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Structural Equation Modelling For Improving Fire Safety Reliability through Enhancing Fire Safety Management on High-Rise Building

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Abstract. The growth of high-rise buildings is triggered by expensive land prices and the need for construction for hotels, offices, and colleges. Besides the great benefits, high-rise building also has a consequence of fire risks. This indicates that its extinction is challenging with the occurrence of fire outbreaks, due to the flammable furniture and characteristics of high-rise buildings. To anticipate this condition, fire safety protection in high-rise buildings should be reliable. Furthermore, the Indonesian government has reportedly issued regulations and technical guidelines regarding the reliability of fire safety, although fires still occur and cause loss of life and property. Science and engineering also provide a performance-based alternative approach. Therefore, this study aims to analyze the reliability of the fire safety model produced from the integration of FSM (Fire Safety Management) variables, namely flame prevention, people safety, monitoring, audit, review and reactive assessment. In a high-rise building, the initial model was validated by experts within the fire safety field. At the initial stage, the identification of FSM implementation was carried out for building functions in Jakarta, where construction surveys were conducted using a questionnaire and checklist for the completeness of the protection system. Using a spreadsheet and the Smart PLS application, the data were also processed to produce the implementation of FSM and test the effect of independent variables on the dependent factors, respectively. Subsequently, the sub-variables with low FSM implementation were used to improve the fire safety conditions in buildings. By implementing all FSM variables, reliability was then achieved, as improvement efforts were prioritized on the sub-variables with low implementation and priority on fire prevention and monitoring, audit, and review. The integration of the FSM variables' implementation also consistently produced fire safety reliability, as well as guaranteed life and property protection.

Keywords: Fire safety management; Fire Safety Reliability; High-rise building; Life and Property Safety

1. Introduction

Fire is a serious threat significantly threatening life, infrastructures, properties, and the environment in developing countries (Kodur et al., 2018). This is confirmed by the provincial government of Jakarta, which recorded more than 500 fire accidents annually in the past five years, causing multiple fatalities and injuries. For example, the fire caused

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46/25 deaths and 118/>150 injuries in 2017 and 2018, respectively (Rahardjo, 2020). It also causes direct economic losses fivefold due to earthquakes, with only one level below drought and flood. In mid-2019, the economic losses due to the fire within Jakarta are estimated at 137.8 billion rupiah (Zhi-Xiang, 2011). This indicates that high-rise building needs to implement a fire safety management (FSM) system, due to multipurpose usages and intensive access of non-specific persons and low environmental sensitivity. These are to effectively guide individuals in abiding with appropriate fire evacuation procedures, towards the guarantee of personal safety (Chen et al., 2012). FSM is also one of the efforts to help manage fire risk from design, construction, and monitoring to operation stages (Ramli, 2010). This is in line with The Ministerial Regulation of Public Works No: 26/PRT/M/2008, concerning Technical Requirement for Fire Protection System in Buildings and Environment, which stated that a building should function safely by having the protection system for planning, operation, development and utilization (Suprapto, 2008; Murtiadi, 2013; Ajizah, 2018). This indicates that fire safety aims to prevent the collapse of the building under flammable conditions, subsequently providing the occupants with sufficient time to escape safely (Suwondo, et.al, 2021).

This study aims to identify the dominant FSM (Fire Safety Management) factors influential to safety reliability. According to Indonesian regulations, fire safety reliability is achieved through the execution of active and passive protection, rescue facilities, and exit routes (Xiang et al., 2011; Chen et al., 2012; Tofilo, et al., 2013). This indicates that the fire potential in high-rise buildings should be minimized. These building facilities should subsequently be adequate in achieving fire safety for occupants and property. Moreover, occupancy management should be regulated for the behaviours and activities of building occupants to be in line with the safety criteria. All utilized pieces of equipment should also be regularly maintained, sustained, and tested. These aforementioned principles are known as fire safety management, whose adequate implementation ensures safety reliability. Based on the FSM implementation in a high-rise building, various functions and recommendations are identified and delivered for continuous improvement. Structural Equation Modeling is also useful in describing the concept of a model with latent variables, which are measured through indicators although not directly. These variables are essentially processed in path analysis using SEM (Chin, 1998), a method used to enable the construction of the unobservable factors measured by indicators (items, manifest variables, or observed measures). It also enables the use of direct measurement models to analyze the observed variables (Chin, 1998).

2. Methods

This study used a questionnaire and SEM-PLS methods to obtain data and assess the indicators, respectively. This indicated that the survey was a qualitative method used to obtain the indicator data on the variables useful in increasing the reliability of fire safety. It also showed that the SEM PLS method was developed to test weak theory and data, small sample sizes, or information normality problems (Wold H., 1982). This method did not require the normal distribution of data, as parameter estimation was directly carried out without the goodness of fit criteria requirements. The analytical method also negated the assumptions of Ordinary Least Squares (OLS) regression, as it did not have to be free from the multicollinearity problems between the exogenous variables (Wold H., 1985).

2.1. Identification Research Variables

The variables were obtained from the literature synthesized on the study framework, which was then validated by fire safety experts to obtain the required factors. These variables included fire prevention, safety, monitoring, audit, review, reactive assessment, and FSR (Fire Safety Reliability). This indicates that Fire Prevention is used to minimize ignition occurrences and flame/smoke distribution, as well as avoid sudden damage (Ferguson & Janicak, 2005; Abolghasemzadeh, 2013; Chen, et al., 2015). The safety of people is also obtained from the pre-construction stage to building operations, for building occupants to escape flammable events (Furness & Muckett, 2007; Jutras & Meacham, 2016; Maluk et al., 2017). Subsequently, monitoring, audit, and review are the process of reducing the risk of fire at the construction operational stage. These are often carried out through numerous methods, especially with the availability of procedures and guidelines for an emergency, periodic infrastructural checks, regulatory procedural evaluation adequacies, and the latest technological developments (Ferguson & Janicak, 2005; Chen, et al., 2015). Reactive monitoring is also known as the effort performed by the building manager at the maintenance stage, for a quick response after the occurrence of a fire/bad event. This is often carried out by investigating to determine the cause of the incident, for the problems not to recur (Ferguson & Janicak, 2005; Chen et al., 2012). In addition, FSR is the reliability of high-rise buildings on fire safety, ensuring the protection of life and property (Ferguson & Janicak, 2005; Abolghasemzadeh, 2013). Based on this study, all the variables had different indicator values, i.e., X1, X2, X3, and X4 (60, 22, 33, and 19 indicators).

The identification of variables was also used to determine the data collection, content technical tools, and construct validation processing, towards the achievement of validated factors in the analysis of the structural equation model (SEM). The implementation of FSM was then carried out by meeting the criteria contained in fire prevention, people safety, monitoring, audit, review, and reactive assessment. In High-Rise Building, the FSR was also achieved when the implementation of all FSM variables was adequate, for the criteria of life and property protection to be met.

2.2. *Study Methodology*

Figure 1 shows the implementation mechanism of each evaluated stage, based on the input-process-output diagram. This indicated that the evaluation of input included an explanation of the utilized data types and collection instruments at each stage. The evaluation of the process was also related to the data analysis methods in each stage. In addition, the output was in line with the results obtained from each stage.

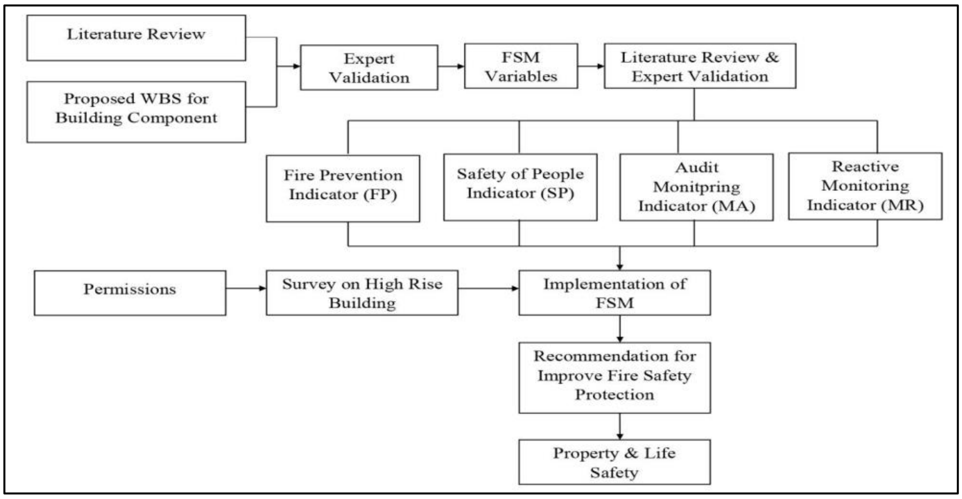

Figure 1 The study methodology

Based on this study, a literature review was initially conducted to determine the variables (Figure 1), which were obtained from various previous references and regulations on fire safety management systems. This was subsequently accompanied by the validation process by experts, to validate the acquired variables. A total of 8 experts were selected with a minimum criterion of master's education in fire safety, and at least 15 years of experience in the construction field. Furthermore, a pilot survey was conducted with 30 respondents, to validate the questionnaire prepared in this study. This was to confirm whether the survey instrument was acceptable to the target respondents, which contained building owners and management of high-rise constructions in Jakarta, whose functions focused on hotels, offices, and colleges. Variables were measured through the implementation of each indicator, as the list of questions was submitted in soft and hard copies. The values of distributed questionnaires and obtained responses were also 225 and 105, respectively, with the respondents' criteria indicating a minimum of bachelor's degree and at least 5 years of working experience. After the collection of the questionnaires, a Structural Equation Model Analysis was carried out with Smart PLS software, to determine the relationship among the variables of fire prevention, people safety, monitoring, audit, review, and reactive assessment. This was then accompanied by the final validation of results, to integrate all variables in achieving fire safety reliability.

3. Results and Discussion

3.1. Study Data Analysis

Validation was carried out by experts to check the variables and indicators obtained from the literature review. This indicated that data collection was carried out after the validation process, through the provision of questionnaires. A total of 8 experts were also selected with a minimum criterion of master's education in fire safety, with at least 15 years experience within the construction field, as shown in Table 1.

Table 1 List of Construction and Safety Expert for Content and Construct Validation

Expert	Position	Education	Experience
Expert 1	Instructor and Lecturer	Doctoral Degree	22 Years
Expert 2	CEO in an insurance company	Master Degree	20 Years
Expert 3	Director of Risk Management in an insurance company	Master Degree	29 Years
Expert 4	Senior Fire Safety Expert in Const. Company	Doctoral Degree	40 Years
Expert 5	Senior Fire Safety Expert	Bachelor Degree	35 Years
Expert 6	Senior Fire Safety Expert in Const. Company	Bachelor Degree	30 Years
Expert 7	Senior Fire Safety Expert in Const. Company	Bachelor Degree	15 Years
Expert 8	Practitioner in Construction Field	Bachelor Degree	20 Years

The first construct in this study was obtained from a literature review, where the variables causing fires in high-rise buildings were initially categorized. This showed that the variable was latent, indicating its inability to be directly measured. The result also indicated that all the variables were thoroughly searched for the indicators with measurable potentials. Moreover, the construct was initially validated by the experts through a pilot survey, which was conducted with 10 respondents, to obtain feedback on the questionnaire. The instrument was then corrected, with the main survey being conducted to acquire complete data, which were processed and analyzed to produce the output of the fire safety reliability model. This final result was subsequently validated by the same experts that performed the initial checking procedure. In this process, the Delphi method was used with structured interviews, to determine the study variables and indicators. This method was used for the decision-making process on the obtained results, through the involvement of several independent experts. The Delphi-based decision-making process was also carried out once to achieve the consensus stage, with validation being gradually conducted for all eight experts. This indicated the achievement of 5 variables, namely fire prevention, people safety, monitoring, audit, and review, reactive assessment, and FSR (fire safety reliability), as shown in Fig. 1. According to the experts, these indicators were in line with the variables obtained from the literature study.

3.2. Implementation of FSM in Jakarta

Based on Table 2, the variables were obtained from a field survey of high-rise buildings in Jakarta. This indicated that the question type focused on the methods by which the implementation of high-rise building indicators was conducted by construction owners and management. The results obtained were also used to measure the value of 4 variables, namely X1 (Fire Prevention), X2 (People Safety), X3 (monitoring, audit, and review), and X4 (Reactive Monitoring). As shown in Table 2, the percentages indicated the value of implementing the indicators of FSM variables in high-rise buildings. In Jakarta, the FSM implementation on high-rise buildings was averagely more than 80%, with the best installation order from the largest to smallest being hotel, office, and college facilities. This indicated that a greater percentage of the FSM implementation in high-rise buildings led to better fire safety reliability. Based on building management, the weight of variable implementation for all functions was similar, with the best and worst installations observed on fire prevention and people safety, respectively. This result was found to corroborate several previous studies. As a service industry, hotel buildings should provide the best service to customers, with early fire protection system equipment being very mandatory for owners. This is in line with Zulfiar & Gunawan (2018) and Wulandari & Trikomara (2018), which assessed the reliability of building a fire system. The results showed that Yogyakarta and Pekanbaru hotel buildings had reliability values of 91.60% and 91.46%, which were in good categories, respectively. The study on reliability was also conducted on an office building, with the results indicating a value of 68.05%, which was lower than the hotels (Mareta & Hidayat, 2020). Subsequently, the college building had a reliability value of 37.26%, which was much lower than the hotels and offices. These results indicated that the observed unsatisfied components were landscape comprehensiveness (water source and yard hydrant), rescue tools, exit route construction, passive protection system, building fire resistance, compartmented room and external safeties, as well as all actively secured parameters (Selena et al., 2019).

Table 2 FSM Implementation in high-rise Building

Occupancy	FSM Implementation in High-Rise Buildings			
	Fire Prevention	People Safety	Monitoring, Audit and Review	Reactive Monitoring
Hotel	96.24%	92.41%	96.55%	96.47%
Office	92.93%	89.50%	89.18%	91.32%
College	84.62%	77.86%	79.79%	81.58%

3.3. Relationship analysis with SEM-PLS Using Smart PLS 3.0 Software

The SEM-PLS aims to test the predictive relationship between the constructs, by observing whether there is a relationship or influence. This method was used because the test was carried out without a strong theoretical basis while ignoring some assumptions (non-parametric). The accuracy parameters of the prediction model were also observed from the coefficient of determination (R^2), indicating that the SEM-PLS was very appropriate for utilization. In addition, the use of Smart PLS 3.0 focused on the estimation of the causal-predictive relationship between the FSM variables and FSR level in a high-rise building.

Table 3 Loading factors Average Variance Extracted (AVE)

Research Variables	AVE
Fire Prevention	0.723
Safety of people	0.571
Monitoring, audit, and review	0.670
Reactive monitoring	0.621
Reliability of fire safety	0.681

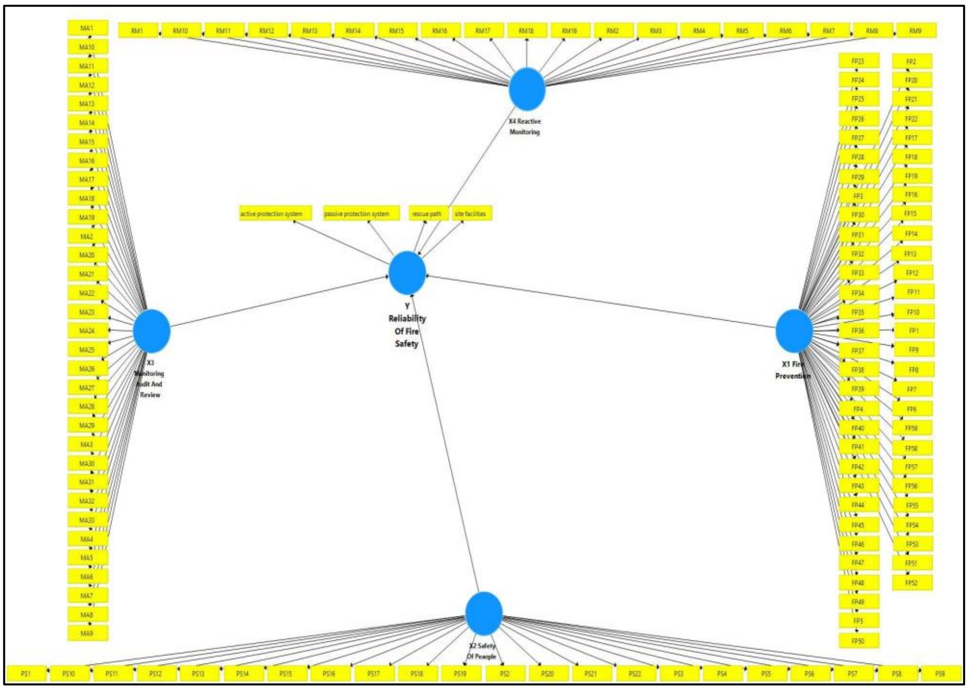

Figure 2 Calculation of PLS Algorithm (Outer Loadings)

Figure 2 showed the reliability relationship between the independent (X) and dependent (Y), where the circular part contained the factors of X and Y. This indicated that X1, X2, X3, X4, and Y were Fire Prevention, People Safety, Audit Monitoring, Reactive Assessment, and the FSR (fire safety reliability), respectively. These variables were analyzed using the SmartPLS 3.0 software, based on the outer model containing the validity and reliability analyses. In the validity test, LFP (loading factor parameters), Average Variance Extracted (AVE), Cross loading, and Sqrt AVE were observed, while the Cronbach's Alpha and CRP (composite reliability parameters) were found for the reliability analysis. This indicated that the obtained data were found to have valid values. According to the inner model, the R^2 value was observed at 0.807 or 80.7%, using the SmartPLS 3.0 software. This indicated that the FSR was assessed by fire prevention, people safety, audit monitoring, and reactive assessment at 80.7%. Based on the T-statistics more than 1.96, all variables had a significant effect on the reliability of fire safety.

From Table 3, the standardized loading factors (SLF) were useful in assessing whether a construct had sufficient discriminant validity. This was obtained by the comparative analysis of the construct indicator correlation with other studies. When this correlation is higher than that of other constructs, high discriminant validity is found to be achieved. The SLF also described the correlation level of each measurement item (indicator), indicating that the indicator with the loading factor value > 0.7 was valid as a measurable source. This showed that the item reliability was assessed from the loading factor, according to the kinds of literature stating that the values > 0.7 was ideal. However, a standardized loading factor value above and below 0.5 was acceptable and excluded, respectively. By calculating the main menu in the Smart PLS 3.0 program, a PLS Algorithm option was observed, where the step was often referred to as the *first-order confirmatory factor analysis*, as shown in Table 4.

Table 4 Interrelation variable for Reliability improvement (R^2)

Research Variable	R Square (R2)
Fire Prevention	0.811
Safety of people	0.521
Monitoring, audit, and review	0.683
Reactive monitoring	0.531
Reliability of fire safety	0.807

Based on Table 4, the R^2 value of FSR was 0.807, indicating that the variability of the construct was explained by Fire Prevention, People Safety, Audit Monitoring, and Reactive Assessment of 80.7%. In this condition, the intervention of fire prevention and audit monitoring approximately contributed 81% and 68% to the achievement of FSR, respectively. This indicated that fire prevention was performed through the planning and elevation of the detector system, alarm and sprinkler, which were useful in averting ignition, as well as hindering fire and fog distribution. The provision of signs, evacuation routes, emergency lighting, and fire lift was also part of the indicators of people safety. Furthermore, the Audit Monitoring containing procedures, fire training, and equipment maintenance was performed by the building management in the operational stage. If fire and harmful conditions occur. This indicated that investigation and checking procedures were often implemented by an investigator during a fire and harmful condition incidents, to prevent recurrences. Therefore, the implementation of all aforementioned efforts was associated with the achievement of fire safety reliability on a high-rise building.

3.4. FSM Improvement on High-Rise Building

The results of the validation process are shown in Table 1, where the intervention of fire prevention, audit monitoring, reactive assessment, and people safety improved FSR. This was conducted by prioritizing the most influencing FSM variables with the aforementioned factors, where improvement efforts were more effective by treating the sub-variable with the lowest level of implementation.

Based on Table 5, the FSM sub-variables and the performance improvement efforts for college building were shown. This indicated that the variable indicators and proposed improvements were identified based on the field surveys with lecture functions on high-rise buildings. The indicators with the lowest implementation values were also identified among the 4 FSM variables. For college building, the FSM implementation had the lowest value, indicating the need for more subsequent emphasis in this aspect. Some of the sub-variables were also identified with an implementation level of less than 70%. This indicated that when the implementation value is small, more attention is required for the sub-variables. Recommended improvement efforts were also placed in the right column, to achieve the fire safety reliability of the college building. In this study, the development of the FSM Improvement Theory subsequently contributed to the reliability of fire safety, due to being more effective when the treatment on the 4 FSM variables was consistently conducted. Meanwhile, the FSM Implementation on hotel buildings had the best value, compared to the office and college facilities, although performance enhancement should still be improved, especially on the variables that have smaller installation. These results indicated that reliability significantly increased with the FSM implementation treatment.

Table 5 FSM Improvement in College Building

No.	Variable	Indicator	Implementation	Improvement
1	Fire Prevention	Fire Lift	16%	The installation of fire and smoke barriers on the flame lift is necessary, to withstand diffusion on the shaft (Haitao et al., 2012).
2	Fire Prevention	Evacuation procedures	68%	In the evacuation procedure, the possession of patterns related to the number of people, emergency stairs, and floors was very necessary (Sharma et al., 2014).
3	Safety of people	Stairwell Intercom Systems/communication system on emergency stairs	58%	The equipment and installation systems should be secured against interferences, such as electromagnetic waves (Chen et al., 2012).
4	Safety of people	Help disabled residents to save themselves	61%	There should be evacuation arrangements and procedures for disabled occupants requiring special assistance during a fire outbreak (Egodage et al., 2020).
5	Safety of people	Fire detection method	65%	The use of the Internet of Things (IoT) was capable of detecting the presence of smoke and fire for evacuation, alerting firefighters, and ensuring the reduction of damages. It also displays the required and correct reports automatically sending the data (Eltom et al.,2018).
6	Monitoring, Audit, and Review	Annual review and report	52%	A responsible management team should be created to independently verify the implementation status of recommendations, as well as performance tracking and reporting functions. The team should also have the necessary technical knowledge to lead the review effort on the annual report (Landa, 2014).
7	Monitoring, Audit, and Review	Level and detailing to be audited, due to the size of the building and organization	65%	The internal inspection software assessing approximately 184 points for 24 different construction categories should be empowered (Government of Western Australia, 2021).

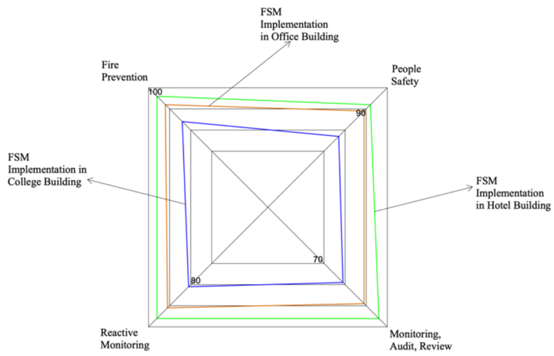

Figure 3 Fire Safety Reliability Level in High-Rise Building

Figure 3 shows the development of a spider web according to a survey on the application of fire safety management indicators (Table 2). This indicated that the hotel and college buildings had the best and worst values in fire prevention, people safety, audit monitoring, and reactive assessment. The application within the office buildings was also found between the hotel and college facilities. This indicated that the results were almost the same as shown in Table 2, compared to other previous studies. Based on the hotel, office, and college functions, the application of *Fire safety Management* in high-rise buildings was found within the good category, with success rates of 95%, 90.5%, and 80.75%, respectively (Nugroho, 2022). According to the validation results, the hypothesis of this study stated that the FSM implementation affected the reliability of fire safety. This was in line with the analysis of all variables through the Smart PLS application, as the theory indicated that the FSR increased with the improved implementation of fire prevention, people safety, audit monitoring, and reactive assessment.

The FSM contained 4 variables, namely fire prevention, people safety, audit monitoring, and reactive assessment, each contributing to the performance of the protection management. This indicated that the adequate implementation of each variable led to a good integration value of FSM factors. These dimensions should be understood and implemented by building managers, for the achievement of reliable performance. FSM implementation also affected the FSR, indicating the correspondence to several previous studies. These showed that building safety was achieved when the design considered the regulations and simulations of many fires events and people (Cowlard et al., 2013). In high-rise buildings, fire safety is always regularly necessary, as goals were achieved by relying on active and passive prevention systems, as well as protection equipment maintenance programs. Stakeholder and occupant management are also important parts of achieving safety strategies (Nimlyat et al., 2017), as protection is often carried out through fire prevention, control, and element resistance plans. Subsequently, safety and emergency facilities should be functionally ensured (Chen et al., 2012), as an integrated program effectively managed all hazards with the implementation of protection techniques. Additionally, extensive testing, inspection, maintenance, auditing, training, planning, and drilling, were still required in all aspects (Chen et al., 2015). Fire safety was also achieved through design regulations and arrangements, with the needs/characteristics of the building and occupants leading to better constructions (Maluk et al., 2017). The fire safety system should subsequently be improved, as protection and flames were the initial principles to reduce accidents and losses. This should be performed by integrating man-machine-environment resources through the optimization of hardware and software (Xiuyu et al., 2012).

4. Conclusions

Based on this study, fire lift indicators showed that the annual reports and emergency exit communications required attention, due to the lowest implementation being 16%, 52% and 58% in college buildings. This indicated that fire prevention, people safety, audit monitoring, and reactive assessment had significant effects on FSR (fire safety reliability), with a success rate of 80.7%. For the hotel, office, and college facilities in Jakarta, the FSM implementation on the high-rise building was categorically good. This indicated that the highest and lowest implementation values were observed in the hotel and college buildings, respectively. Meanwhile, the implementation value of the office buildings was found between the hotel and the college facilities. For improvement on each FSM variable, several recommendations were provided on the low implementation factors. To achieve optimum FSR, treatment should be conducted on the dominant and influential variables, namely fire prevention and audit monitoring. This indicated that the FSR model was affected by fire protection, people safety, audit monitoring, and reactive assessment, indicating that higher variable implementations led to better reliability. Additionally, the integration of all FSM variables supported the assurance of life and property safety in high-rise buildings.

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