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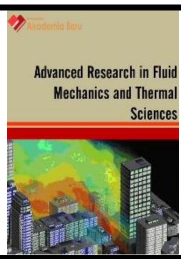

Tenability Analysis of Office Rooms Using Probabilistic Fire Load Energy Density Data

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Abdul Haqeem Akhyani[1], Mohd Zahirasri Mohd Tohir[2,*]

[1] Maktab Rendah Sains Mara Pendang, Kedah, Malaysia
[2] Safety Engineering Interest Group, Department of Chemical and Environmental Engineering, Faculty of Engineering, Universiti Putra Malaysia, Selangor, Malaysia

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ABSTRACT

One of the most important component in performance-based design is tenability analysis study in a compartment. What it means by tenability analysis in this study is by getting the Available Safe Egress Time (ASET) based on several tenability criteria parameters namely Fractional Effective Dose (FED) for gases and thermal, smoke layer and visibility. To perform the tenability analysis; (1) selection and measurement of place of study i.e. two different room size in Faculty of Engineering, Universiti Putra Malaysia, (2) conduct fire load energy density survey at the place of study, (3) simulate probabilistic zone model simulation using B-RISK design fire tool; and finally (4) the tenability analysis itself. As a conclusion from the work, the values for each tenability criteria and results from B-RISK simulations suggest that the ideal time taken for Toxicity (FED Gases) ≤ 60s, Heat Transfer (FED Thermal) ≤ 60s, and Smoke Layer Height ≤ 30s. Thus, the ASET for both office layouts are set at 30s due to the shortest time to reach tenability criteria.

1. Introduction

Recently, the performance-based design approach has gained acceptance in the engineering community around the world. This has prompted an expanded demand in engineering approaches to the assessment of fire safety in structures. The concept of performance-based approach is to demonstrate a proposed design meets the defined objectives using engineering calculations and modelling [1]. One part of the approach is to perform a tenability study in the proposed structure design. Tenability in terms of building design focuses on the survivability of occupants during fire events. In simple terms, the available safe egress time (ASET) should be greater than the required safe egress time (RSET), which means the time for occupants need to be evacuated must be less than the time for life-threatening conditions to develop within that space with an appropriate margin of safety. In studying the tenability, it is important to know how fire develops in the particular

* *Corresponding author.*
E-mail address: zahirasri@upm.edu.my (Mohd Zahirasri Mohd Tohir)

compartment in order to establish timeline for occupants to escape. The outcome from the work also may assist fire service in devising rescue tactics.

Probabilistic assessment methodologies as part of a risk-based approach for performance-based design is becoming more popular in the fire engineering community. These methodologies provide an objective quantification of risk which could lead to an optimization of the selection of fire protection measures in a cost-effective manner [2]. Thus, the application of probabilistic assessments into fire development scenarios in a particular compartment will enhance the confidence level of the results to be analysed [3, 4]

Out of many possible structure/compartment scenarios, the scope of this study is limited to office rooms due to geometrical simplicity, practicality and accessibility. From Malaysia's statistics, during the three-year period of 2011 - 2013, Fire and Rescue Department of Malaysia (FRDM) [5] stated the reported of fires in office rooms have an average of 141 cases annually. There were 165, 127 and 132 fire incidents recorded in 2011, 2012 and 2013 respectively. Figure 1 shows the leading causes of fire in offices where electrical and lighting equipment failure stands out the highest at 1765 cases in 2011 and decreases in the following year as there is only 934 cases in 2013. The statistics shows the importance of studying the tenability in office rooms.

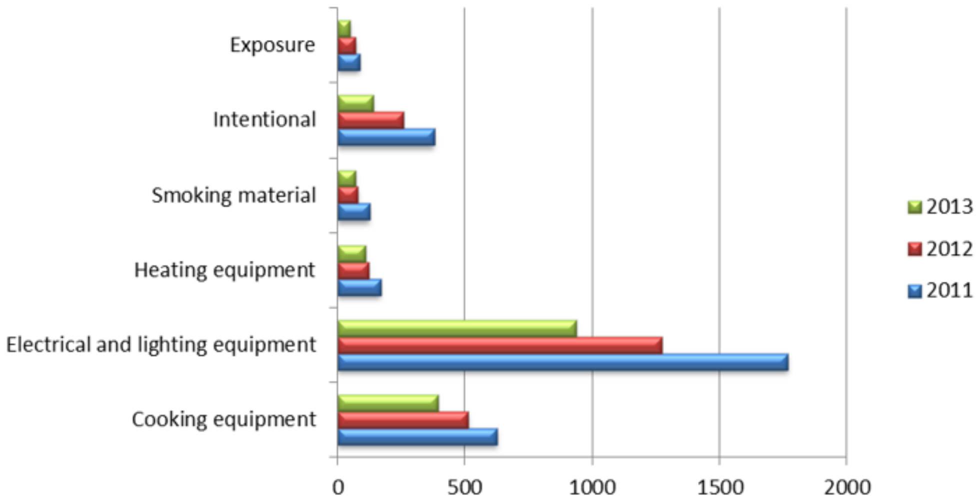


Fig. 1. Leading causes of structure fires in offices in Malaysia, 2011-2013 [5]

One of the important aspects in developing fire scenarios are the fuel content in a compartment. In offices, the combustible items i.e. the fuel load usually range from paper based products, plastic/polymer based products, fabrics; and wooden furniture [6]. There is not much study on fire load energy density in office rooms has been done throughout the years. One of the study was conducted by Baldwin [7] in which he did a survey of fire loads in modern office buildings using two different office layouts. The results showing that the average fire load per unit floor area (fire load density) is 20 MJ/m², and is independent of the size of the room. However, it is arguable whether the results can still be used or not at this point of time.

Therefore, to perform a tenability analysis study in office rooms, several steps have to be completed; (1) selection and measurement of place of study, (2) conduct fire load energy density survey at the place of study, (3) simulate probabilistic zone model simulation; and finally (4) the tenability analysis itself. This study could be a benchmark for further study in tenability analysis in using different parameters and for different applications for other types of occupancies.

2. Methodology
2.1 Place of Study

The study was conducted for two different layout of single occupant office room in Faculty of Engineering, Universiti Putra Malaysia, Malaysia. The total floor area for Layout A office room is 12.52 m² and for Layout B office room is 15.20 m². In terms of venting, both office rooms have same the dimension and measurement of windows which is 2.28 m² of area in total. In total, 12 rooms of Layout A and 13 rooms of Layout B were surveyed for its combustible content. The detailed information of the two office layouts can are shown in Table 1. An example of an office layout is shown in Figure 2. The figure shows an example layout for the office room layout A type with common furniture in a lecturer's room.

Table 1
Measurement of office rooms layouts and floor area

Type of Office		Office Room Layout A	Office Room Layout B
Length	(m)	3.63	3.80
Width	(m)	3.45	4.00
Height	(m)	2.62	2.62
Floor Area	(m²)	12.52	15.20

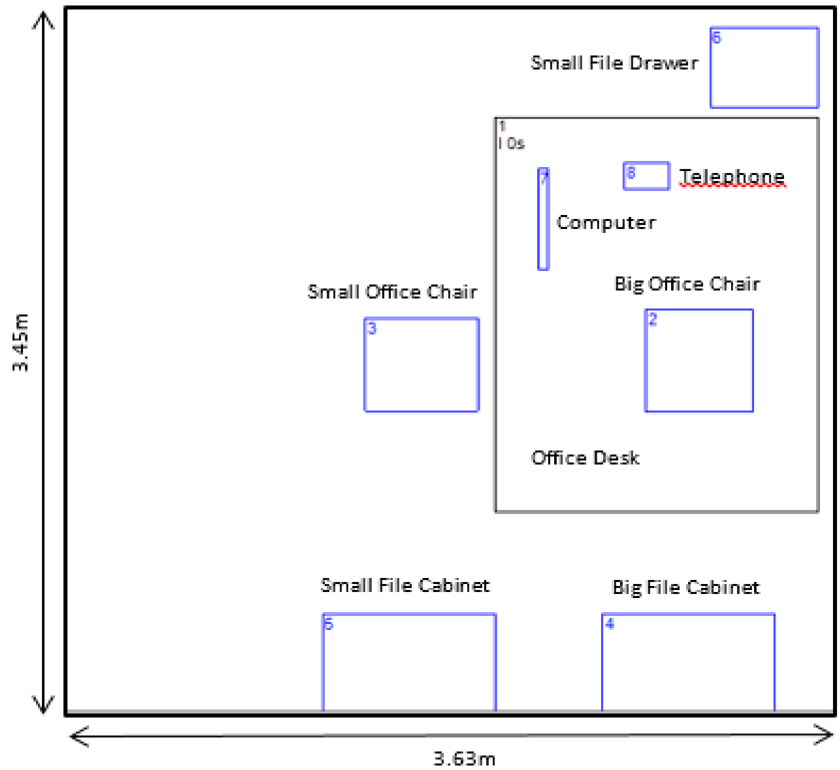


Fig. 2. An example layout for Office Room Layout A

2.2 Fire Load Energy Density Survey

Zalok [8] determined how to establish a structured approach to validate the fire load survey methodology proposed in the NFPA Standard 557 and to enhance and develop guidance on mean to correlate the results from the fire load data surveys developed using various other methodologies. He found that combination method which is inventory and weighing was considered the best survey methodology since it combines best practices from both methods and hence minimizes the degree of uncertainty and error.

Work by Zalok is simplified by Wei Gao [9] where the fire load is defined as the total heat content upon complete combustion of all the combustible materials contained inside the fire compartment. Fire load energy density (FLED), is defined as the weight of combustible contents per unit floor area,

$$\text{FLED} = \frac{\Sigma M_v \Delta h_c}{A_f} \quad (1)$$

where FLED is the fire load density (MJ/m^2), *Mv* is the total weight of each single combustible material in the fire compartment (kg), △*hc* is the effective calorific value of each combustible material (MJ/kg) and *Af* is the floor area of the fire compartment, (m^2). According to the survey data, FLED was determined from each office rooms and being categorized into highest, average and lowest value. The outcome will be used as probabilistic input for the simulation.

2.3 Simulation

This study uses B-RISK zone modelling software to simulate probable design fire scenarios. B-RISK is developed based on an existing deterministic fire zone modelling software named, BRANZFIRE and was developed by Building Research Association of New Zealand (BRANZ) and the University of Canterbury [10]. Three simulations i.e. probabilistic input of lowest FLED value, average FLED and highest FLED were conducted for office layout A and B. This means that for each room, the fuel contents and arrangements of contents in the room were randomly based on the amount of probabilistic FLED input. Each simulation was set to run 1000 iterations to produce results which satisfy the modeling purpose. The more iterations are performed, the higher the probability the simulation will encompass the spectrum of real fuel content of the rooms. The number of iterations are deemed to be enough as when the number of simulation approaches 1000, the results of B-RISK converges [11]. The output of the simulations produced fire development timeline for all 1000 iterations, which will be analysed for its tenability criteria.

2.4 Tenability Study

The tenability parameters are important in setting up the B-RISK simulations as they play a role in determining the available time taken for occupants before the compartment is becoming untenable due to fire event [12, 13]. The parameters that will be used in these fire simulations are the value of fractional effective dose (FED) of thermal and toxic gases, the height above the floor which indicated the maximum height of smoke layer above the occupant head, and the distance of the occupant visibility.

This analysis focused on the tenability which is the likelihood that persons exposed to a specific dose of toxic products will be capable of escaping of the fire floor. Another factor is visibility which focuses on time taken of which the occupants aren't able to see the exit signage or to locate the exit path out of the room of fire origin. According to Poh [14], the reduction in visibility is because of smoke obscuration and it may reduce the walking speed of individuals, thereby increasing the exposure time to heat and toxic gases. Combustion gases that cause irritation to the eyes may have a similar effect to reduced visibility. Moreover, this analysis is also focused on tenability study which the occupants are exposed to smoke layer that cannot be maintained above body height.

This work adopts the tenability parameter of 0.3 as standard value for fractional effective dose (FED) because it related to the population range of most sensitive populations which are elderly, young, or those with compromised immune systems [15].

3. Results

3.1 Fire Load Density Energy Survey

The survey was conducted for 25 office rooms at Faculty of Engineering, University Putra Malaysia to quantify the amount of fire load in each rooms. According to the survey data, the Fire Load Energy Density was determined from each office rooms and being categorized into highest, average and lowest value.

Table 2 and 3 show the recorded data for office layout A and B where the highest FLED value calculated were 1368.94 MJ/m² and 1651.56 MJ/m² respectively. The lowest FLED value for office layout A and B are 372.33 MJ/m² and 727.22 MJ/m² respectively. The difference between the highest and the lowest FLED for office layout A and B are 996.61 MJ/m² and 924.34 MJ/m² respectively. These differences show that the fuel content in each room totally depends on the occupants even though the room size is the same. The study also shows that the bigger the room size, the amount of fuel load also increases.

Table 2
Fire load energy density values for office layout A and B

Office Layout A	Total Fire Load Energy Density, MJ/m²	Office Layout B	Total Fire Load Energy Density, MJ/m²
Office 1	605.27	Office 1	1452.04
Office 2	510.61	Office 2	1651.56
Office 3	918.64	Office 3	1094.67
Office 4	480.70	Office 4	901.15
Office 5	1368.94	Office 5	730.20
Office 6	372.33	Office 6	727.22
Office 7	395.88	Office 7	935.50
Office 8	829.95	Office 8	954.79
Office 9	742.52	Office 9	996.39
Office 10	755.96	Office 10	1143.08
Office 11	644.38	Office 11	1160.72
Office 12	811.89	Office 12	1119.11
-	-	Office 13	799.13
AVERAGE	703.1	AVERAGE	1051.2

Table 3
Summary of fire load energy density for Office Layout A and B

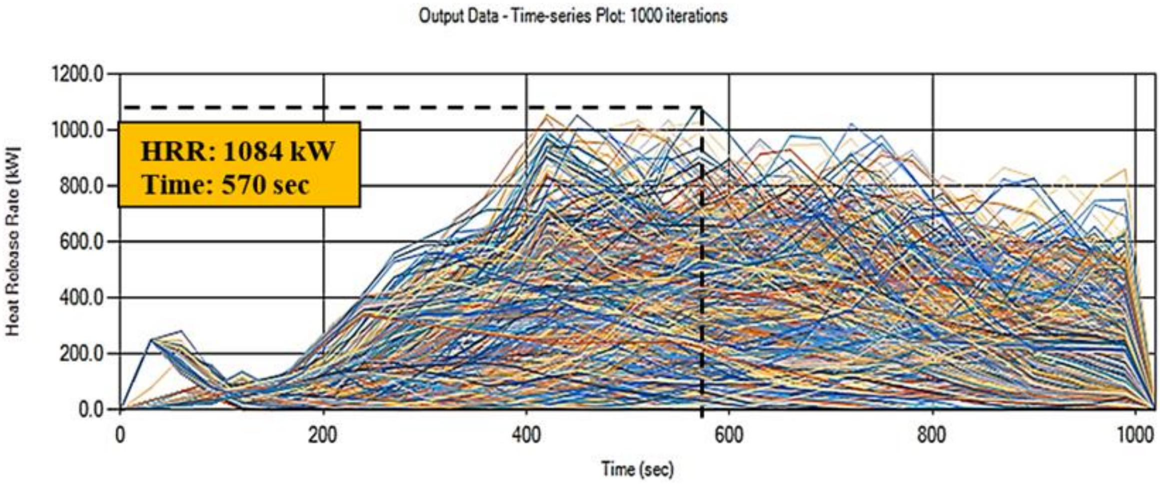
FLED, MJ/m²	Office Layout A, MJ/m²	Office Layout B, MJ/m²
Highest Value	1368.94	1651.56
Average Value	703.10	1051.20
Lowest Value	372.33	727.22

3.2 Simulation Results: Heat Release Rates

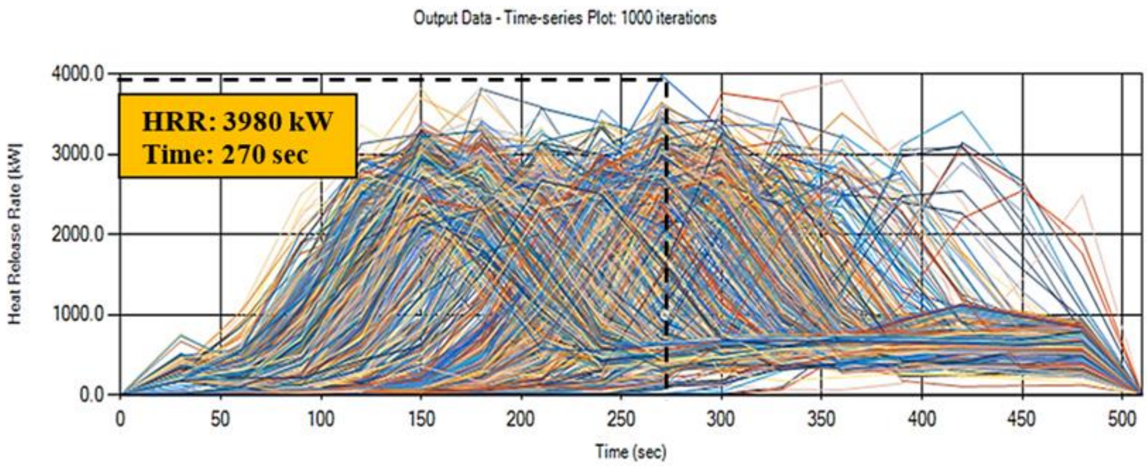
Figure 3(a), (b), (c) and (d) shows the results for the 1000 iterations of simulations. The colourful lines indicate the heat release rate for each iteration hence all of the figures are stacked with lines. However, this is useful as the lines signals the range of possibilities of heat release rate profiles in an office fire.

Figure 3(a) and Figure 3(b) shows the heat release rate (HRR) profile for office room layout A with the lowest FLED value (372.33 MJ/m²) and the highest FLED value (1368.94 MJ/m²) respectively. The iterations of 1000 have indicated that the highest heat release rate of this room is 1084 kW and the time at HRR peak is 570 s while the lowest heat release rate of this room is 47 kW and the time at HRR peak is 120 s. While for the highest FLED value, the highest heat release rate of this room is 3980 kW and the time at HRR peak is 270 s.

Figure 3(c) and Figure(d) shows the heat release rate (HRR) profile for office room layout B with the lowest FLED value (727.22 MJ/m²) and with the highest FLED value (1651.56 MJ/m²) respectively. The iterations of 1000 have indicated that the highest heat release rate of this room is 7405 kW and the time at HRR peak is 270 s while the lowest heat release rate of this room is 170 kW and the time at HRR peak is 30 s. While for the highest heat release rate of this room is 21646 kW and the time at HRR peak is 240 s while the lowest heat release rate of this room is 8383 kW and the time at HRR peak is 180 s. It is obvious from the results that office layout B may possibly release more energy as compared to office layout A due to higher average fire load energy density.



(a)



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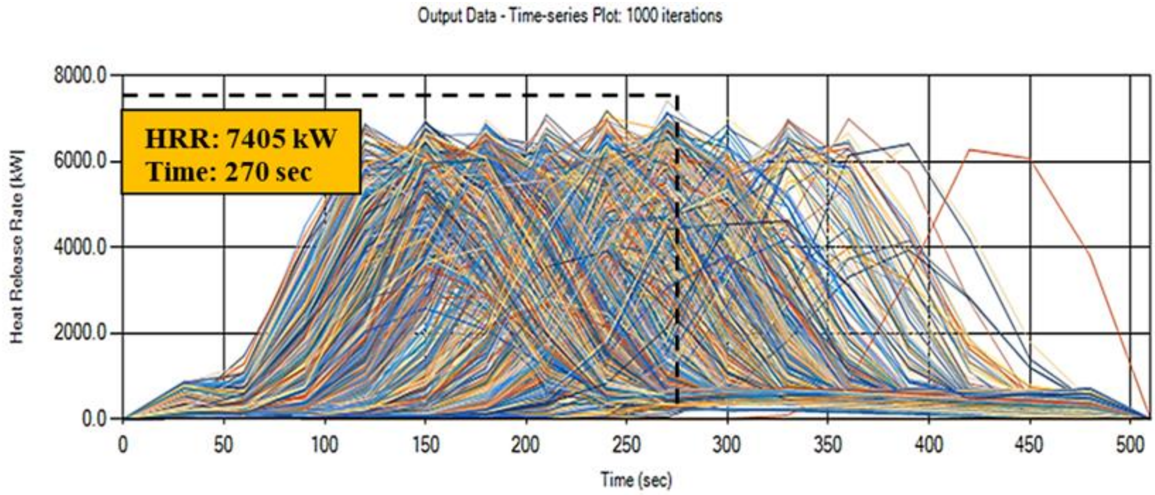
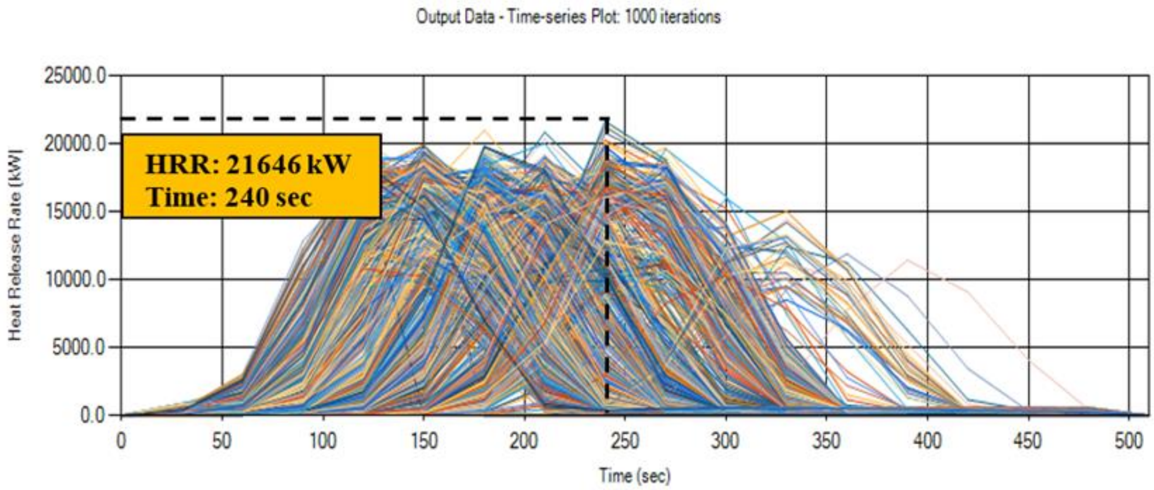


(c)



(d)

Fig. 2. (a) Heat release rate profile of office layout A with lowest FLED (b) Heat release rate profile of office layout A with highest FLED (c) Heat release rate profile of office layout B with lowest FLED (d) Heat release rate profile of office layout B with highest FLED

3.3 Simulation Results: Tenability Analysis for Available Safe Egress Time (ASET)

From the simulations results, the tenability analysis for ASET for both room layouts were done for the worst possible case and for the minimum consequence case. The lowest FLED value from survey will be the minimum consequence case for fire event while the highest FLED value will be the worst case of fire event. The reasons for the tenability analysis only considering these two cases are because; to know how much time the occupants have if there is a minimum consequence fire and also how much time the occupants have if the fire is the worst possible consequence.

Table 4, 5, and 6 show the comparison of collected data on available time taken occupants can escape before it becomes life-threatening conditions or untenable in fire event for small office rooms and big office room based on different FLED categories and tenability criteria. The data are based on the minimum, average, and maximum time taken for 1000 iterations and the most frequent time taken that appeared from the iterations results. In the results, the time to reach tenability criteria is regarded as the ASET. The results from the simulation were rounded up to interval of 30s due to limitation of B-RISK.

Table 4
Results for time to reach tenability criteria: FED gases of 0.3

Office Layout	FLED (MJ/m²)	Time to reach FED = 0.3 for 1000 iterations (s)			Frequency of time to reach FED = 0.3 for 1000 iterations (s)	
		MIN	AVG	MAX	1st	2nd
A	Lowest 372.33 MJ/m²	90	278	990	270 sec	240 sec
A	Highest 1368.94 MJ/m²	60	174	330	90 sec	210 sec
B	Lowest 727.22 MJ/m²	60	154	480	90 sec	60 sec
B	Highest 1651.56 MJ/m²	60	131	300	90 sec	60 sec

Table 5
Results for time to reach tenability criteria: FED thermal of 0.3

Office Layout	FLED (MJ/m²)	Time to reach FED = 0.3 for 1000 iterations (s)			Frequency of time to reach FED = 0.3 for 1000 iterations (s)	
		MIN	AVG	MAX	1st	2nd
A	Lowest 372.33 MJ/m²	120	217	480	180 sec	150 sec
A	Highest 1368.94 MJ/m²	60	136	240	180 sec	120 sec
B	Lowest 727.22 MJ/m²	60	136	240	180 sec	60 sec
B	Highest 1651.56 MJ/m²	60	122	180	150 sec	90 sec

Table 6
Results for time to reach tenability criteria: smoke layer height of 1.8 m

Office Layout	FLED (MJ/m²)	Time to reach FED = 0.3 for 1000 iterations (s)			Frequency of time to reach FED = 0.3 for 1000 iterations (s)	
		MIN	AVG	MAX	1st	2nd
A	Lowest 372.33 MJ/m²	30	46	90	30 sec	60 sec
A	Highest 1368.94 MJ/m²	30	51	180	60 sec	30 sec
B	Lowest 727.22 MJ/m²	30	41	90	30 sec	60 sec
B	Highest 1651.56 MJ/m²	30	40	150	30 sec	60 sec

It can be concluded that the ASET for toxicity FED (gases) in office layout A for the minimum consequence case is 990s which was generated from average of lowest FLED simulations and for the worst case is 60s which was generated from average of highest FLED simulations. It is obvious from the simulations that the higher content of fuel has shorter ASET as compared to lower content of fuel with the same room size. For both highest and lowest FLED simulations, the average ASET is 174s. For thermal FED, the ASET obtained from the simulations for office layout A were for the minimum consequence case is 480s and the worst case is 60s. It has to be noted that when fire is occurring, it is expected that the smoke will first affect the tenability of occupants. While smoke is filling the room, asphyxiant gases will be released and follow up with heat from fire. Therefore it is expected that the ASET for toxicity FED (gases) will be quicker than thermal FED. Next is the ASET for smoke layer height for office layout A for minimum consequence is 180s and the worst case is 30s. The analysis shows that the shortest time to reach the tenability criteria of smoke layer height for average of highest FLED values is 30s. Therefore, for office layout A, the ASET is set at 30s since the occurrences of scenario from 1000 iterations also shown the highest for smoke layer height. This ASET has shown that in practical the occupant is able to evacuate the room safely due to the small size of the room. Also, the ASET will not be an issue since in a single occupant office, usually the occupant is already familiar with the exit path.

Meanwhile, for office layout B, the ASET for toxicity FED (gases) for the minimum consequence case is 480s and the worst case is 60s. It is observed that the minimum consequences case is lower than of office layout A due to the average lowest FLED for office layout B is double than office layout B. The ASET for thermal FED for minimum consequence is 240 s and the worst case is 60s. Finally, the ASET for smoke layer height criteria for minimum consequence case is 990s and the worst case is 30s. The outcomes for office layout B is similar to of office layout A i.e. the shortest time to reach tenability criteria of smoke layer height is 30s. The ASET for office layout B is also set at 30s due to the highest occurrences of scenario out of 1000 iterations. The outcomes are almost similar due to the size difference of the rooms are not that much, in which this could be due to the bigger room layout has more fuel load which in the end offsets the size of the room.

3.4 Comparison of Smoke Layer Height and Visibility

Smoke layer and obscuration can lead to a reduction in visibility, which is not directly life-threatening [16]. Smoke reduces the walking speed of individuals, thereby increasing the exposure time to heat and toxic gases [17]. Combustion gases that cause irritation to the eyes may have a similar effect to reduced visibility. The results for visibility were initially considered, however the results show the best value of time taken to escape from untenable condition in smoke layer height criteria is 30 second while in visibility criteria is 60 second. As people that do travel through smoke will move slower that in clear conditions, this study can conclude that occupants who can escape the rooms before 30 second which overcome the limit of smoke layer height can neglect the visibility time taken limitation which is 60 second.

4. Conclusions

As a summary it was found that the ASET of each parameters for both office layouts are given as

Toxicity (FED Gases)	$\leq$ 60 seconds
Heat Transfer (FED Thermal)	$\leq$ 60 seconds
Smoke Layer Height	$\leq$ 30 seconds

From the tenability analysis, it can be concluded that the ASET for both office layouts are 30s based on the time to reach untenable condition for smoke layer height tenability criteria. It was also shown in this work that the slight differences in size of the office rooms has little effect to the simulation. It was found that from this work, the methodology can be applied to any compartments given enough information to perform fire scenarios. However, in order to improve the robustness of the study, it is strongly recommended that cone calorimeter tests on recent furniture have to be done extensively since the HRR is the one of the most important parameter in this study. Also as a recommendation in the future, RSET for this specific case can be studied in order to determine the time taken to evacuate the building. Thus, complete an ASET and RSET study.

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References
[1] Baker G., Wade C., Spearpoint M.J. , and Fleischmann C.M. "Developing probabilistic design fires for performance-based fire safety engineering." *Procedia Engineering* 62 (2013): 639-647.
[2] Tohir M.Z.M. and Spearpoint M.J. "Distribution analysis of the fire severity characteristics of single passenger road vehicles using heat release rate data." *Fire Science Reviews* 2, no. 1 (2013): 5.
[3] Spearpoint M. J., Tohir M. Z. M., Abu A. K., and Xie P. "Fire load energy densities for risk-based design of car parking buildings." *Case Studies in Fire Safety* 3 (2015): 44-50.
[4] Sum R. M. "Using Mathematics to Quantify Subjective Decisions: Application of Analytic Hierarchy Process to Risk Assessment." *Journal of Advanced Research Design* 44, no. 1 (2018): 7-19.
[5] Jabatan Bomba dan Penyelamat Malaysia, 2014. 2014 Annual Report for Fire Service and Rescue Malaysia.
[6] Kakegawa S., Yahshiro Y., Satoh H., Kurioka H., Kasahara I., Ikehata Y., Saito N., and Turuda T. "Design fires for means of egress in office buildings based on full-scale fire experiments." *Fire Safety Science* 7 (2003): 975-986.
[7] Baldwin R., Law M., Allen G., and Griffiths L. G. "Survey of Fire-loads in Modern Office Buildings-Some Preliminary Results." *Fire Safety Science* 808 (1970): 1-1.
[8] Zalok E. "Design fires for commercial premises." PhD diss., Carleton University, 2006.
[9] Gao W., Sun J., Zhang Y., and Rong J. "Fire Loads In Student's Dormitory Buildings." *International Journal of Recent Research and Applied Studies* 14, no. 2 (2013): 456-463.
[10] Wade C. A., Baker G., Frank K., Robbins A. P., Harrison R., Spearpoint M.J., and Fleischmann C.M. *B-RISK user guide and technical manual*. BRANZ, 2013.
[11] Tohir M.Z.M. and Spearpoint M.J. "Development of fire scenarios for car parking buildings using risk analysis." *Fire Safety Science* 11 (2014): 944-957.
[12] Lemaire T. and Kenyon Y. "Large scale fire tests in the second Benelux tunnel." *Fire Technology* 42, no. 4 (2006): 329-350.
[13] Jin T. "Studies on human behavior and tenability in fire smoke." *Fire Safety Science* 5 (1997): 3-21.
[14] Airah W. P. M. "Tenability criteria for design of smoke hazard management systems." *Ecolibrium* (2011).
[15] Cleary T. G. *Improving Smoke Alarm Performance: Justification for New Smoldering and Flaming Test Performance Criteria*. US Department of Commerce, National Institute of Standards and Technology, 2014.
[16] Delichatsios M. "Tenability conditions and filling times for fires in large spaces." *Fire safety journal* 39, no. 8 (2004): 643-662.
[17] Poh W. "Tenability In Building Fires: Limits And Design Criteria." *Fire Australia* (2010): 24-26.