potential to experience a disaster, several activities need to be done in the pre-disaster phase, including preparedness, early warning, and mitigation.

Emergency response is a series of activities carried out immediately during the occurrence of a disaster to deal with the resulting adverse effects. Thus, the emergency response process consists of the rescue and evacuation of the victims and property, fulfilment of basic needs, protection, management, caring for refugees, and rehabilitation of the infrastructure and facilities. During the emergency response phase, disaster management activities include: (1) conducting a quick and precise assessment of the disaster location, damage, and resources; (2) determining the emergency status of the disaster; (3) rescuing the victims by providing humanitarian services and evacuating them from the affected area; (4) fulfilling basic needs, such as clean water, sanitation, food, clothing, health services, psychosocial services, and shelter; (5) providing protection to vulnerable groups (babies, toddlers, children, pregnant and breastfeeding women, the disabled, and the elderly) by prioritizing them to gain access to basic needs provision (Awange, 2012); and (6) immediate recovery of vital infrastructure and facilities.

The action in this emergency response phase is divided into two sub-phases: the acute phase and the sub-acute phase. In the acute phase, the first 48 hours after the disaster are considered to be the rescue and medical assistance phase. The sub-acute phase occurs in the first 2–3 weeks after the disaster.

In the post-disaster phase, the activities of disaster management include: (1) rehabilitating and improving all aspects of public services to an acceptable level, with the main objective of stabilizing and normalizing the government and community life in the post-disaster areas; and (2) reconstructing the infrastructure and facilities at the government and community levels, with the main objective of restoring economic, social, and cultural activities.

1.1.1. Disaster preparedness phase

Disaster preparedness is an effort to develop an initial response to a disaster (Herrmann, 2007). While disaster preparedness and response are two different periods of a disaster, having a solid basis and sound framework for disaster preparedness can improve the effectiveness of the actions carried out in the response phase (Anson et al., 2017).

Preparedness enables the stakeholders, such as the government, organizations, communities, and individuals, to respond to the disaster situation rapidly and effectively (Granville et al., 2016). Based on the 2007 Indonesian Law Number 24 concerning Disaster Management, preparedness is a series of activities conducted to anticipate disaster through effective and efficient planning and organizing. The preparedness phase activities are: (1) preparing and testing the disaster emergency managements plans; (2) organizing, installing and testing an early warning system; (3) preparing and providing the goods to fulfil basic needs; (4) organizing, counseling, training, and rehearsing the emergency response mechanisms; (5) preparing the evacuation site; (6) compiling information data and updating emergency response procedures; and (7) providing and preparing materials and equipment to fulfill the requirements for the recovery of infrastructure and facilities.

Preparedness measures tend to be more oriented toward the action of individual organizations, because the significant number of organizations that are involved in a disaster highlight the requirement for strong coordination. Hence, some critical matters must be addressed. A national disaster policy, disaster management agencies, and organizational structure for disaster preparedness are essential to ensure that the disaster response is given proper consideration, and that it will be implemented, whenever necessary, by formally appointed legislative body. An adequate assessment of the disaster threat is necessary so that a reasonable forecast of the effects caused by disasters can be determined, which can impact the preparedness measures. To be fully effective, the preparedness measures need to be identified in an appropriate plan so the necessary resources can be arranged, monitored, and updated to ensure that they will still be in their best condition when they are required.

Preparedness involves activities that will be carried out by organizations, so an organizational framework is needed for the operation to be successfully accomplished. Adequate preparedness is also needed for the facilities and systems required for the response operations. These include emergency or stand-by communications, a warning system, a system for organizational structure activation, emergency operation centers, a system for damage survey, and emergency relief arrangements for food, shelter materials, medical assistance, etc. Appropriate surveillance is also needed to ensure the availability and condition of the facilities and systems. Training is another important component in preparedness, so there should be a permanent training system that addresses all the needs of government officials and nongovernmental organizations (NGOs). One of the most valuable assets for preparedness is an aware, alert, and informed public. Thus, public awareness programs are needed, and they are a long-term investment to increase the chances of survival.

1.1.2. Disaster response phase

Disaster response should be carried out immediately after a disaster event (Carter, 2008). It includes implementing plans, implementing disaster response systems, conducting search and rescue activities, providing logistics, surveying and assessing the damage, and evacuating victims. Disaster response is carried out over a short period of time, about 2–3 weeks after the event. Disaster response aims to reduce the number of victims, reduce the effects of the damage, restore life and community support systems, reduce losses, and provide a basis for recovery. Potential problems that may occur are influenced by several factors that must be considered in response strategies, one of which is unreliable information management, such as information gathering, information evaluation, and information dissemination. This is contrary to meeting the requirements for achieving effective response measures, since information and resources are the two fundamental aspects of an effective response (Carter, 2008). The success of an emergency response operation depends on the time needed to conduct a rescue operation, where the rescue response window is approximately 72 hours after the disaster occurs. If people are not rescued within 72 hours of the disaster occurrence, they will most likely die (Aghamohammadi et al., 2013).

According to Carter (2008), the keys to emergency response actions include the rescue activity for trapped disaster victims, the handling the victims, such as corpse management, the provision of first aid provision, and the identification of the needed medical treatment. Evacuation is also a key activity; thus, the priority victims that should be evacuated immediately are identified. Other key factors that should also be considered are the provision of temporary shelter, management of food distribution for the survivors, improving the performance of communication facilities, access to open roads to accommodate travel needs, and the provision of temporary facilities that have a sufficient supply of water and energy. To maintain the level of health in areas affected by the impact of the disaster, the provision of sanitation facilities should be considered. Public information ensures that the victims know how to handle themselves during the incident; it also improves security so criminal activities can be avoided. The last two key factors that should be considered regarding imminent recovery are the estimation of buildings that must be reconstructed and the provision of mental health services to assist victims in recovering from the trauma they experienced.

According to the 2007 Law No. 24 concerning Disaster Management, the disaster response phase in Indonesia is considered to be an emergency response phase that includes activities, such as rapid and precise assessment of the location, damage, and resources, determination of the level of the disaster emergency condition, rescuing and evacuating the affected people, fulfilling basic needs, protecting vulnerable groups, and immediate recovery for vital infrastructure and facilities.

The assessment mentioned above was explained in Article 49 of the law; it should contain information about the extent of the disaster location, the number of victims, the extent of the damages to facilities and infrastructure, the interruption to the function of public services, and the state of the area's natural and artificial resources. As the disaster management agency, BNPB should establish a disaster emergency response command that all stakeholders can use to integrate the deployment of human resources, equipment, and budgets.

The emergency response command, as stated in the 2008 Regulation of the Head of National Disaster Management Agency Number 10 concerning Guidelines for Disaster Emergency Response Command, consists of several main tasks, including: (1) planning a disaster response operation; (2) submitting requests for assistance; (3) implementing and coordinating the mobilization of resources for handling the disaster response appropriately, efficiently, and efficiently; (4) collecting information using a problem formulation that contains 5W+1H as the basis for district/city/provincial/national disaster response command planning; and (5) disseminating information about disaster events and providing them to mass media outlets and the public.

1.2. Indonesia Disaster Response Management

Indonesia has several institutions that are involved in the process of disaster response: BPNB, the Regional Disaster Management Agency (BPBD), BASARNAS, the Office of Search and Rescue, Potensi SAR (auxiliary element with no educational background and training in search and rescue), mass media, the Meteorological, Climatological, and Geophysical Agency (BMKG), and national and local governments. The scheme shown in Figure 2 illustrates how communication works when a disaster occurs in Indonesia.

In the event of a disaster, BMKG will verify information about its occurrence, and once verified, it delivers that information to BPBD and the regional SAR office in the areas affected by the disaster, while, simultaneously, sending the information to mass media outlets to provide the public with an early warning. In this process, BPBD will also provide initial information to the public, so people can immediately evacuate when necessary.

BPBD and the regional SAR office will create a quick response team to conduct an initial assessment after receiving information from BMKG. Based on the 2007 Law No. 24 concerning Disaster Management, this initial assessment is conducted to identify the scope of the disaster site, the number of victims, the damage to the infrastructure and facilities, intrusions on the function of public and government services, and the condition of the natural and artificial resources. The results of this disaster assessment are handed to BNPB and BASARNAS; later, the information is shared with the government. Simultaneously, along with the initial assessment, personnel from the regional SAR office, known as Siaga SAR, are mobilized to administer first-aid procedures to the disaster victims.

After the information is collected, the government determines the level of the disaster that occurred. If the disaster is classified as a national disaster, the central government appoints BNPB officials to serve as the central command responsible for managing the emergency response. If the disaster is classified as a local disaster, the local government will appoint BPBD officials to serve as the command to conduct the emergency response (Hartono et al., 2010). Furthermore, command officers coordinate with the central and regional SAR officers and the government to provide public services.

SAR will appoint SAR personnel to conduct SAR operations assisted by Potensi SAR, which consists of the Indonesian Red Cross Society (PMI), the Indonesian National Armed Forces

(TNI), the Indonesian National Police, and the community. The 2009 National SAR Agency Regulation No 22 concerning Guidelines for SAR Operations states that the search time for victims is no longer than 7 (seven) days, but it can be extended if needed. The SAR operation is conducted according to International Search and Rescue Advisory Group (INSARAG) standards.

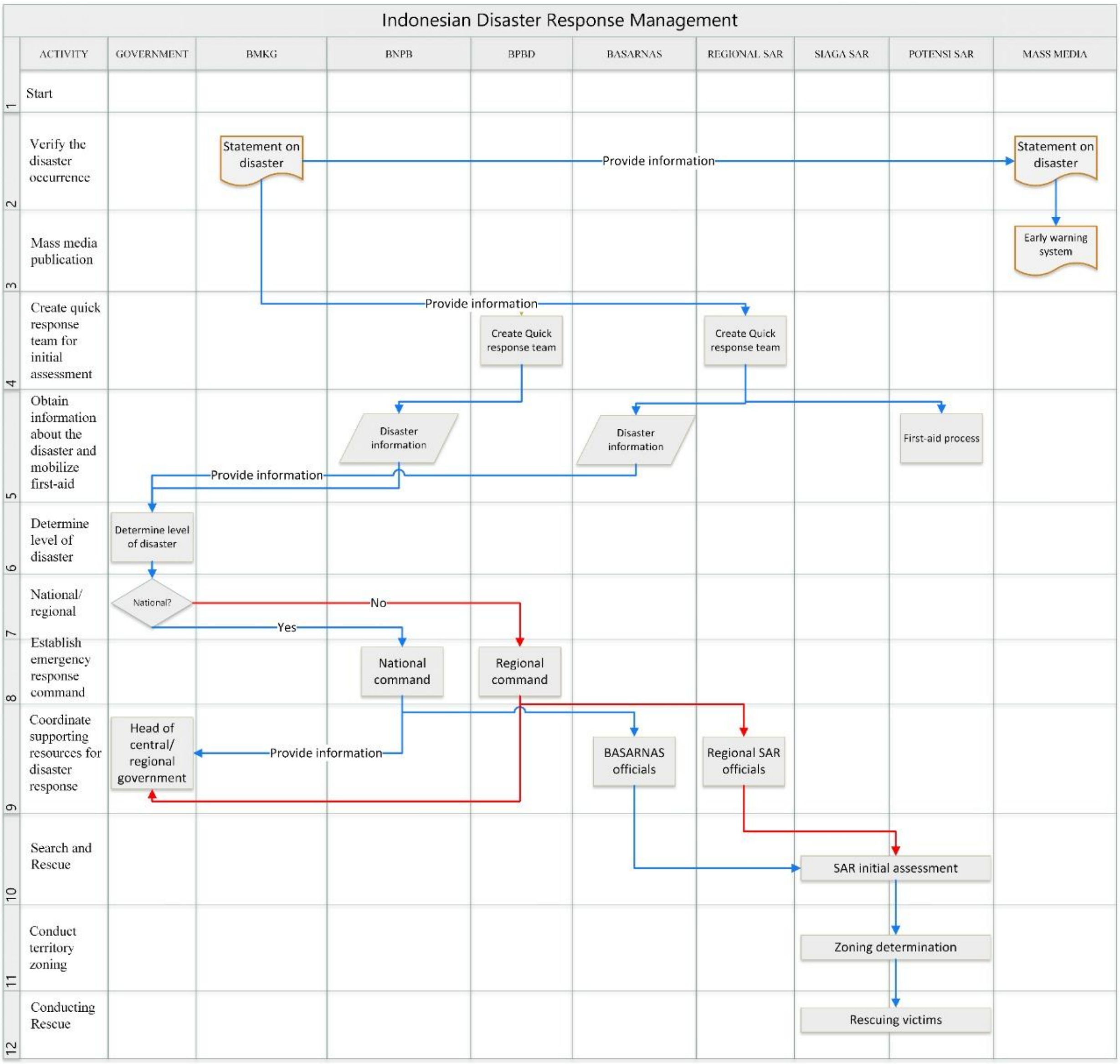

Figure 2 Indonesian disaster response management

As seen in Figure 2, several institutions play a significant role in the disaster response process. The institution in charge of disaster response management is appointed based on the level of the disaster. It will coordinate with the central government during the disaster response process.

1.3. Disaster Management and Information & Communication Technologies (ICTs)

Mastery of ICTs is very important in the globalization era (Qosasi et al., 2019). ICTs play a significant role in disaster prevention, mitigation, and management (Berawi, 2018). In the digital era, computers are used to access, process, and present information. They are also used to explore the intra-network (intranet) and international networks (internet), individually or in groups.

The development of science and technology is characterized by progress (Shoushtary, 2013). For example, thanks to technology, the victims of a disaster can be detected by creating a system that enables them, when they are trapped in ruins, to use their cell phones to send messages to the SAR team, indicating that they are fine and can be saved (Matos & Blake, 2006). Furthermore, the message can also be used to let the families of the victims know they are still alive.

Satriano et al. (2011) also reported on an application that determines the locations and strengths of earthquakes in real-time in order to increase the accuracy of the early echo warning system. However, occasionally, it provides false alarms.

2. METHODOLOGY

First, a literature review was conducted to identify the independent variables that will determine the allocation of SAR personnel needed when a disaster occurs. Some of the previous studies that were conducted and the provisions that have been applied in other countries are listed in Table 1, below.

Table 1 Research variables and associated studies

Variables	Literature Sources
SAR Personnel Allocation	Schweier and Markus (2004)
Number of Buildings	Schweier and Markus (2004)
Search Area	Abi-Zeid and Frost (2005)
Population Density	Wu (2018)
Building Density	Schweier and Markus (2004)
SAR Personnel Equipment	Tang et al. (2017)

Additional stages for processing the variables were obtained from the literature review. First, in-depth interviews with experts were used to validate the variables. In these interviews, experts added or deleted the existing variables based on the conditions in Indonesia. The experts used in these interviews are staff members from BNPB and BASARNAS and SAR personnel that are experienced in disaster management, especially regarding SAR operations. Furthermore, after obtaining the new variables (if any), a questionnaire was created to determine the degree of membership of each variable for fuzzy processes. These were obtained by normalizing the results from the obtained questionnaire data; therefore, a graph was created to illustrate the level of suitability of each dataset. Furthermore, data processing was done using machine learning to obtain the relationship between the variables and the model; and, the best accuracy was chosen. Finally, the data for the degree of membership and the relationship of each variable were obtained.

After obtaining the data, the input process was carried out using the MATLAB-based fuzzy inference system. (FIS) Furthermore, the relationship between the independent and dependent variables was identified.

In the last step, the models which have been made with the operating system were combined. The literature review and the interviews that were conducted with experts in the field of operating systems were used to validate the proposed models. Finally, the SAR operations activities were created to integrate the existing information systems with the models made by the researchers.

3. RESULTS AND DISCUSSION

After the questionnaires were distributed and the responses were analyzed, the obtained data were tested for validity and reliability. Both of these tests were conducted using the IBM SPSS Statistics 24 software, with a minimum r of 0.288. Then, the reliability and validity tests were compared with the r-value. Based on the validation test, some of the questionnaire items needed to be discarded because the r-value was below the minimum r. In the questionnaire items used to determine the personnel allocations, 7 out of 56 of the items were invalid and needed to be discarded. The result of the reliability test dataset was 0.864 for personnel allocation. It can be seen that all items have a value of r, which is above the r minimum; therefore, all the items are reliable.

The fuzzy rules show how a system operates. This will be used in the FIS, which is obtained from the machine learning models that have the best classification accuracy (CA). This CA is one of the parameters used to measure the success rate of a model.

The following models were tested in this study: decision tree, k-nearest neighbors (kNN), Naive Bayes, and logistic regression. After the test, the model with the largest CA value was used as the basis for decision making to create the fuzzy rules. The data to be tested underwent a training process using 80% of the sample data; the remaining 20% data were tested using the trained data. The data used in the testing process were obtained from the questionnaires given to the experts with experience in disasters, human resources, and use of heavy equipment. The following total data were obtained: 1692 for personnel allocation and 180 for excavators. After testing, the CA was determined, as seen in Figure 3, below.

Method	AUC	CA	F1	Precision	Recall
Tree	0.970	0.806	0.806	0.816	0.806
Naive Bayes	0.951	0.778	0.775	0.797	0.778
kNN	0.936	0.778	0.774	0.807	0.778
Logistic Regression	0.941	0.750	0.710	0.683	0.750

Figure 3 Machine learning test results

As seen in Figure 3, the decision tree model has the highest level of accuracy for both datasets. The relationship between the parameters is based on predictions made by the decision tree model. The allocation of personnel had a CA of 80.6%; the excavators had a CA of 81.8%.

The Function Fuzzy Logic membership function is used to calculate the degree of membership of a fuzzy set. It is a curve that shows the mapping of the data inputs and points in the membership value (membership degree), which has an interval ranging from 0 to 1.

3.1. Personnel Allocation

The personnel allocation number is 0–250 personnel. The membership function is divided into four categories I, II, III, and IV. By dividing the number of personnel, which are 0–50, 50–100, 100–200, and 200–250, the membership functions become:

$$\mu_{\mathrm{I}(x)} = \begin{cases} 0 & x \leq 0 \quad or \quad x \geq 50 \\ (x-0)/(50-0) & for \ \ 0 \leq x \leq 50 \\ 1 & for \quad x = 50 \end{cases} \tag{1}$$

$$\mu_{\mathrm{II}(x)} = \begin{cases} 0 & x \leq 50 \quad or \quad x \geq 100 \\ (x-50)/(100-50) & for \ \ 50 \leq x \leq 100 \\ 1 & for \quad x = 100 \end{cases} \tag{2}$$

$$\mu_{\mathrm{III}(x)} = \begin{cases} 0 & x \leq 100 \quad or \quad x \geq 200 \\ (x-100)/(200-100) & for \ \ 100 \leq x \leq 200 \\ 1 & for \quad x = 200 \end{cases} \tag{3}$$

$$\mu_{\mathrm{IV}(x)} = \begin{cases} 0 & x \leq 200 \quad or \quad x \geq 250 \\ (x-200)/(250-200) & for \quad 200 \leq x \leq 250 \\ 1 & for \quad x = 250 \end{cases} \tag{4}$$

3.2. Search Area

The search area is 0–5 km, and its membership function is divided into two categories: broad and narrow. The degree is obtained to form the dataset, which was obtained from the questionnaires. The membership contract is then evaluated by removing all the invalid items. Then, the data are normalized. Therefore, the peak is at a full membership level (x) = 1. Based on the degree above, the function is as follows:

$$\mu_{\mathrm{Luas}(x)} = \begin{cases} 0 & for \quad x \leq 0 \\ (x-0)/(3-0) & for 0 \leq x \leq 4 \\ 1 & for \quad x \geq 4 \end{cases} \tag{5}$$

$$\mu_{\mathrm{Sempit}(x)} = \begin{cases} 0 & for \quad x \geq 9,6 \\ (5-x)\,/(5-2) & for 2 \leq x \leq 6 \\ 1 & for \quad x \leq 2 \end{cases} \tag{6}$$

3.3. Population Density

The population density is 0–5000 people/km^2, and its membership function is divided into three categories: solid, medium, and rare. The degree of membership is obtained to form the dataset, which was obtained from the questionnaires. Then, the degree is evaluated by removing all the invalid items. The data are then normalized. Therefore, the peak is at a full membership level (x) = 1. Based on the degree stated above, the function is as follows:

$$\mu_{\mathrm{Padat}(x)} = \begin{cases} 0 & for \quad x \leq 0 \\ (x-50)/(500-50) & for 50 \leq x \leq 500 \\ 1 & for \quad x \geq 500 \end{cases} \tag{7}$$

$$\mu_{\mathrm{Sedang}(x)} = \begin{cases} 0 & x \leq 0 \quad or \quad x \geq 4299,749 \\ (x-0)/(300-0) & for \quad 0 \leq x \leq 300 \\ (5000-x)/(5000-300) & for \quad 300 \leq x \leq 4299,749 \end{cases} \tag{8}$$

$$\mu_{\mathrm{Jarang}(x)} = \begin{cases} 0 & for \quad x \geq 5216,993 \\ (5000-x)\,/(5000-50) & for \; 50 \leq x \leq 5216,993 \\ 1 & for \quad x \leq 50 \end{cases} \tag{9}$$

3.4. Building Density

Building density is 0–30 buildings/km^2, and its membership function is divided into three categories: solid, medium, and rare. The degree is obtained to form the dataset, which is obtained from the questionnaire. Then, the degree is evaluated by removing all the invalid items. The data are normalized. Therefore, the peak is at a full membership level (x) = 1. The results of processing the degrees and the functions are as follows:

$$\mu_{\mathrm{Padat}(x)} = \begin{cases} 0 & for \quad x \leq 0 \\ (x-1)/(20-1) & for 0 \leq x \leq 20 \\ 1 & for \quad x \geq 20 \end{cases} \tag{10}$$

$$\mu_{\mathrm{Sedang}(x)} = \begin{cases} 0 & x \leq 1 \quad or \quad x \geq 64,768 \\ (x-0)/(7,5-0) & for \quad 1 \leq x \leq 7,5 \\ (30-x)/(30-7,5) & for \quad 7,5 \leq x \leq 64,768 \end{cases} \tag{11}$$

$$\mu_{\text{Jarang}(x)} = \begin{cases} 0 & for \quad x \geq 33{,}97 \\ (30 - x)\,/(30 - 5) & for 5 \leq x \leq 33{,}97 \\ 1 & for \quad x \leq 5 \end{cases} \tag{12}$$

3.5. Personnel Equipment

The personnel equipment is 0–100%, and its completeness level is obtained when the operation begins. The membership function is divided into two categories: complete and incomplete. They are as follows:

$$\mu_{\text{Lengkap}(x)} = \begin{cases} 0 & for \quad x \leq 50 \\ (x - 50)/(100 - 50) & for 50 \leq x \leq 100 \\ 1 & for \quad x \geq 100 \end{cases} \tag{13}$$

$$\mu_{\text{Tidak Lengkap}(x)} = \begin{cases} 0 & for \quad x \geq 60 \\ (60 - x)\,/(60 - 0) & for 0 \leq x \leq 60 \\ 1 & for \quad x \leq 0 \end{cases} \tag{14}$$

After the two models are built, predictions can be made by inputting the crisp values (1, 2, 3, 4, etc.) for each variable. The accuracy of these two models was tested before by using the decision tree as machine learning for both models, where each model had an accuracy value or classification accuracy >80%. The input processing carried out by FIS was also fast, although it did not use a special computer, which will prevent obstacles to managing emergency responses, such as a disaster. The model that was built in a search area underwent a simulation process, in an area of 3 km^2, a population density of 1000 people/km^2, and a building density of 7/km^2. The available personnel to be deployed have an average equipment completeness of 80%. The input result indicated that 126 personnel need to be deployed to respond to the disaster.

4. CONCLUSION

Fuzzy logic and decision trees can be used to determine the number of victims trapped during an earthquake. Furthermore, a model based on these methods can be used to accelerate the planning phase for SAR operations. However, the accuracy of this model can be improved by defining the variables in more detail and by adding the existing variables. In the future, this model can easily be enhanced based on more specific areas or conditions.

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