Fire Risk Assessment Model for Residential Buildings Using Bow-tie Method

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Table of Contents

LIST OF TABLES

LIST OF FIGURES

Executive Summary

Ensuring the safety of citizens is a responsibility of the government. Fire incidents can create many adverse impacts on human, property, environment and reputation. In this research, a probabilistic model to assess the fire risk in residential buildings using the Bow-tie Method was developed. A user-friendly predictive tool called "DynamicFire" was developed based on the aforementioned predictive model. This tool is focused on fire risk assessment of multi-unit residential buildings (MURB), due to their recent popularity. "DynamicFire" is expected to support risk management decisions to minimize fire risk and its adverse impacts on MURBs, especially on human, property, environment and reputation. Furthermore, this tool includes a list of safeguards for prevention and protection to reduce the probability of a fire incident. Potential benefits of the proposed methodology and the tool are as follows.

Quantitative fire risk management decision making: The proposed tool will enhance the local fire department's ability in making risk-based decisions in daily operation as well as for long-term capital investment and resource allocation for effective fire risk management. For example, the fire department could strategically locate the fire engines in areas where buildings with highest fire risk. Annual fire risk assessments using the proposed method would inform insurance companies of the fire risk level of a particular building.

Flexibility of use: The user-friendly interface allows users to change the parameters according to the current context. Furthermore, based on up-to-date information, users could adjust the fire risk probabilities. No expert input is required for the use of this tool.

Excel-based platform for convenient adoption: The Excel-based platform allows wider use of this tool. Therefore, benefits of this method could be reaped by a wider group of users, from building managers, to fire departments and insurance providers.

Problem Statement

According to the 2016 census, 28% percent of Canadians live in multi-unit residential buildings [1]. For growing communities such as Kelowna, there has been a 42% increase in MURB living from 2011-2016 [1]. The number of MURBs continues to increase in order to cater the housing needs of the growing Canadian urban population [2]. Multi-unit residential buildings (MURB) construction exceeded single-family detached house construction in 2012 [2]. Based on the number of building permits issued in Canada's three largest metropolitan areas, more than 50% of the total planned residential developments are MURBs [2]. MURBs have been popular due to a number of trends, such as declining household size, changing household characteristics, an ageing population, high prices of single-family homes in certain areas, as well as land shortages and development policies of municipal governments.

Fire incidents are one of the most devastating events in buildings, posing a significant threat to public safety and property. In 2014, building fires accounted for 62% of fire incidents in Canada [3]. Out of all building fires, 65% of the incidents were reported in residential buildings. Ensuring the safety of residents is a key responsibility of the government. Statistics show that even though the number of fire incidents has been declining, the expenditure on firefighting has increased [4]. Consequently, municipalities are pressured by the need for additional resources to maintain their firefighting services [4]. Importance of fire safety in MURB has been highlighted in previous literature [3].

Several strides have been made to minimize and eliminate fire risk. These efforts include establishing effective fire risk management frameworks, enforcing building code regulations, promoting public education on fire hazards, and conducting evacuation training and drills [5]. An effective fire risk management framework is of vital importance in the control and prevention of fire incidents. ISO 31000 recommends risk assessment and risk treatment as steps in fire risk management. The fire risk assessment of a system involves synthesizing all available information to estimate fire risk to life, property, and the environment. The fire risk assessment process is comprised of fire risk prediction, risk analysis, and risk evaluation [5]. Fire risk prediction is the process of investigating the probabilities of fire incidents occurrence under certain circumstances. Fire risk analysis is the process of estimating extents and probabilities of the adverse effects resulting from fire incidents [6]. The fire risk prediction and analysis can be expressed either in qualitative, mixed, or quantitative ways, depending on the type of risk, the purpose of risk analysis, and the availability of information resources [5]. Fire risk evaluation involves applying the developed risk criteria to decide the level of fire risk. Fire risk treatment is the process of improving existing risk controlling measures and implementing these measures to reduce fire risk. As the first step of fire risk management, fire risk prediction serves as the foundation of regulatory decision-making on actions to reduce risk [7]. Studies on fire risk prediction are, therefore, critical and essential.

Many modelling tools were developed to facilitate fire risk management from different perspectives and levels. For example, models such as FIRECAM and FIERA system were utilized to calculate the expected life risk and fire cost expectations [8][9]; a Bayesian belief net model was introduced to assess the risk of human fatality in fire incidents [10]; Probabilistic methods have been used to assess levels of people's safety in buildings [11] and quantitative risk assessment approaches have also been used to quantify the risk to occupants using stochastic factors [12]. However, few models can predict the probability of fire occurrence based on the information of various fire risk factors such as time, location, the characteristics of occupants, building conditions, and the environment. The information revealed by statistical studies on fire risk factors could be critical for fire risk prediction [13][14]. Moreover, the causal factors of fire outbreaks are dynamic, e.g., building material deterioration, stochastic nature of igniting objects (e.g., frying pan, oven, toaster handling), weather, occupant characteristics (e.g., temporary loss of judgment due to alcohol, sleep, fatigued). In addition, the causal factors interact with each other, increasing the complexity of fire prediction. The model allows for the effective trade-off analysis of multi-scenarios and the multi-attributes of fire incidence prediction over time [15]. Therefore, the systems dynamics model can assist decision makers to understand the implications of investment decisions and actions on fire risk management [16].

The main objective of this research is to develop a fire risk rating methodology for MURBs. The proposed methodology assesses the risk of fire incidence in MURBs. The Bow-tie Method was used as the fire risk assessment method. A user-friendly risk-based predictive tool called "DynamicFire" was developed based on the developed methodology. The proposed tool will serve as a decision aid tool to formulate and prioritize fire response planning decisions.

Methodology

The analysis of risk and safety scenarios needs to take threats and safeguards into consideration effectively. The Bow-tie method is capable of considering threats and safeguards, can be used to prevent the incident occurrence, and to protect from undesirable consequences. Bow-tie analysis has been applied in many different areas, such as oil and gas industries, petrochemical companies, defence and security, shipping (taking into consideration ports and harbours), mining, medical, aviation, and emergency response. Therefore, the Bow-tie method was identified as a feasible method for fire risk analysis in residential buildings. The overall fire risk assessment methodology is illustrated in Figure 1. The features of the Bow-tie method are presented to illustrate its credibility as a reliable technique for risk and safety assessment as follows: (i) Provides a visual representation of the causes of unintended events, (ii) Easy to understand by all levels of operations and management, (iii) Provides explicit linkages between inputs (causes) and outputs (consequences), and (iv) Defines the preventive and the protective barriers to reduce the occurrence of the top event and the severity of its consequences, respectively.

Bow-tie analysis (BTA) is one of the quantitative methods which has proven its efficiency for risk management in many industries [17]–[20]. In BTA, causal scenarios need to be derived from possible hazardous events, and safety goals should be defined. Among the different models available to identify and analyze accident scenarios, the Bow-tie method has been well proven to be a reliable and efficient technique. Bow-tie analysis is used to prevent, control, and mitigate undesirable events by formulating a logical relationship between the causes and consequences of an undesired event. The method is based on the integration of two well-established techniques, namely fault tree analysis (FTA) and event tree analysis (ETA) [21]–[24]. Bow-tie analysis as the graphical presentation was originally developed by the Royal Dutch/ Shell group.

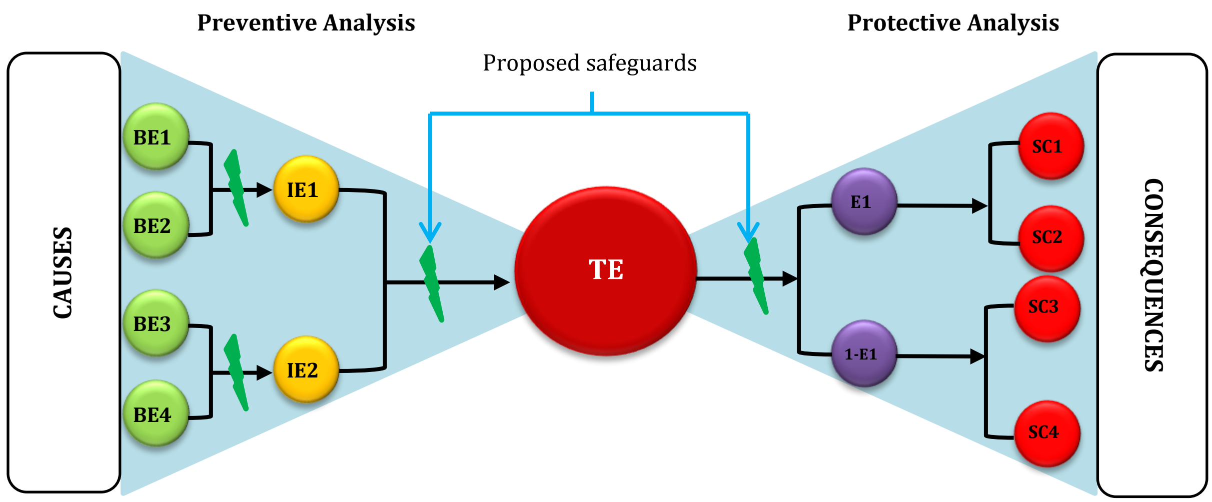


FIGURE 1: DIAGRAM OF BOW-TIE ANALYSIS METHOD

Construction of the Bow-tie method is based on mathematical operations. Fault tree analysis relies on AND and OR gates that formulate the relation between basic events and the top event. However, ETA is only based on AND gates to build the relationships between the top event and the consequences. Mathematical equations for both AND and OR gates are presented in Table 1:

TABLE 1: EQUATIONS USED FOR BOW-TIE METHOD

Gate	Input pairing	Calculation of output
$\boldsymbol{OR}$	$P_A\ OR\ P_B$	$P(A\ OR\ B) = 1 - (1 - P_A) \cdot (1 - P_B)$ $= P_A + P_B - P_A \cdot P_B \approx P_A + P_B$
	$f_A\ OR\ f_B$	$f(A\ OR\ B) = f_A + f_B$
$\boldsymbol{AND}$	$P_A\ AND\ P_B$	$P(A\ AND\ B) = P_A \cdot P_B$
	$f_A\ AND\ f_B$	$f(A\ AND\ B) = f_A \cdot f_B$
	$f_A\ AND\ p_B$	Unusual pairing, reform to $f_A\ AND\ p_B$

Where P is probability and f is frequency

The dynamic fire tool incorporates five steps as follows:

1. Identify common threats and probabilities of fire incidents
2. Define preventive and protective safeguards and their probabilities
3. Determine the level impact of consequences to people, properties, environment, and reputation
4. Determine risk level based on scenarios probability with the level of impact
5. Propose safeguards for prevention and protection to reduce fire incident probability and the impact of consequences.

STEP 1: IDENTIFICATIONS OF COMMON THREATS AND PROBABILITIES OF FIRE INCIDENT

A comprehensive literature review was conducted to identify threats and their respective probabilities [25]. Appendix A-1 presents a summary of the literature review. This data was used in constructing the left-hand side (fault tree) of the Bow-tie. Table 2 presents the threats resulting in fire hazards for MURBs and their respective probabilities. The probability of a fire incident can be calculated using the following equation:

$$TE = \sum_{i=1}^{n} C_i\, S_i$$

TE: top event,

C: causes, and

S: Safeguard

i: number of scenarios that involve causes and safeguards

TABLE 2: FIRE THREATS AND PROBABILITIES OF OCCURRENCE FOR MURB [25]

Threat	Probability
Arson	1.55E-01
Open fires	6.60E-02
Arson by children	2.90E-02
Heating	3.80E-02
Cooking	5.40E-02
Electric distributor (cables)	4.50E-02
Heat radiation from other sources	2.40E-02
Natural fires (lightning)	1.30E-02
Explosion & fireworks	3.00E-02

STEP 2: DEFINE PREVENTIVE AND PROTECTIVE SAFEGUARDS AND THEIR PROBABILITIES

Define the preventive and protective safeguards using FTA and ETA. Fault tree analysis involves the preventive safeguards or suggesting the appropriate precautions. Event tree analysis defines the safeguards for fire incident protection along with the probabilities of success and failure. Success and failure of various fire protection systems were identified from the literature [25]. Three fire protections are defined; (i) smoking material with a failure probability of 3.0E-01, (ii) sprinkler system with a failure probability 4.0E-02, and (iii) regular evacuation drills with a failure probability of 2.0E-01. The probability for each scenario is defined using the probability of a fire incident with a probability of the success of safeguards with the following equation:

$$P_{SC} = \prod_{i}^{n} P_{Ei} \cdot P_{Si}$$

P_{SC}: probability of scenario,

P_E : probability of events

P_S : probability of safeguards

i: number of scenarios

STEP 3: DETERMINE LEVEL IMPACT OF CONSEQUENCES TO PEOPLE, PROPERTIES, ENVIRONMENT, AND REPUTATION

The impact level of the scenarios was determined to estimate the impact on four factors; people, property, environment, and reputation. A fire incident would impact the four factors with different weights based on the importance of influenced factors. Various impact levels for categories were defined based on literature and expert consultation (Table 3).

TABLE 3: IMPACTS OF FIRE EVENTS

Impact level	People	Properties	Environment	Reputation
Very Low	No/Slight Injury	No/Slight damage	No/Slight effect	No/Slight Impact
Low	Minor injury	Minor damage	Minor effect	Local Impact
Medium	Major injury	Local damage	Local effect	Regional Impact
High	Fatality	Regional damage	Regional effect	National Impact
Very High	Multiple fatalities	Extensive damage	National effect	International impact

General impact level is determined using the following equation:

$$I_g = \sum_{i=1}^{4} (W_i \cdot I_i)$$

I_g: general impact

W: weight for each factor based on its importance

I: impact on factors; people, properties, environment, and reputation

i: number of impacts

STEP 4: DETERMINE RISK LEVEL BASED ON SCENARIOS PROBABILITY WITH THE LEVEL OF IMPACT

The fire risk level for MURBs was defined using a five-level scale. Table 4 defines the fire risk levels for MURBs. Risk level is defined using a matrix, where risk probability is defined using the following equation:

$$R_L = \frac{1}{2}\left[(log(Pr_{SC}) + 6) + I_g \ \right]$$

R_L: Risk Level

Pr_{sc}: Probability of scenario

I_g: general impact

TABLE 4: FIRE RISK DEFINITION

Risk	Level	Definition
Absolutely	5	Urgent action required
Extreme	4	Immediate action required
High	3	Senior management action required
Moderate	2	Management responsibility specified
Low	1	Managed by routine procedures

STEP 5: PROPOSE SAFEGUARDS FOR PREVENTION AND PROTECTION TO REDUCE FIRE INCIDENT PROBABILITY AND THE IMPACT OF CONSEQUENCES

The following preventive and protective measures are proposed to mitigate fire threats and enhance fire event management. These measures were identified from published literature, reports, and guidelines from reputable institutions [25]–[42]. As more than 50% of fire incidents' causes are not clear [25], the proposed precautions are for the mentioned common causes as well as the possible threats.

TABLE 5: PREVENTIVE AND PROTECTIVE MEASURES

			Suggestions for prevention
1	To avoid Electrical as Source of Ignition	A	Appliance and combustible materials should be separated by a distance at least of the ½ metre.
		B	Combustible or flammable storage should not be in the electrical intake room.
		C	Verification of equipment to be off at the end of the working day.
		D	The sources of heat (plugs) should not be overloaded with electrical equipment.
		E	Electrical fuses and circuit breakers should be inspected frequently.
		F	Inspections and tests of electrical equipment should be completed by a competent electrician.
2	To avoid open fires (candles, heaters, etc) as source of ignition	A	The open fires should be away from combustible materials
		B	The candles and heaters should be far from children reach
4	To avoid heating as Source of Ignition	A	Maintain a safe separation distance of ½ metre between appliances and combustible materials.
		B	Heaters should be secured to walls with appropriate safety guards
		C	Portable heaters should not be under desks and heating appliances should be well arranged
5	To avoid Cooking as Source of Ignition	A	Provide a 5Kg CO2 and a 6 Litre wet chemical extinguisher in the kitchen.
		B	There should not be combustible storage in the gas boiler room.
		C	Maintain a safe separation distance of ½ metre between appliances and

			combustible materials.
		D	Heaters should be secured to walls with appropriate safety guards
		E	Portable heaters should not be under desks and heating appliances should be well arranged
6	To Avoid Arson	A	Add precautions by introducing external lighting, secure boundaries, increased security patrols, or external CCTV.
7	To Avoid Explosion & fireworks from residents, Outside Contractor and Building Works Hazards	A	Introduce a permit to work system for contractors who carry out 'hot work' involving processes such as welding or flame cutting.
		B	Designate smoking areas.
		C	Prohibiting smoking in residential buildings should be enforced.
		D	Appropriate safety data sheets should be verified
		E	Training to all persons for appropriate firefighting equipment should be taken into account.
		F	Hazard management of explosives should be inspected frequently
		G	Isolating dangerous substances has to be by competent persons.
8	To Avoid Natural Fires Due to Lightning	A	A suitable lightning protection system should be added to the building.
Suggestions for protection			
1	Enhancement of Procedures and Arrangements	A	Inform visitors and guests of fire evacuation arrangements in the building.
		B	Coordinate fire safety arrangements with other occupants through the managing agents in the building.
		C	A suitable job description should be appointed for/by a fire safety manager in writing
		D	Provide details of the fire emergency plan to residents during fire awareness training.
		E	Inform maintenance contractors and cleaners of the fire evacuation arrangements and working of safety systems in the building.
		F	Fire information and instruction details should be recorded in the fire emergency plan.
		G	Appoint sufficient fire wardens to help in evacuating the premises.
2	To Increase Efficiency of Training and Drills	A	Arrange fire drills at least once every six months for the building occupants and workers
		B	Coordinate fire safety training and fire drills with other occupiers through building managers.
3	To Improve Testing and Maintenance	A	Schedule regular inspections and maintenance.
		B	Ensure verification of emergency lighting is carried out by competent persons on a monthly basis.
		C	Ensure weekly tests and periodic inspection of sprinkler installations are carried out and recorded by competent persons.
		D	Ensure that appropriate methods of training are made available for workers with language difficulties.
		E	Monthly checks and annual maintenance of portable firefighting

			appliances should be carried out by competent persons.
		F	Ensure that weekly fire alarm tests and periodic servicing is carried out by competent persons.
4	To Improve Means of Escape Level	A	Buildings (especially multi-storey buildings) should be constructed to ensure that fire, heat and smoke will not spread through the building to the extent that people are unable to use the escape routes.
		B	The existing escape routes should be adequate for the numbers and type of people that may need to use them, e.g. members of the public, young people, and disabled people.
		C	The width of the escape corridors should be no less than 1.2 metres.
		D	The exits and the escape routes should lead as directly as possible to a place of total safety.
		E	Install suitable interlocks on doors normally kept closed for security reasons and openable when necessary in the direction of escape.
		F	Fire doors should be provided with appropriate fire door signs, such as "fire door keep shut" and "fire door keeps locked," at eye level on both faces of the fire doors.
		G	The people who work in the building should be aware of the importance of maintaining the safety of the escape routes by ensuring that fire doors are not wedged or held open.
5	To Protect the Spread of Fire	A	Combustible construction and fire-resisting should be verified.
		B	Frequent programs for testing and maintenance of fire dampers and control systems should be well followed.
		C	Appropriate signs, such as firefighting equipment and emergency telephones signs, and storage of hazardous substances should be well managed.
		D	The capacity of the emergency lighting system should be from 1 to 3 hours in duration.
6	To Improve Escape Lighting	A	Ensure there is a backup power supply for emergency lighting.
		B	Ensure there is emergency lighting to illuminate the escape routes and fire points with appropriate directional arrows and to indicate the secondary escape routes.
7	To improve Fire Safety Signs and Notices	A	Maintain all necessary signs and notices so that they continue to be correct, legible, and easily understood.
		B	The means of warning should be clearly heard or be perceptible and understood by everyone throughout the whole building when initiated from a single point.
		C	Ensure red flashing lights are linked to the fire alarm system. Install an auto-dialler device to inform a remote manned centre of a fire alarm activation via a secure telephone line.
8	To Improve Fire Warning	A	The fire control panel should be located at an exit and visible to emergency services from the outside of the building. Provide a repeater panel on the front face of the building.
		B	There should be enough fire extinguishers, they should be located close to fire hazards, and positioned so they can be used without exposing the user to increased risk.
		C	Firefighting appliances should be maintained and checked at least monthly.

DynamicFire Tool

The fire risk assessment method developed in this research was used to develop the Dynamicfire tool. This tool was developed in the Microsoft Excel platform. The user interface of Dynamicfire is presented in Figures 2-5.

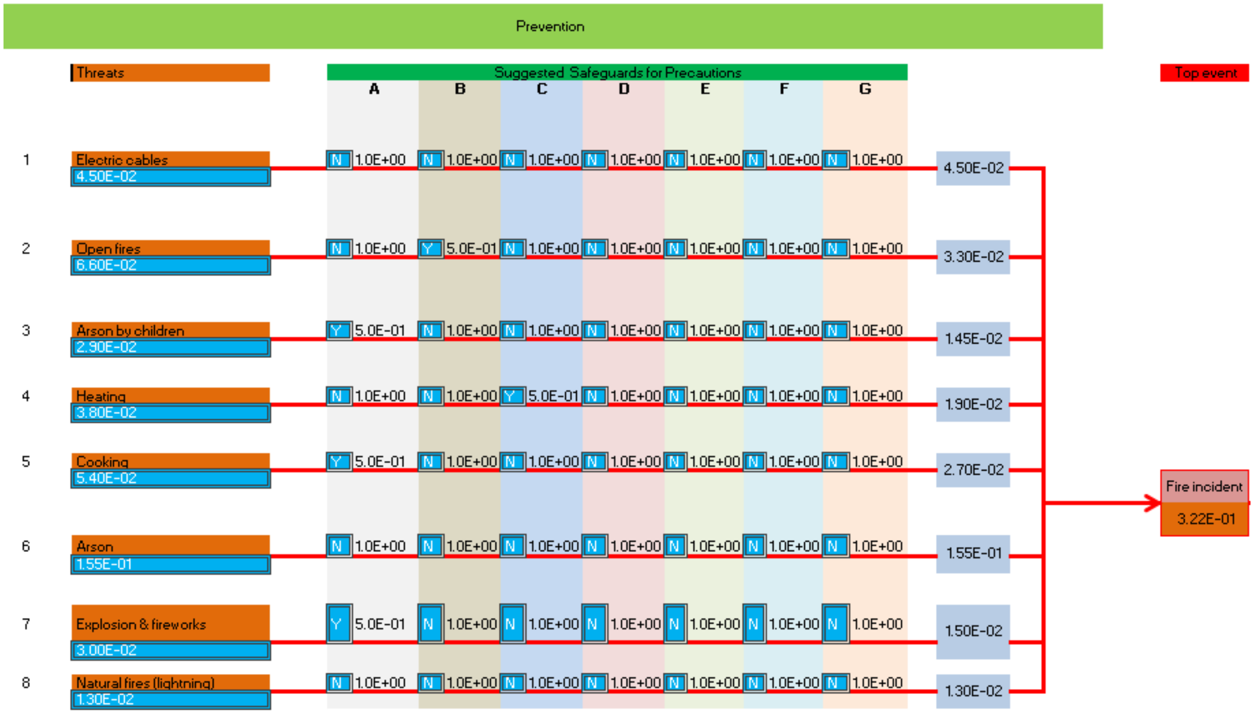


FIGURE 2: ANALYSIS OF THREATS AND PREVENTIVE SAFEGUARDS USING FAULT TREE ANALYSIS

FIGURE 3: PROTECTIVE SAFEGUARDS ANALYSIS

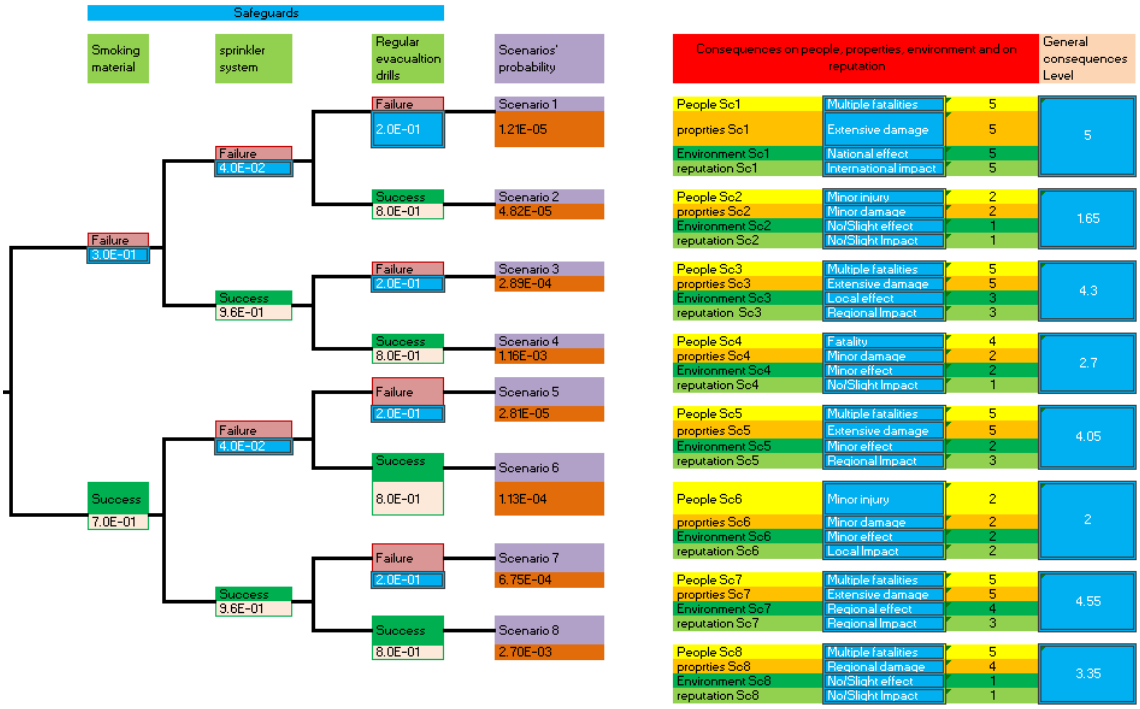
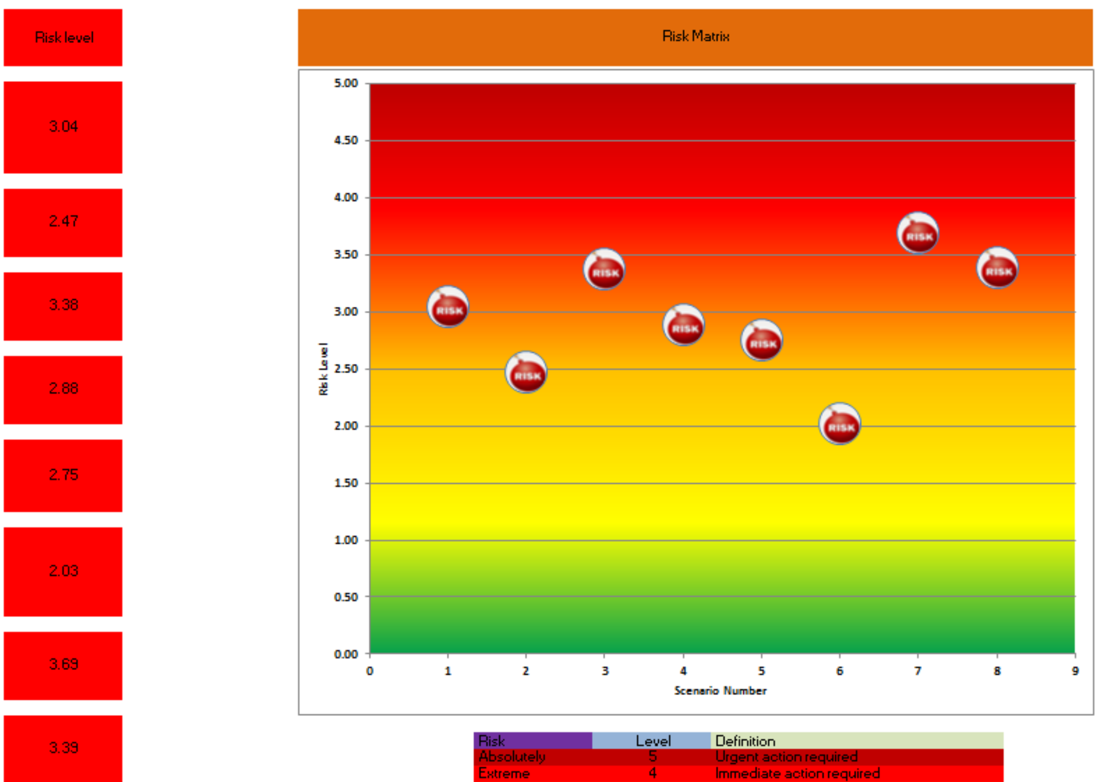


FIGURE 4: ANALYSIS OF PROTECTIVE SAFEGUARDS WITH IMPACT OF SCENARIOS



Risk	Level	Definition
Absolutely	5	Urgent action required
Extreme	4	Immediate action required
High	3	Senior management action required
Moderate	2	Management responsibility specified
Low	1	Managed by routine procedures

FIGURE 5: RISK LEVEL FOR EIGHT SCENARIOS

The developed tool helps to define the probability of fire incidents by determining the probability of threats with preventions and safeguards using fault tree analysis. The tool enables the determination of all possible scenario probabilities based on the existing safeguards with ETA. The impact level of all scenarios on people, properties, environment, and reputation are considered. The risk is then determined for all scenarios. The user manual of DynamicFire tool is attached as Appendix B.

FEATURES OF DYNAMIC FIRE TOOL

The developed fire risk assessment method for MURB is a unique approach for determining the fire risks level in MURBs. The advantages of this model are: (i) identifications of common threats and probabilities of occurrence of a fire incident, (ii) Identification of preventive and protective safeguards and their probabilities, (iii) determine level impact on people, properties, environment and reputation, (iv) Determine risk level taking probability of scenario with level of impact, (v) Safeguards for prevention and protection are found to reduce fire incident probability and the impact of consequences.

Other benefits of the proposed tool are as follows:

Enhanced fire risk management decision making: The proposed tool will enhance the local fire department's ability in making risk-based decisions in daily operation as well as for long-term capital investment and resource allocation for effective fire risk management. The fire department could strategically locate the fire engines in areas where MURB with highest fire risk. An annual fire risk assessment using the proposed method would inform insurance companies of the fire risk level of a building.

Flexibility: The user-friendly interface will allow users to change the parameters according to the current context. Furthermore, based on up-to-date information, users could adjust the fire risk probabilities. No expert input is required for the use of this tool.

Excel-based platform: Excel-based platform will allow wider adoption of this tool. Therefore, benefits of this method could be reaped by a wider group of users, from building managers, to fire departments and insurance providers.

For the efficient and effective execution of this project, the research team consisted of two principal investigators who have diverse and in-depth experience of civil infrastructure and life cycle assessment, environmental risk assessment, and engineering decision making. In the last decade, these two researchers have been involved in numerous national and international projects related to various environmental and public health risk assessment related projects.

Future Research

The method developed in this research can be enhanced in the following areas.

Regional fire risk assessment: The Same concept can be used to predict the fire risk of various types of buildings and other facilities. By combining the aforementioned risks, a regional fire risk level could be determined. Geographic information systems (GIS) could be used to present the individual and regional fire risk level. This information will assist in regional planning as well as fire risk management planning.

Incorporating data uncertainty: Data uncertainty can be accounted for by using the suitable mathematical methods (e.g., fuzzy logic). Moreover, a method such as fuzzy set theory enables the incorporation of vague, qualitative, and uncertain information into the analysis. This approach will further enhance the analysis method.

Time modelling: The proposed method can be extended to analyze threats, safeguards, and consequences with time. This analysis will enable prioritizing scenarios and find the appropriate safeguards for each scenario.

Developing a web-based tool: Developing the proposed method using a web-based approach will enable easy adoption and access to a wider community. The web portal could become a database with detailed fire risk information about various MURBs in the region. This data would support better resource allocation to mitigate fire risks.

References

[1] Statistics Canada, "Dwellings in Canada," 2017. [Online]. Available: http://www12.statcan.gc.ca/census-recensement/2016/as-sa/98-200-x/2016005/98-200-x2016005-eng.cfm. [Accessed: 20-Dec-2017].

[2] Statistics Canada, "Evolution of housing in Canada, 1957 to 2014," 2016. [Online]. Available: http://www.statcan.gc.ca/pub/11-630-x/11-630-x2015007-eng.htm. [Accessed: 03-Aug-2016].

[3] Statistics Canada, "Fire statistics in Canada, Selected Observations from the National Fire Information Database 2005 to 2014," Ottawa ON, 2017.

[4] Fraser Institute, "Municipal Fire Services in Canada: A Preliminary Analysis," Vancouver, BC, 2015.

[5] D. Hopkin, "A Review of Fire Resistance Expectations for High-Rise UK Apartment Buildings," *Fire Technol.*, vol. 53, no. 1, pp. 87–106, 2017.

[6] A. M. Hasofer, V. R. Beck, and I. D. Bennetts, *Risk Analysis in Building Fire Safety Engineering*. London: Butterworth-Heinemann, 2006.

[7] T. Bedford and R. M. Cooke, *Probabilistic risk analysis: Foundations and methods*. Cambridge: Cambridge University Press, 2001.

[8] FiRECAM, "Fire risk evaluation and cost assessment model," Ottawa, ON, 2008.

[9] N. Benichou, A. H. Kashef, and I. Reid, "FIERAsystem: A fire risk assessment tool to evaluate fire safety in industrial buildings and large spaces," *J. Fire Prot. Eng.*, vol. 15, pp. 145–172, 2005.

[10] D. Hanea and B. Ale., "Risk of human fatality in building fires: A decision tool using Bayesian networks," *Fire Saf. J. J.*, vol. 44, pp. 704–710, 2009.

[11] G. H. Kristiansson, "On probabilistic assessment of life safety in building on fire. Report," Lund, 1997.

[12] J. K. Vrijling, W. Van Hengel, and R. J. Houben, "Acceptable risk as a basis for design," *Reliab. Eng. Syst. Saf.*, vol. 98, pp. 141–150, 1998.

[13] Ontario Ministry of Community Safety & Correctional Services, "Comprehensive fire safety effectiveness model: Fire risk sub-model," 2016. [Online]. Available: http://www.mcscs.jus.gov.on.ca/english/FireMarshal/FireServiceResources/ComprehensiveFireSafetyEffectivenessModel/FireRiskSub-Model/Fire_risk_submodel.html . [Accessed: 03-Nov-2016].

[14] J. Xin and H. C., "Fire risk assessment of residential buildings based on fire statistics from China," *Fire Technol.*, vol. 50, pp. 1147–1161, 2014.

[15] G. Sehlke and J. Jacobson, "System dynamics modeling of transboundary systems: the bear river basin model.," *Ground Water*, vol. 43, no. 5, pp. 722–30, 2005.

[16] S. J. Kenway, P. a. Lant, a. Priestley, and P. Daniels, "The connection between water and energy in cities: a review," *Water Sci. Technol.*, vol. 63, no. 9, p. 1983, 2011.

[17] N. Khakzad, F. Khan, and P. Amyotte, "Dynamic risk analysis using bow-tie approach," *Reliab. Eng. Syst. Saf.*, vol. 104, pp. 36–44, Aug. 2012.

[18] R. Ferdous, F. Khan, R. Sadiq, P. Amyotte, and B. Veitch, "Handling and updating uncertain information in bow-tie analysis," *J. Loss Prev. Process Ind.*, vol. 25, no. 1, pp. 8–19, Jan. 2012.

[19] K. Mokhtari, J. Ren, C. Roberts, and J. Wang, "Application of a generic bow-tie based risk

analysis framework on risk management of sea ports and offshore terminals.," *J. Hazard. Mater.*, vol. 192, no. 2, pp. 465–75, Aug. 2011.
[20] A. Badreddine and N. Ben Amor, "A Bayesian approach to construct bow tie diagrams for risk evaluation," *Process Saf. Environ. Prot.*, vol. 91, no. 3, pp. 159–171, May 2013.
[21] V. M. Trbojevic, "Optimising hazard management by workforce engagement and supervision," *Heal. Saf. Exec. UK Res. Rep.*, 2008.
[22] M. Irani, "Development and Application of Bow-tie Risk Assessment Methodology for Carbon Geological Storage Projects," 2012.
[23] A. Badreddine, T. Ben Romdhane, M. A. Ben HajKacem, and N. Ben Amor, "A new multi-objectives approach to implement preventive and protective barriers in bow tie diagram," *J. Loss Prev. Process Ind.*, vol. 32, pp. 238–253, 2014.
[24] C. Qinqin, Q. Jia, Z. Yuan, and L. Huang, "Environmental risk source management system for the petrochemical industry," *Process Saf. Environ. Prot.*, vol. 92, no. 3, pp. 251–260, May 2014.
[25] D. T. L. Yung, *Principles of fire risk assessment in buildings*. 2008.
[26] J. Bhatt and H. K. Verma, "Design and Development of Wired Building Automation Systems," *Energy Build.*, vol. 103, pp. 396–413, 2015.
[27] Z. Qing-shun and W. E. I. Hong-yang, "The Characteristic Fire Protection Design of Mountainous City and Hillside Building - Illustrated by the Example of Chongqing," vol. 11, pp. 701–709, 2011.
[28] F. Nilson, C. Bonander, and A. Jonsson, "Differences in Determinants Amongst Individuals Reporting Residential Fires in Sweden: Results from a Cross-Sectional Study," *Fire Technol.*, vol. 51, no. 3, pp. 615–626, 2015.
[29] R. Kang, G. Fu, and J. Yan, "Analysis of the Case of Fire Fighters Casualties in the Building Collapse," *Procedia Eng.*, vol. 135, pp. 343–348, 2016.
[30] "Sprinklers for Safer Living," 2010.
[31] X. Li, X. Sun, C.-F. Wong, and G. Hadjisophocleous, "Effects of Fire Barriers on Building Fire Risk - A Case Study Using CUrisk," *Procedia Eng.*, vol. 135, pp. 444–453, 2016.
[32] BC, "ASSISTED LIVING and RESIDENTIAL CARE Fire and Life Safety Fire and Life Safety."
[33] N. E. Groner, "A decision model for recommending which building occupants should move where during fire emergencies," *Fire Saf. J.*, vol. 80, pp. 20–29, 2016.
[34] C. Keogh and J. Lord, "Society of Fire Protection Engineers Guidelines for Designing Fire Safety in Very Tall Buildings," 2012.
[35] S. H. I. Long, Z. Ruifang, X. I. E. Qiyuan, and F. U. Lihua, "Improving analytic hierarchy process applied to fire risk analysis of public building," vol. 54, no. 50536030, pp. 1442–1450, 2009.
[36] G. Baker, C. Wade, M. Spearpoint, and C. Fleischmann, "Developing probabilistic design fires for performance-based fire safety engineering," *Procedia Eng.*, vol. 62, no. c, pp. 639–647, 2013.
[37] G. Newfield and D. Watts, "Stage 1 Report Building Code Provisions for Residential Buildings and Identification of Technical and Process Risks," 2008.
[38] S. Safety, "Case Studies on the Verification of Fire Safety Design in Sprinklered Buildings," 2012.
[39] F. Safety, "Code of Practice for Fire Safety in Buildings," 2011.
[40] C. L. Chow and W. K. Chow, "Heat release rate of accidental fire in a supertall building

residential flat," *Build. Environ.*, vol. 45, no. 7, pp. 1632–1640, 2010.
[41] J. Xin and C. Huang, "Fire risk analysis of residential buildings based on scenario clusters and its application in fire risk management," *Fire Saf. J.*, vol. 62, no. PART A, pp. 72–78, 2013.
[42] J. Liu and K. W. Chow, "Determination of fire load and heat release rate for high-rise residential buildings," *Procedia Eng.*, vol. 84, pp. 491–497, 2014.
[43] K. Huang, "Population and Building Factors That Impact Residential Fire Rates in Large U.S. Cities," Texas State University, 2009.
[44] K. Huang, "Population and Building Factors That Impact Residential Fire Rates in Large U.S. Cities," Texas State University, 2009.
[45] Ministry of Community Safety and Correctional Services Ontario, "Comprehensive Fire Safety Effectiveness Model," 2016. [Online]. Available: https://www.mcscs.jus.gov.on.ca/english/FireMarshal/FireServiceResources/ComprehensiveFireSafetyEffectivenessModel/FireRiskSub-Model/Fire_risk_submodel.html. [Accessed: 23-Jun-2017].
[46] Department for Communities and Local Government Publications, "Fire safety risk assessment," London, 2006.
[47] M. Omidvari, N. Mansouri, and J. Nouri, "A pattern of fire risk assessment and emergency management in educational center laboratories," *Saf. Sci.*, vol. 73, pp. 34–42, 2015.
[48] Federal Emergency Management Agency, "SOCIOECONOMIC FACTORS AND THE INCIDENCE OF FIRE," Washington, DC, 1997.
[49] Ministry of Community Safety and Correctional Services Ontario, "Comprehensive Fire Safety Effectiveness Model," 2016. .
[50] Y. W. Shao, S. F. Kao, N. C. Yu, Y. S. Wu, C. J. Huang, and K. Y. Chang, "Fire Hazard Factors of Residential-Commercial Composite Buildings through Fire Hazard Cases," *Autom. Equip. Syst. Pts 1-4*, vol. 468–471, pp. 1753–1757, 2012.
[51] M. Omidvari, N. Mansouri, and J. Nouri, "A pattern of fire risk assessment and emergency management in educational center laboratories," *Saf. Sci.*, vol. 73, pp. 34–42, 2015.
[52] M. Kobes, I. Helsloot, B. De Vries, and J. G. Post, "Building safety and human behaviour in fire : A literature review," *Fire Saf. J.*, vol. 45, no. 1, pp. 1–11, 2010.
[53] M. Kobes, I. Helsloot, B. De Vries, and J. G. Post, "Building safety and human behaviour in fire : A literature review," *Fire Saf. J.*, vol. 45, no. 1, pp. 1–11, 2010.

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Appendix A

Factors contributing to the fire incidence in MURBs were identified from the literature.

TABLE 6: IDENTIFICATION OF RISK CRITERIA

Category	**Criteria**	**Subcriteria**	**Reference**
Exterior Factors	Physical/Natural Environment		[43]
	Climate	Heating degree days	[44]
	Adjoining buildings	Vacancy rate (In the neighbourhood)	[44][45]
		Proximity to the adjoining structure	[46]
Building	Age of the building		[44][47][48]
	Building height and area		[49]
	Quality of construction	Existing layout and construction	[44]
		Material	[50][51]
	Interior	Availability of flammable articles	[50]
		Housekeeping	[46]
		Dangerous substances: storage and use	[46]
		Electrical system safety	[46][51]
		Insulated core panels	[46]
		Heating and cooling system	[51]
	Past incidents		[49]
Human Action	Occupancy		[44][49] [48]
	Income		[48]
	Demographics		[44][51] [49]
	Knowledge & experience	Education	[44][52][51]
		Powers of judgement & Observation	[53] [48]
	Life style	Smoking	[46]
		Arson	[46] [48]

Appendix B

“DynamicFire” is a fire risk assessment tool for multi-unit residential buildings (MURB), that supports risk management decisions to minimize fire risk and its adverse impacts on residential buildings. “DynamicFire” assists users in the following tasks:

1. Prediction of fire risk in buildings
2. Suggestions for fire risk management

GUIDELINES:

This tool operates on the Microsoft Excel platform. The users could change the data in the cells with a background of "sky blue"colour and white font colour to a specific building. The steps for applying the tool are as follows:

Identify threats, preventive and their respective probabilities: Identify threats, preventive and their respective probabilities in constructing the left-hand side (fault tree) of the Bow-tie. Literature-based probabilities are already included in the tool. However, users can modify the probabilities according to a specific building. Figure 6 presents the common threats causing fire incidents for MURBs, preventive safeguards and their respective probabilities.

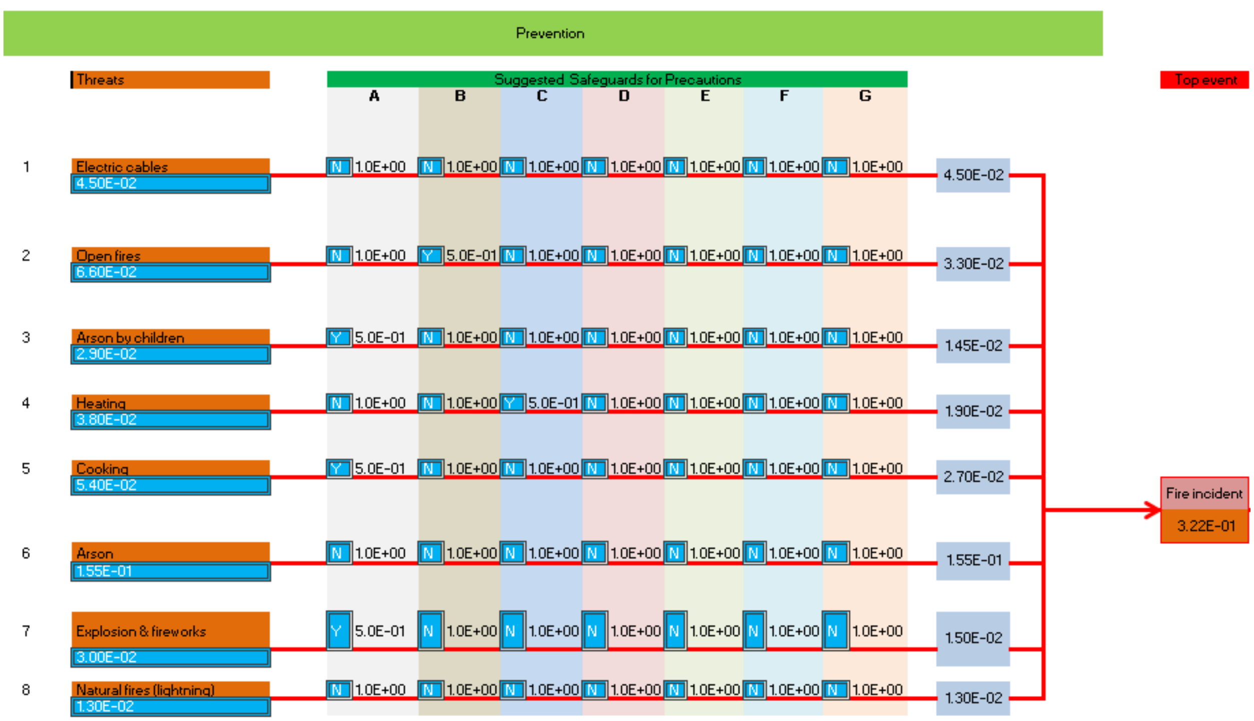

FIGURE 6: ANALYSIS OF THREATS AND PREVENTIVE SAFEGUARDS USING FAULT TREE ANALYSIS

Define safeguards: The common safeguards are defined in ETA for fire incidents protection along with the probabilities of success and failure. Eight suggested safeguards and three fire protections are defined: (i) smoking material with a failure probability of 3.0E-01, (ii) sprinkler system with a failure probability of 4.0E-02, and (iii) regular evacuation drills with a failure probability of 2.0E-01. The suggested safeguards for protection will decrease scenario probabilities (Figures 7-8). The probability for each scenario is defined using the probability of a fire incident with the probability of the success of safeguards.

FIGURE 7: PROTECTIVE SAFEGUARDS ANALYSIS

Define the scenarios: scenarios are used to estimate the impact on four factors; people, property, environment, and reputation. Various impact levels for categories were defined based on literature and expert consultation. Users need to define the scenarios based on their knowledge (Figure 8).

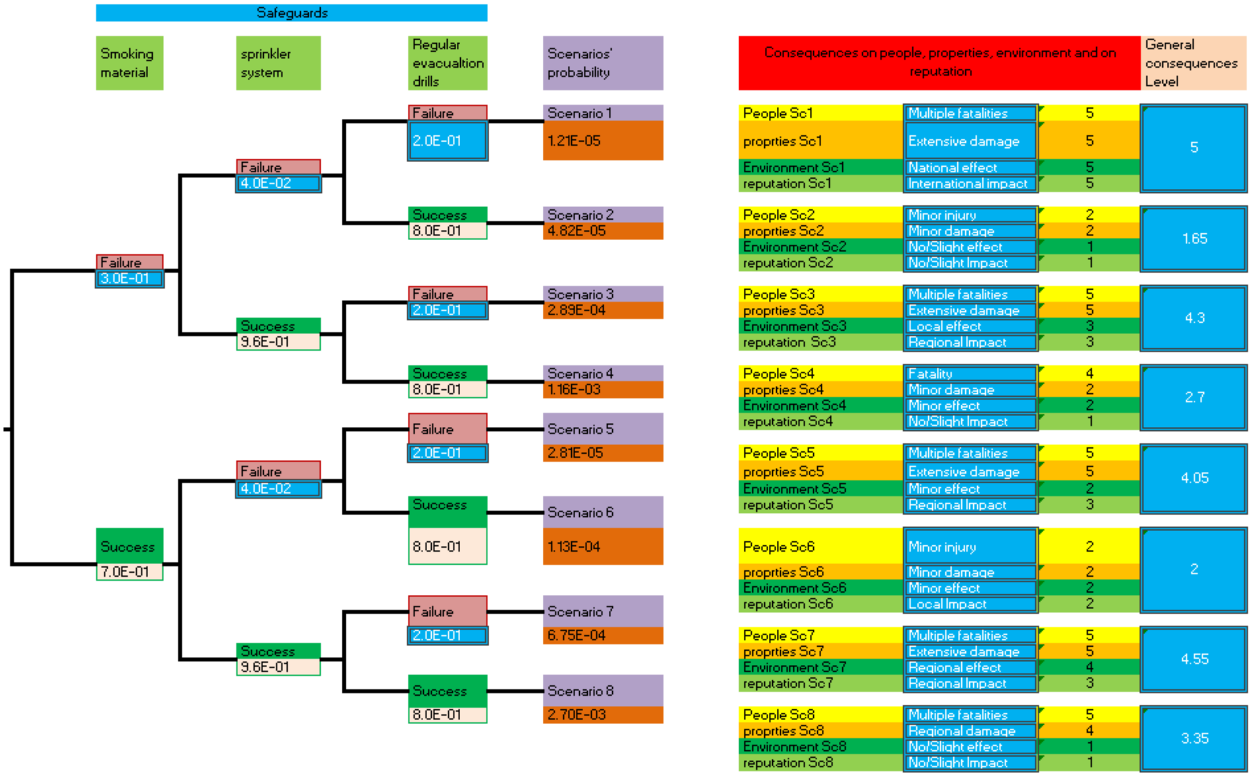

FIGURE 8: ANALYSIS OF PROTECTIVE SAFEGUARDS WITH IMPACT OF SCENARIOS

Fire risk definition: The fire risk level for the MURB can be defined using a five-level scale. Table 7 presents the fire risk levels for MURBs. Risk level is defined using the Table 7 and Figure 6.

TABLE 7: RISK LEVELS

Risk	Level	Definition
Absolutely	5	Urgent action required
Extreme	4	Immediate action required
High	3	Senior management action required
Moderate	2	Management responsibility specified
Low	1	Managed by routine procedures

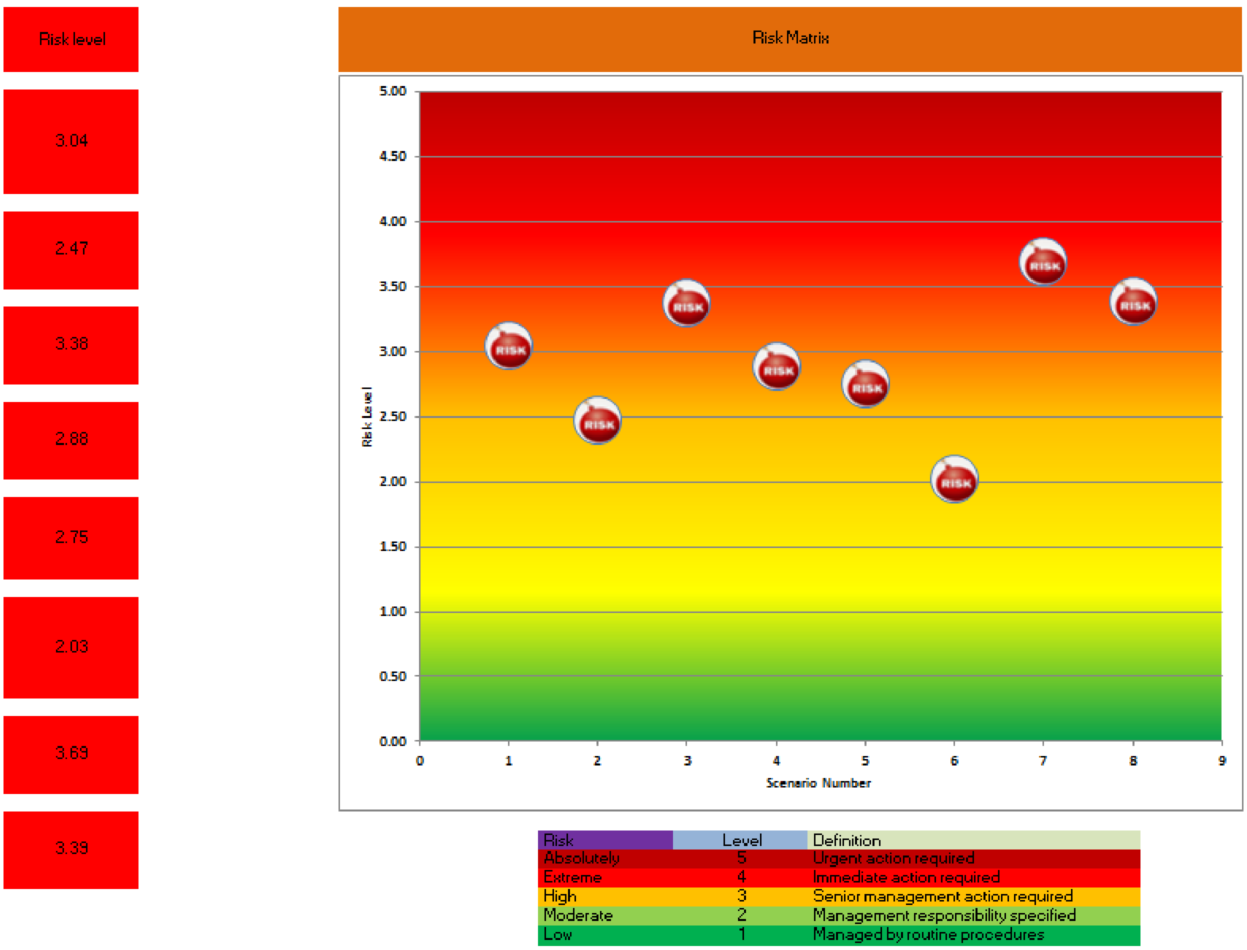

FIGURE 9: RISK LEVEL FOR EIGHT SCENARIOS

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