Development and Case Study of a Risk Assessment Model CUrisk for Building Fires

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ABSTRACT

A fire risk computer model CUrisk is being developed at Carleton University to evaluate fire safety designs for four-story, timber-frame commercial buildings. The model consists of the system model and a number of subsidiary submodels. The system model implements the risk analysis framework and controls data flow of the submodels; it is also responsible for calculating the life hazard of each scenario. Other submodels include Fire Growth and Smoke Movement, Boundary Failure and Fire Spread, Occupant Response and Evacuation, and Building Cost and Economic Loss. Using the outputs of the submodels, the system model calculates three decision-making parameters, the Expected Risk to Life, the Expected Risk of Injury, and the Fire Cost Expectation. These parameters are based on possible fire scenarios and their associated probabilities. This paper provides a brief description of CUrisk, and presents the results of a multi-scenario risk analysis for a four story commercial building.

KEYWORDS: fire risk, life hazard, modeling, risk assessment

INTRODUCTION

As countries move towards the development and implementation of performance-based codes, the need for quantitative risk assessment methods to evaluate whether building fire safety designs comply with these codes is increasing. A number of fire risk assessment models have been developed over the last decade such as FiRECAM [1] and CESARE-risk [2], which were developed specifically for apartment and office buildings, and FIERAsystem, which was developed for light industrial buildings [3].

The development of the fire risk computer model CUrisk at Carleton University is one of the research activities of the recently established Industrial Research Chair in Fire Safety Engineering, partially funded by Natural Science and Engineering Research Council of Canada and Forintek Canada Corporation. The main objective of CUrisk is to facilitate the evaluation of fire safety designs for four-story timber-frame commercial buildings; however, the model can be applied to a variety of buildings as long as the necessary input data are available to define design fires and probability of scenarios for those buildings.

Following the approach used by the other risk models, CUrisk calculates both the life hazard and economic costs. Life hazard is expressed in terms of an expected risk to life parameter as well as expected risk of injury.

A brief description of the system model has been provided in Hadjisophocleous and Fu [4]. The system model of CUrisk and all its submodels have been completed except of the Boundary Failure and Fire Spread submodel, which is used to calculate the probability of

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fire spread to other compartments through computing the probability of failure of the compartment boundaries, such as walls, floor and ceiling as a result of fire attack.

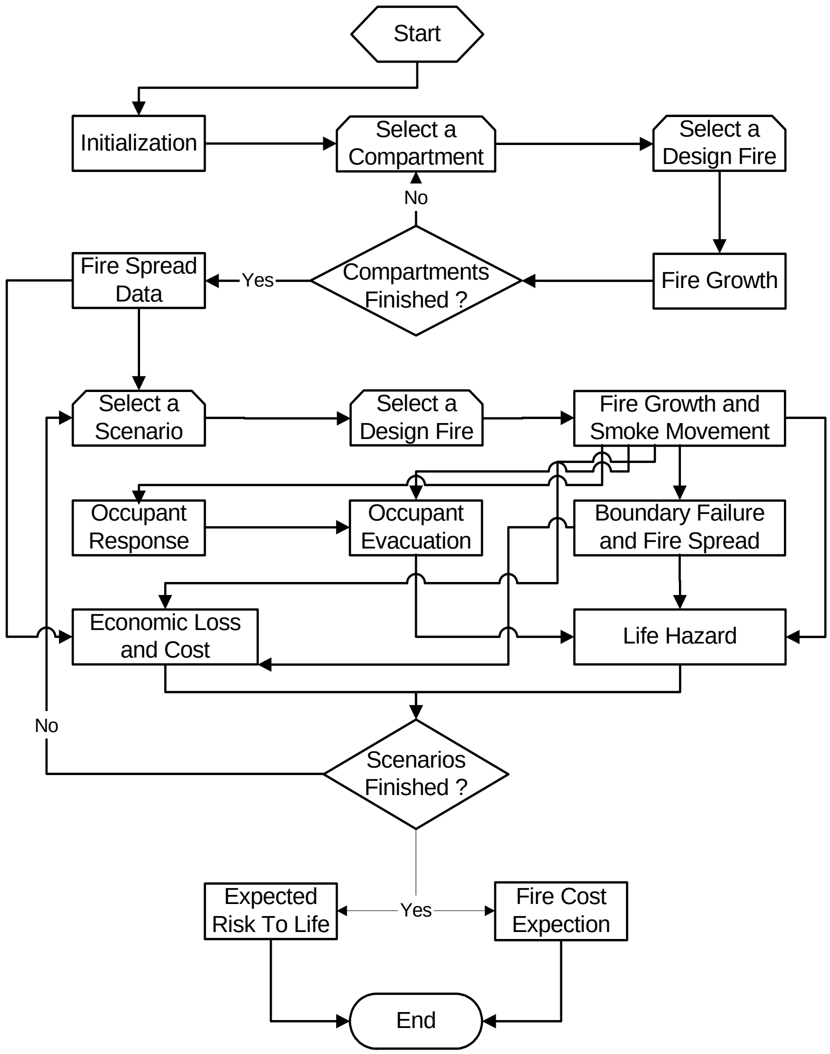

Fig. 1. System model flowchart.

In the following sections, a brief description of CUrisk and its main submodels is given, as well as results of a multi-scenario risk analysis case study for a four-story commercial building. The results shown do not consider the effects of fire spread.

SYSTEM MODEL

Framework of the System Model

The risk analysis procedure of CUrisk is shown in Fig. 1. The system model performs a risk analysis in which the consequence of each scenario is defined in terms of the expected risk to life, expected risk of injury and expected damages. For each fire scenario, the fire growth and smoke movement model is run to predict the fire conditions in the fire compartment and other compartments. The Occupant Response model is then run to predict the probabilities of occupants responding to fire warnings and taking various actions. Based on the information of fire conditions and occupant response, the evacuation model is then used to predict the evacuation route and timeline of each occupant in the building. The economic model is then run to predict the building costs and economic loss for this scenario. Given the evacuation route and time of occupants, fire and smoke conditions, and the probability of fire spread to any compartment, the life hazard model is used to predict the expected number of deaths and injuries of occupants for the scenario. After finishing all the scenarios, the three parameters, i.e., ERL, ERI, and FCE, are calculated based on the probabilities of these scenarios.

Decision Making Parameters

Similar to CESARErisk, FiRECAM and FIERA, the parameter ERL, is defined as the expected probability of dying in the building per year per occupant. A new parameter ERI is also defined similar to ERL. The following gives the equations:

$$ERL = \frac{F\sum_{i=1}^{K} P_i ND_i}{POP} \tag{1}$$

where F is the annual fire frequency of the building, P_i is the probability of scenario i, ND_i is the number of deaths of scenario i, K is the number of scenarios, and POP is the population of the building.

$$ERI = \frac{F\sum_{i=1}^{K} P_i NI_i}{POP} \tag{2}$$

where NI_i is the number of injuries of scenario i.

Another parameter FCE, is used to calculate the expected fire losses and the costs for building. In this model, it is assumed that the fire costs are composed of three parts, fixed capital investment for the building and its active and passive fire protection systems, maintenance and inspection costs of the active fire protection systems, and expected losses due to fire and smoke spread. The total costs can be calculated as follows:

$$ECOF = COST_{Fixed} + DL\left(COST_{Maintain} + COST_{Loss}\right) \tag{3}$$

Where DL refers to the design life of the building in years considering the last two terms are both annually based. $COST_{Loss}$ can be calculated using a similar approach to calculating ERL as follows:

$$COST_{Loss} = F\sum_{i=1}^{K} P_i EL_i \tag{4}$$

where EL_i is the economic loss of scenario i, obtained from the Economic model.

LIFE HAZARD MODEL

The Life Hazard submodel is used to calculate the number of deaths and injuries in each fire scenario as a result of exposure to toxic gases, hot gases, high heat fluxes, and fire spread. This model allows the user to specify two thresholds for death and injury, making the model more flexible not only to calculate the number of deaths but also the number of injuries.

The probability of death due to breathing toxic gases is calculated based on the techniques developed by Purser [5]. The approach is also described in the SFPE Handbook of Fire Protection Engineering [6] and has also been adopted by ISO [7]. The time-dependent probability of death from exposure to high thermal radiation heat fluxes is calculated using the revised vulnerability model of Tsao and Perry [8]. When the fire reaches flashover, it may result in boundary failure and fire spread to other compartments and thus cause harm to occupants. For this, CUrisk also calculates the probability of death caused by fire spread. More details on this calculation can be found in reference [4]. Although the Life Hazard model has been developed to consider the effects of fire spread, these effects are not included in the results presented in this paper because the Fire Spread model has not been completed.

FIRE GROWTH AND SMOKE MOVEMENT MODEL

In CUrisk, a submodel called CUsmoke developed based on the 2-zone model FIERAsmoke is used for predicting fire growth and smoke movement. Details of the basic theory behind the model can be found in reference [9]. In addition, some results using this smoke model to predict and compare experimental results in a high-rise smoke tower have been published in references [10-11]. Based on the approach described in reference [12], a simplified approach has been added to CUsmoke to calculate the effect of sprinkler suppression on heat release rate. Similarly, a simplified fire department action model is also included to predict the interaction between the fire department fire fighting activities and the fire development based on the work done in references [13-15].

OCCUPANT RESPONSE MODEL

The Occupant Response model is used to predict the response of occupants to the various cues and warnings, including early fire and smoke cues, local smoke detector alarm, central alarm signals, and warnings from other occupants. The output of this model is a time dependent probability of response for occupants in the building. This model is developed based on the concept of PIA process, i.e., perception, interpretation and action. The theory and calculation behind this model are similar to the approach in references [16-18].

The response of occupants to a fire will also depend on where the occupants are located; occupants are separated into three groups: occupants in the fire compartment (OFC), in adjacent compartments (OAC), and in other compartments (OOC) as the cues perceived by each group of occupants will be different. Occupant response is closely related to the times of occurrence of important events during the development of a fire. In this model, five fire states are used to identify these events; they are: start of fire, time when fire cues are available, local alarm and smoke detector activation, heat detector and sprinkler activation, and flashover. Data on fire states are obtained from the fire growth and smoke movement model.

OCCUPANT EVACUATION MODEL

This model attempts to represent occupant behaviour and movement that might be seen in an actual evacuation of a building by generating the route taken by each occupant. A rule based behavioural system is used in the model allowing the occupants to make decisions on whether to evacuate or how to respond to building conditions.

Random procedures are used in the decision making process so that not all occupants make the same decisions. In each compartment, all occupants travel the same distance but at different times, based upon the probability of response to fire cues obtained from the Occupant Response Model. Once an occupant has decided to leave the building, he will never decide to try to stay in one room but he will continue moving until he exits the building. Each exit is given an associated probability of use. When an occupant has reached a doorway, a possibility of queuing will be checked based on a simplified calculation. Probability of selecting an exit will be affected by a factor associated with previous use of the exit and a factor for the level of smoke in the compartment connected by the exit. Speed will be adjusted based on levels of smoke, population density within a given compartment and the standard deviations of experimental data on occupant speeds at different smoke levels. The base speed of each occupant is based on the age, gender and location. For more details, please refer to the reference [19].

ECONOMIC MODEL

The economic model is used to assess the capital costs of building construction, fire protection systems, contents, as well as the cost of damages and the cost of downtime. The output of the model includes the total cost of damages for each individual compartment, the cost of adding fire protection systems such as active, passive and emergency systems along with the total annual cost for maintenance, inspections and replacement of active, passive and emergency systems.

The contents of the building are considered in the calculation of the expected damages due to a fire. Contents are categorized by their sensitivities to temperature, smoke, and water. The contents of the building are divided into 11 major categories, including books, electronic equipment, clothes, food, appliances, upholstered furniture, wood furniture, plastics, machinery, interior linings and finishes as well as lighting. The categories developed include contents that could readily be found in commercial buildings. For more details, please refer to the reference [20].

A CASE STUDY OF A 4-STORY COMMERCIAL BUILDING

This section presents the results of a case study of a four story commercial building performed using the developed risk model CUrisk. Details are presented in the following.

Geometry and Fire Protection System of the Building

The building considered is a four-story commercial building called CTTC (Carleton Technology and Training Centre) located on the campus of Carleton University. Each floor of the building is divided into a number of units. The second floor has 6 units, the fourth floor has 5 units, and the first and third floors each have four units. The building has two internal stairways fully separated from the building using fire rated walls and doors. The first floor has two other exits directly to outside, and the second floor has one other exit directly to outside. Furthermore, each floor has one corridor connected to each unit and stairways. Figure 2 shows a schematic floor plan of the fourth floor, where 31 and 32 refer to stairs one and two. The building was assumed to have 298 occupants.

The building has a sprinkler system, as well as heat and smoke detectors installed at places such as air ducts, stairways, and elevators. There is a central alarm system but no voice alarm system.

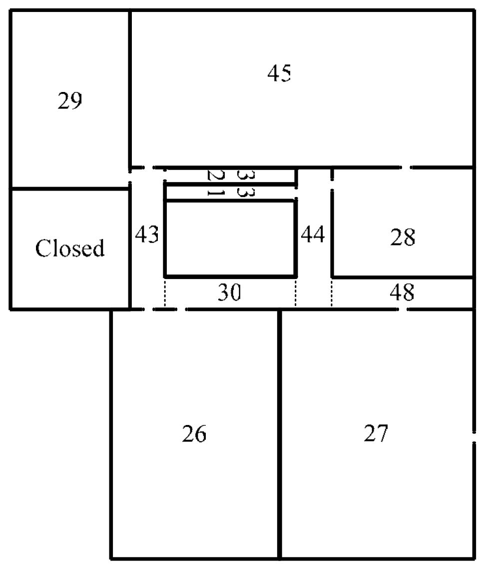

Fig. 2. Schematic floor plan of the fourth floor.

Setup of Scenarios

In this case study, to simplify the problem, one unit is selected from each floor as a representative compartment to have a fire: the parking office, a small restaurant, and two offices. It is further assumed that the probability of fire occurrence in each of the four compartments is the same. For each fire room, the scenario event tree includes three events, sprinkler activation, fire department action, and central alarm system activation. Thus in total, 32 scenarios are analyzed, with the assumed probability of each scenario shown in Table 1. In Column P_{FD}, Opt 1 means the first option with the response time of the fire department being 5 minutes, and Opt 2 being 10 minutes.

Table 1. List of scenarios of CTTC building case study.

No	Fire Rm	P_{SPK}	P_{FD}	P_{CA}	$P_{Scenario}$	NI	EL
						Persons	$ x 10^3
1	1st Floor Parking Office 0.25* Medium Fire Sofa	Yes 0.95	Opt 1 0.8	Yes 0.9	0.171	0	91
2				No 0.1	0.019	0	91
3			Opt 2 0.2	Yes 0.9	0.04275	0	91
4				No 0.1	0.00475	0	91
5		No 0.05	Opt 1 0.8	Yes 0.9	0.009	0	995
6				No 0.1	0.001	0	995
7			Opt 2 0.2	Yes 0.9	0.00225	0	1062
8				No 0.1	0.00025	0	1062
9	2nd Floor Restaurant 0.25 Medium Fire PU	Yes 0.95	Opt 1 0.8	Yes 0.9	0.171	0	140
10				No 0.1	0.019	0	140
11			Opt 2 0.2	Yes 0.9	0.04275	0	140
12				No 0.1	0.00475	0	140
13		No 0.05	Opt 1 0.8	Yes 0.9	0.009	0	999
14				No 0.1	0.001	0	999
15			Opt 2 0.2	Yes 0.9	0.00225	0	1099
16				No 0.1	0.00025	0	1099
17	3rd Floor Office 0.25 Medium Fire Sofa	Yes 0.95	Opt 1 0.8	Yes 0.9	0.171	0	138
18				No 0.1	0.019	0	138
19			Opt 2 0.2	Yes 0.9	0.04275	0	138
20				No 0.1	0.00475	0	138
21		No 0.05	Opt 1 0.8	Yes 0.9	0.009	0	1024
22				No 0.1	0.001	0	1024
23			Opt 2 0.2	Yes 0.9	0.00225	0	1196
24				No 0.1	0.00025	0	1196
25	4th Floor Office 0.25 Fast Fire Sofa	Yes 0.95	Opt 1 0.8	Yes 0.9	0.171	0	166
26				No 0.1	0.019	0	166
27			Opt 2 0.2	Yes 0.9	0.04275	0	166
28				No 0.1	0.00475	0	166
29		No 0.05	Opt 1 0.8	Yes 0.9	0.009	1	1226
30				No 0.1	0.001	10	1226
31			Opt 2 0.2	Yes 0.9	0.00225	3	1316
32				No 0.1	0.00025	11	1316

* Given a fire in the building, probability of fire start in this compartment.

Results of Scenario 32

From Table 1 it can be found that scenario 32 has the largest risk to injury and economic damages, and thus some data on this scenario is presented in the following. As mentioned before, fire growth and smoke movement are calculated using the two-zone model CUsmoke. Figure 3 shows the temperature profile of the smoke layer in the fire compartment, and Fig. 4 depicts the hot layer temperature of other compartments with considerable temperature rise. In the figures, the related room number can be referenced to Fig. 2. Figure 5 presents the hot layer CO_2 concentrations of the compartments where there has been considerable temperature rise.

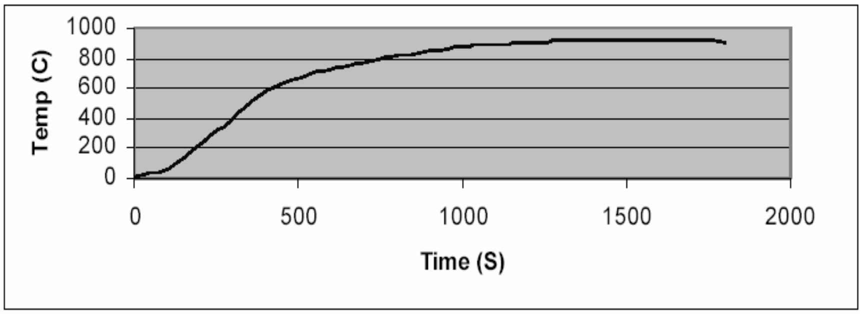

Fig. 3. Temperature profile of fire compartment.

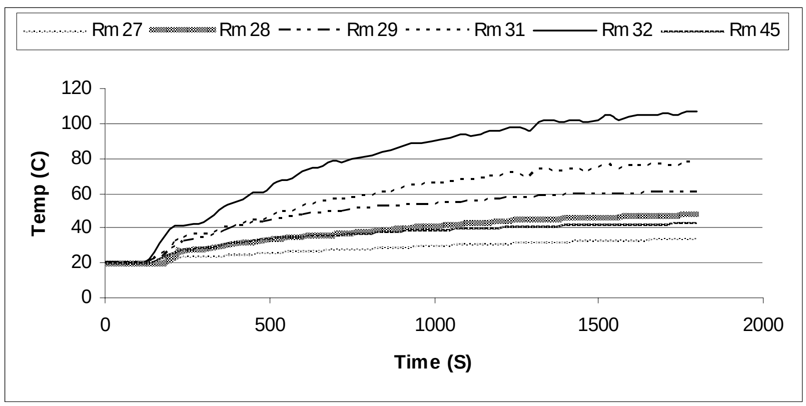

Fig. 4. Temperature profile of other compartments.

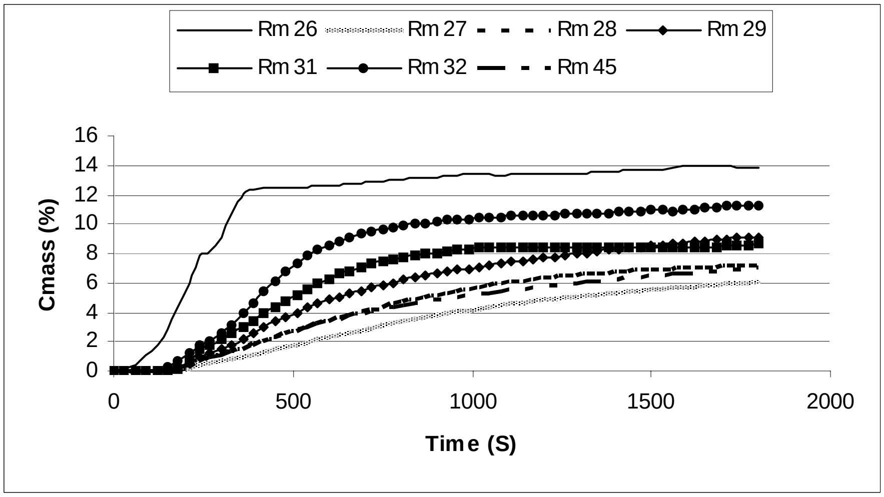

Fig. 5. CO_2 concentration profile of the compartments.

Based on the calculation of occupant response and evacuation, Fig. 6 presents the number of occupants in the building at different times. It can be seen that after 11 minutes or so all the occupants have evacuated. Table 1 shows results of number of occupant injuries. In this case study, no one was killed but some were injured.

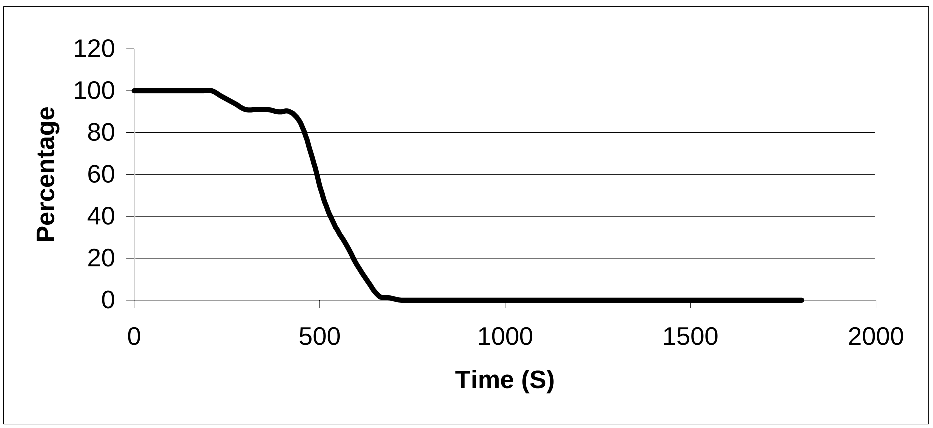

Fig. 6. Number of occupants in the building.

Table 1 also shows results of economic loss for each scenario. The decision parameters can be calculated by assuming fire frequency being 0.04 [19] and design life being 50 years. Note that in this model it is assumed that the thresholds for death and injury are expressed using FID, fractional incapacitating dosage at 0.8 and 0.1. Then the ERL is calculated as zero; the ERI is 6.8E-06, and the FCE is 2,734 thousand dollars.

DISCUSSION

From Table1, it can be seen that only the 4 scenarios with a fast growing fire on the 4th floor have occupants injured. For the medium growing fires on other floors, no one was injured. From the four scenarios with occupants injured on Table 1, it can be seen that the activation of central alarm has largely reduced the number of people injured. It can also be found from the four scenarios that later arrival of fire department has considerable impact on life hazard and economic loss. It is very obvious from Table 1 that whenever sprinklers activate, economic losses and life hazards are greatly reduced. These results are preliminary results of the model, as the model does not consider the effects of fire spread.

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