Probabilistic Risk Assessment of Life Safety for a Six-Storey Commercial Building with an Open Stair Interconnecting Four Storeys: A Case Study

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Abstract

The gold standard for complying Performance Requirements is based on a Quantitative Probabilistic Risk Assessment (QPRA) method. This case study demonstrates the application of this approach to performance based design of a six-storey commercial building with an open stair interconnecting four storeys. Computational Fluid Dynamics (CFD) based and zone fire as well as evacuation simulations are used to quantify consequences whilst detailed event trees underpinned by statistical data and analysis are utilised to calculate corresponding probabilities. Results are combined in a trade-off analysis tool which calculates the Expected Risk to Life (ERL) based on the trial design features included in each design option. The approach was used to determine a preferred design that achieves an acceptably low ERL and compliance with the Performance Requirements of the Building Code of Australia (BCA). The benchmark ERL was set as 1.36 deaths/1000 fires or a probability of death from a fire of 1.36×10^{-3} based on local statistical data. To obtain an optimum fire safety design (Alternative Solution) a layered approach was adopted in which fire safety systems were added until the risk to occupants in the building due to a fire is the same or less than the benchmark ERL. Eventually three sets of trial design were considered and in all cases the calculated ERL were roughly 22% lower than the benchmark. Eventually the trial design with the least number of fire safety systems were recommended as the Alternative Solution. The trade-off analysis shows the sprinklers and wall-wetting sprinklers in the office area resulted in a 20-fold difference in the building wide ERL, each.

1 Introduction

In order to comply with the Building Code of Australia (BCA) [1], a building design must comply with the Deemed to Satisfy (DtS) provisions of the code or otherwise demonstrate that the underlying Performance Requirements of the BCA have been met. Performance-based designed buildings offer more flexibility to the fire safety engineers to adopt new design concepts and technologies to improve aesthetic and acoustic values, material and energy efficiencies, and cost effectiveness while complying with regulatory building codes.

The gold standard for complying Performance Requirements is based on a Quantitative Probabilistic Risk Assessment (QPRA) method [2-4]. Such methods have been used in fire safety engineering in Australia since the early 1990s [5, 6], though not frequently. The release of the ABCB's draft proposal on the verification method [7] has generated renewed interest in applying QPRA for the verification of performance requirement. In recent years, probabilistic method has been used for the aspects of evacuation [8, 9] and structural design [10-13]. For cost-benefit analysis also probabilistic method was used [14, 15]. Some recent research has highlighted probability based quantification of various aspects of fire safety engineering [16-21]. Examples of application of comprehensive QPRA on a performance-based designed building are rare in archival journals. In this study, a unique approach has been taken that involved the development of a QPRA tool which calculates the Expected Risk to Life (ERL) [5, 22] based on the desired design features which have been included in the various alternative designs. ERL calculations were underpinned by results from Computational Fluid Dynamics (CFD) based and zone fire models as well as an evacuation model for the nominated fire scenarios and design features under investigation. This allowed for consideration of the design features necessary to achieve an acceptably low ERL.

Other quantitative risk assessment techniques such as F-N curves for acceptance criteria [23] and/or Monte Carlo Simulation [8] for probabilistic risk calculations can also be applied to this case study.

The case study presented outlines fire safety issues associated with a six-storey commercial building with an open stair interconnecting 4 storeys and the likely Performance Solution based on a hazard analysis and quantitative assessment of the safety levels for various alternative building designs. The International Fire Engineering Guidelines (IFEG) [22] has been used to provide reference to the fire engineering process and assessment methodologies. This case study is used as an example so that the same design approach can be applied to other types of building. This will encourage technical practitioners to increase the adoption rate of QPRA methodology for real life buildings and to elucidate the methodology to regulators and legal practitioners.

2 Methodology Used

The methodology used in this case study is quantitative, absolute and probabilistic. The aim of the assessment is to demonstrate that the risk to occupants in the event of a fire in the subject building will be less than the ERL taken from past statistical data involving fires in a similar building. Risk is often calculated as the product of probability and consequence [24]. Probability can be determined by statistical data and reliability studies. Consequence can be calculated using CFD/zone and evacuation modelling or expert judgement. The ERL is quantified in terms of the number of expected deaths caused by fire over the life of the building.

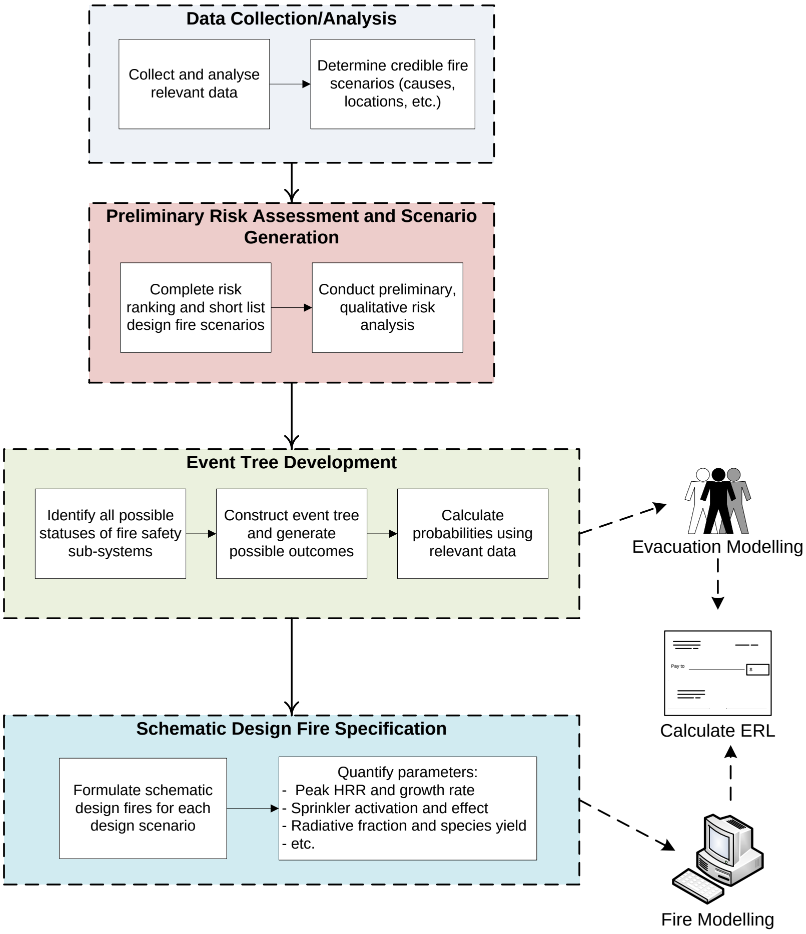
The QPRA tool is predominantly based on event trees. Based on hazard analysis, various fire scenarios are developed. After an initial qualitative risk assessment, some scenarios are nominated for CFD and evacuation modelling as shown in Figure 1(a). Event trees are then developed based on the fire scenarios. Depending on the failure of various fire safety measures (detection, suppression, window breakage, barrier failure etc), various branches of the event tree are evolved as exemplified in Figure 1(b). The probabilities (P_{XX} in Figure 1b) of occurring different branches need to be determined by historical data and/or fault tree analysis.

Each end node of an event tree will have a probability and a quantitative design fire. A design fire is the representation of fire severity in terms of heat release rate (HRR) and time. It is to be noted that HRR is the most important parameter for fire safety analysis [25-27] which can be derived using various correlations [22]. The design fire becomes the main input into the CFD or zone model and associated product yields from fire (such CO yield, CO2 yield, soot yield etc which can be obtained from bench-scale experiments and/or various databases) are also provided as the inputs.

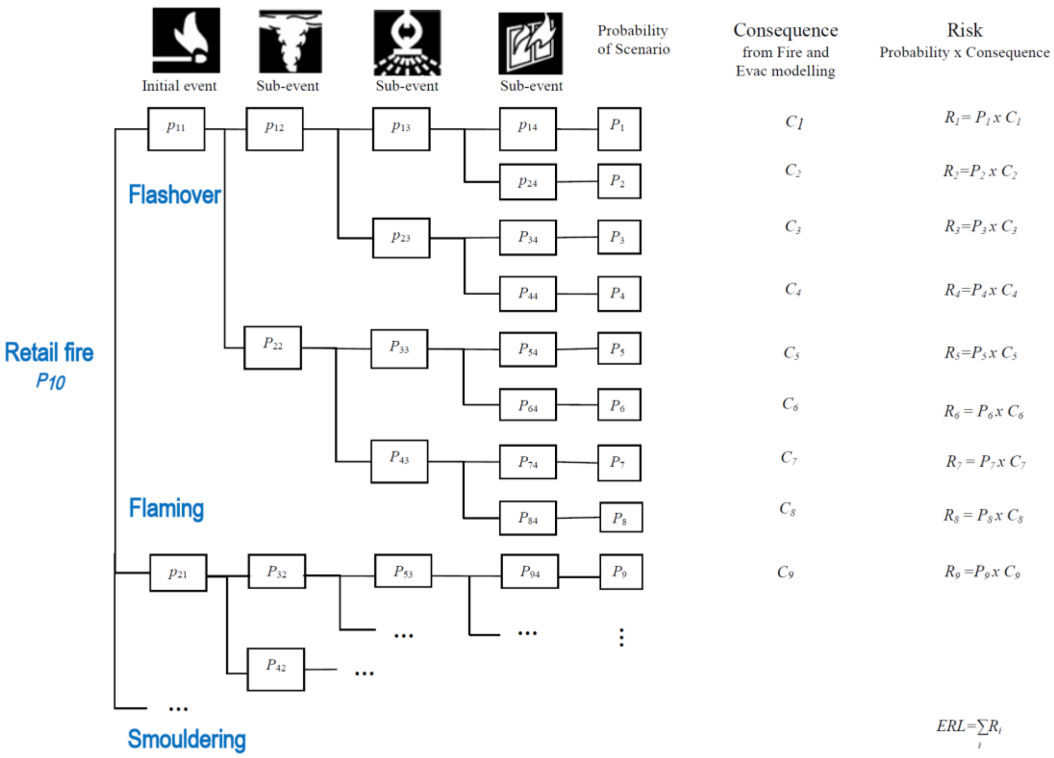
The CFD/zone model analyses give us by what time untenable condition (in terms of heat flux, room temperature, toxicity etc) is reached for a particular fire scenario and design fire. An evacuation model calculates how many occupant can evacuate to a safe place by that time. The rests are considered as casualty and hence, consequence. So for each end node we can have a probability and consequence. This whole set up of event tree, fault tree, fire modelling and evacuation modelling can be regarded as the risk model.

The risk to occupants is determined by multiplying the consequence by the probability for each end node in the risk model. When we add risks of all end nodes, we get the cumulative risk which is known as the ERL (Figure 1b). In summary, the ERL is calculated as follows:

a. Event trees were used to calculate the probability of all possible outcomes for each scenario;
b. Corresponding design fires were assigned at appropriate junctures in the event tree to account for those events effecting the magnitude of the fire such as sprinkler activation.



(a) Risk Modelling Approach



(b) Calculation of ERL from an event tree

Figure 1. Overall QPRA approach

c. Fire modelling was used to calculate tenability levels over time for each of the identified scenarios;
d. Evacuation modelling was performed for each scenario;
e. Corresponding evacuation and fire simulation results were overlaid (essentially an Available Safe Egress Time, ASET/ Required Safe Egress Time, RSET analysis) to determine the number of casualties (i.e. the consequence) for each event tree outcome;
f. The probability, encompassing the likelihood of initiating events, and consequence of all possible outcomes for each scenario were used to calculate the ERL.

Fire brigade intervention (FBI) has also been considered as some performance requirements of the BCA, namely (1) CP1 Structural stability during a fire; (2) CP2 Avoiding spread of fire; and (3) EP2.2 Evacuation time of occupants are related to FBI. Therefore, the use of the Fire Brigade Intervention Model (FBIM) forms part of the assessment in order to provide a quantification of the fire hazard exposure to fire brigade personal during their search and rescue tasks.

Finally a trade-off tool has been developed to enable the analysis of trial design features to determine the preferred solution and its associated ERL based on the simulation results, and underpinned by statistical data.

It is recognised that in some jurisdictions, a design that is proven to reduce risk to an absolute value may not be adequate. An alternative approach may be to demonstrate that risks have been reduced So Far As Is Reasonably Practicable (SFAIRP) [28, 29]. The methods used in this paper may be suitable to compare the risks from several trial concept designs however a separate framework may be required if risks are required to be reduced SFAIRP [30].

It is also recognized that the results from the QPRA are highly dependent on the inputs provided. It is extremely important to acknowledge and account for all uncertainties associated with the inputs. This can be achieved through several ways – one example is to analyse a range of range of values for each input as part of a sensitivity analysis. Another is to represent the range of possible values for each input parameter as appropriately quantified numerical distributions, then perform calculations using Monte Carlo or equivalent simulation to determine probabilistic results.

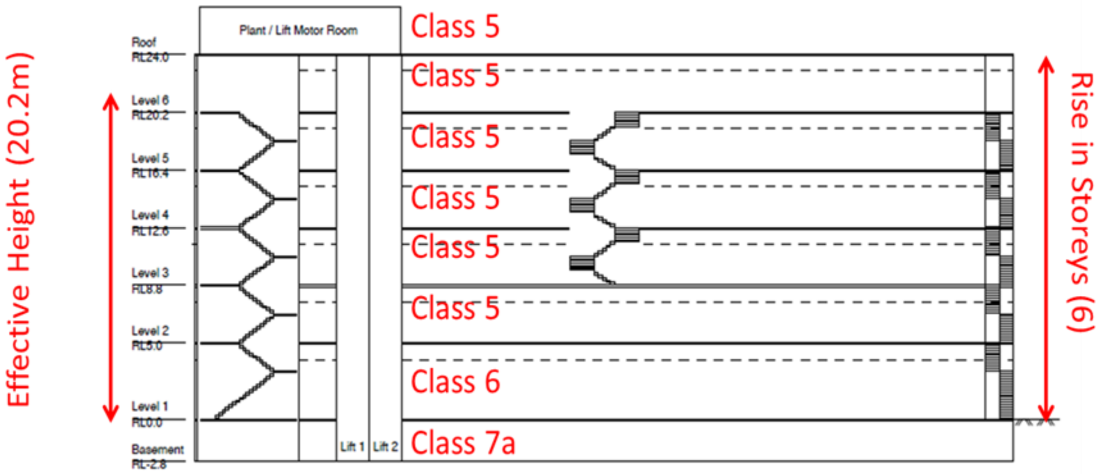


Figure 2 – BCA Classification, Rise in Storeys and Effective Height

3 Building Description

The proposed building, as shown in Figure 2, consists of a mixed used retail and office development comprising a rise in storeys of six (6) as per clause C1.2 of the BCA [31]. In accordance with clause C1.1

of the BCA, based on the rise in storeys (6) and the relevant building classifications the proposed building is to comprise of Type ‘A’ construction as defined by Specification C1.1 of the BCA.

Buildings of Type ‘A’ construction are required to have non-combustible external wall, common wall, floor and floor-framing lift pit, non-load bearing walls (required to be fire-resisting) and non-load bearing lift, ventilation, pipe, garbage, and the like shafts (which do not discharge hot products of combustion). In addition, all load bearing internal walls (including shaft walls) and load bearing fire walls need to be either masonry or concrete. The Architect and Structural Engineer have defined the building architectural/structural characteristics for the proposed development as having masonry/ concrete lift shaft, fire-isolated stair shaft and fire-isolated passage way; steel/concrete composite floor; protected steel structure frame; metal deck/concrete roof; glazed curtain walls; and steel/concrete open stair (level 3 – to 6).

The building is served by two (2) fire isolated stairs located at the far North East and West ends of the building. Two (2) passenger lifts are located within the ground floor lobby situated on the North-West side of the proposed building, the lifts for functional purposes service the building from the Basement Carpark to level six (6).

The floor area of the basement (carpark), Level 1 (shops) and Level 2 (office) are ~1800 m^2 each. Their ceiling heights are 2.7 m, 3.9 m and 2.7 m, respectively. Level 2-6 have interconnected office space with a total floor area of ~7200 m^2 and each of these Levels has 2.7 m height. At the roof, there is a plant room with a floor area of ~222 m^2 and 3.1 m height. Therefore the effective height of the building is ~20.2 m (measured as per clause A1.1 of the BCA).

4 Dominant Occupant Characteristics

4.1 Number of Occupants

Building occupancy numbers have been determined from a mixture of sources, namely; clause D1.13, Table D1.13 of the BCA and utilisation of occupant densities from the Fire Code Reform Centre (FCRC) Project 6 [32]. The occupant densities for shops as per [32] are half the densities than that of the BCA Deemed-to-Satisfy (DtS) requirements. The reduced densities are based on statistical research data collected by the Project 6 research development team given typical normal shopping periods. Occupant numbers denoted below in table 1 have been confirmed by the project stakeholders.

Table 1 – Building Population

Level	BCA Class	Floor Area	Floor Area excluding Lobby, Stair, and Amenity Areas	Population Density	MIPs	Occupant Number
Basement	7a	~1800 m^2	N/A	30m^2 per person	2	60
Level 1 (Ground)	6	~1800 m^2	N/A	6m^2 per person [32]	6	300
Level 2	5	~1800 m^2	1385m^2	10m^2 per person	6	139
Level 3	5	~1800 m^2	1385m^2	10m^2 per person	6	139
Level 4	5	~1800 m^2	1385m^2	10m^2 per person	6	139
Level 5	5	~1800 m^2	1385m^2	10m^2 per person	6	139
Level 6	5	~1800 m^2	1385m^2	10m^2 per person	6	139
Plant	5	~222 m^2	N/A	30m^2 per person	N/A	8
Total					38	1063

4.2 State of Occupants

Occupants within the Basement Carpark are expected to be awake, alert and familiar with the building, as access to the carpark is for building tenants only. The occupants within the basement carpark will be aware of the locations of alternative exits.

Occupants within the level one 1 (Ground) floor shops are expected to be transient, awake and not familiar with the building (exception for staff), however the occupants will be familiar with the route that they have entered the shop/building and as such further consideration is to be made in order to facilitate safe egress from each shop.

Occupants within the building office floor levels (2-6) can be categorized into two types of occupant groups, namely office/tenant staff which are expected to be awake, alert and familiar with the building, as access to the office is for building tenants only (i.e. security lift card swipe pass). The second group of occupants expected within the office floor levels is visitors to the building and these occupants are expected to be unfamiliar with the building and the respective egress layouts. Within the office levels, unlike the Level 1 (Ground) floor shops, occupants are expected to be escorted at all times by office staff, and in the event of an emergency, it is anticipated that the visitors will be directed by office staff to evacuate via the most direct building exit.

We also assume that 97% are ambulant and 3% are mobility impaired persons (MIP). Statistics from the Australian Bureau of Statistics (ABS) have been used to establish a benchmark for the number of people who are disabled and MIP. According to the ABS 18% of Australians have some form of disability with 2.9 % of Australians always requiring assistance with regards to mobility, communication and care [33]. A figure of 3% has been used to discern the number of disabled and MIP occupants located on each level of the building. This figure is considered a conservative assumption due to the wide range of disabilities included within this percentage such as those who are bedridden and hence unlikely to be an occupant of this building.

4.3 Emergency Management Training

As part of the building fire safety system a building emergency management strategy is to be developed, which in turn will provide the building owners/managers with a means of training the individual shop/office employees and employers of the actions necessary upon activation of the building occupant warning system.

5 Hazards Analysis and Safety Measures

5.1 Mobility Impaired Occupants

The primary hazards relevant to Mobility Impaired Personnel (MIP) in terms of the building fire safety strategy are (1) MIP's are not able to evacuate using stairs, (2) the travel speed for MIP's is likely to slower than compared to able-bodied occupants, and (3) MIP's are more sensitive to how well-maintained paths of travel are to exits. The fire safety strategy is therefore likely to include (1) reduced pre-movement time by requiring staff to alert evacuating MIP's upon first knock of the smoke detection system, (2) the use of lifts for the evacuation of MIP's, and (3) the use of lobbies on Levels 2 to 6 for the MIPs to the benefit of MIP's and intervening fire brigade in the event of a fire.

5.2 Car Park

Relatively little is reported in terms of injuries or fatalities to occupants and fire brigade from fires in car parks. Fires in car parking areas of residential buildings account for approximately 2% of fires (New

South Wales Fire Brigade [34-38]). No fatalities were reported as a result of fires in car parks under statistics obtained from the New Zealand Fire Service [NZFS] between 1999 and 2004 [39].

The possible fire scenarios for the basement include a vehicle either parked or whilst in motion. However due to the relatively open layout of the car park, it is reasonable to assume that occupants could rely on either visual, audible or olfactory cues to detect a fire. The risk to occupants of the building is likely to be offset through the provision of the trial design in Table 2.

5.3 Retail Areas

Retail areas are generally well defined in terms of layout however can represent a high fuel load. Therefore, the risk to occupants is primarily due to awareness (if occupants are under the influence of alcohol or are otherwise engaged in another activity), potentially fast-growing fires that has a high soot content and paths of egress that often have only one choice of direction available. The risk to occupants and fire brigade from fires in retail areas is likely to be offset by the provision of the trial design in Table 2.

Table 2 –Trial Design Features

Fire Safety System	**Extent of trial design**
Egress	All exit doors are required to be outward swinging exit doors. The retail tenancies on the Ground Floor are required to be served with individual exits with a minimum width of 1.7 m each (i.e. Double doors). Two of these exits are required to open into the pedestrian path to the east. These exits are required to be separated at least 6 m apart. Exit doors separating the office areas from the adjacent amenities lobby on Levels 2 to 6 are required as shown in Figure 3c and 3d.
Protected lobby construction	Lobbies with protected construction are required as shown in Figure 3. The glazed lobby walls are to consist of 6 mm toughened glass. Glazed lobby walls are to be protected with Tyco WS Specific Application Window Sprinkler Heads to achieve an FRL -/120/120. Doors within the lobby wall are to be fitted with smoke seals.
Fire rated construction	The lifts are required to be fire separated with FRL (60)/60/60. The switch room is required to be fire separated with FRL (60)/60/60 walls and a self-closing FRL -/60/60 self-closing door. This is shown in Figure 3. The ground floor lobby is to be separated from the rest of ground floor (i.e. tenancy shops) with fire rated construction achieving a FRL of 60 minutes.
Smoke detection system	The building is required to be provided with an AS1670.1 compliant detection system.
Sprinkler system	The building is required to be sprinkler protected in accordance with AS2118.1.
Occupant warning system	The building is required to be provided with an occupant warning system in accordance with AS 1670.1. Visual warning indicators are to be provided throughout to provide additional assistance for people who may have hearing impairments. Manual call points are required on Levels 2-6 inclusive (to AS1670.1)
Smoke hazard management	The skylight above the roof is required to automatically open when a fire is detected in the building. The louvers on the façade on the second floor are required to open automatically when a fire is detected in the building. The size, shape and extent of automatically openable louvers will be the outcome of a performance-based assessment.
Lifts for evacuation	Lifts are to be used for egress purposes for people with MIP.
Management in use	An evacuation management strategy is to be developed and implemented in accordance with AS3745-2010.
Fire hydrants	A compliant fire hydrant system is required.
Fire hose reels	A compliant fire hose reel system is required.

5.4 Travel distances

The hazard with an extended travel distance to an alternative exit is that in case of a fire blocking one exit, occupants will have to walk a longer distance to the alternative exit in conditions that may be hazardous due to the fire. The risk to occupants and fire brigade due to an extended distance of travel is likely to be offset by the provisions of the trial design in Table 2.

5.5 Open Stair Interconnecting Four Levels

The risks to occupants from a stair interconnecting more than one fire compartment are (1) an increased risk to occupant and fire brigade due to smoke and fire spread and (2) potentially increased fire size and burning duration.

The hazards are likely to be offset by the provisions in the trial design shown in Table 2.

6 Fire Safety Systems Design for Evaluation

6.1 Fire Safety Strategy

The strategy adopted was to develop a design that was independent of FBI, rather relies on passive and active fire safety measures. The aim of the strategy is to add fire safety systems in a layered approach until the risk to occupants in the building due to a fire in the same is less than that defined in the acceptance criteria. This approach has the benefits of (1) the interrelationship between different sub-systems can be tested and understood and (2) a quantifiably proven method can be used and therefore any unnecessary subsystems can be removed due to either (a) not having provided a worthwhile safety benefit and having little effect on the ERL; or (b) not being required to achieve an acceptable ERL.

6.2 Trial designs

Two trial designs were initially investigated to address the fire safety issues discussed in previous sections with a number of key design features and management strategies. These are underpinned by their main differentiating design feature: Option 1 - No Sprinklers; and Option 2 – Sprinklers. Both designs incorporate varying levels of fire protected compartments, smoke management solutions, protected construction, building management strategies as well as a combination of smoke isolated refuges and lifts for evacuation.

After close consideration of the fire safety issues and client objectives, one trial design was formulated for further development, trial and evaluation. The trial design detailed in Table 2 is an evolution of the two options considered above. The trial design is a mix of items that are required by the BCA DtS provisions and those that are required for a performance based design. It must be noted that all requirements given below will ultimately be due to the requirement arising from a performance based assessment.

Circulation corridors were assumed to be located to the north of the floor plan on Level 2-6. This is on the basis that these corridors would lead to shared amenities such as toilets and therefore result in a design that was efficient in terms of useable area. These corridors were therefore also chosen for the location of refuges for the mobility impaired. Lobbies were sized based on guidance from AS1428.1-2009 [40] which calls for (1) Unisex disabled toilets at 2300 mm deep minimum; and (2) Minimum corridor width 1000mm with 1800mm wide passing bays every 20 m. Therefore, approximate lobby width is 2.3 + 1.8 = 4.1 m.

Following the quantitative analysis, the trial design features were subjected to a trade-off analysis to determine the effectiveness of each feature and to determine those required to achieve an acceptable ERL.

7 Assumptions

The following assumptions have been made in this analysis

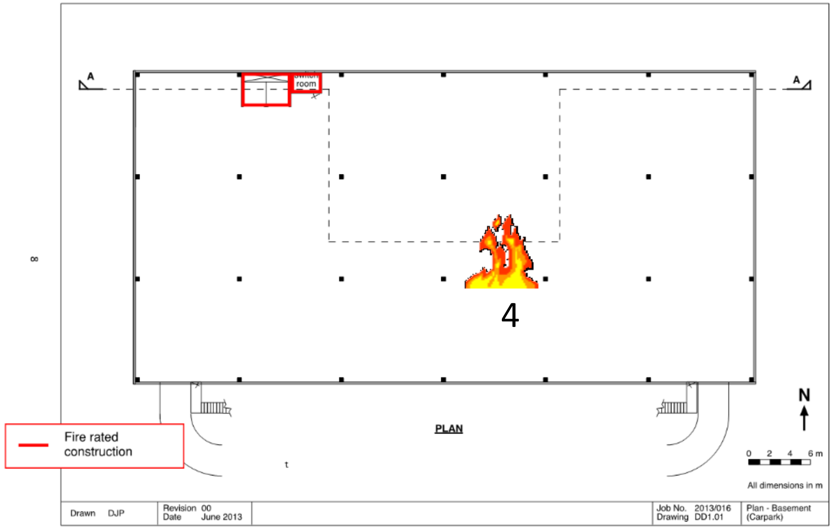
1. Smouldering fires would not result in occupant fatalities as there is plenty of ventilation available in this building;
2. Fires less than $1m^2$ in floor area would not result in conditions becoming untenable for occupants. It is considered that for fires less than $1m^2$ (i.e. confined to object of origin) for this occupancy type, unless someone is intimately involved with the fire, it would not cause any fatality.
3. Corridor is assumed to be on the North
4. Due to the open plan nature of the building spaces, in most cases, fires will be well ventilated and mostly fuel controlled. It is acknowledged that these conditions may change as the fire grows, however the time taken to reach such a point is considered well beyond the time taken to reach untenable conditions.
5. Although the building may operate on the weekend, all fire scenarios take place on weekdays as this will be when the level of activity in the building is at its highest.
6. Due to the relatively low rise in storeys, stack effects are considered negligible and were not be incorporated into the analysis.
7. It is assumed that dampers will close as necessary in the event of a fire to limit smoke spread.
8. The required fire resistance levels of protected steel structure and Bondek[1] slabs for the fire compartments that are served with a sprinkler system have been separately determined.
9. The efficacy of the sprinkler system is taken into account by considering the following modes of sprinkler activation:
    a. The fire being controlled in size by the first activated sprinkler head;
    b. The fire being controlled after activation of the fourth sprinkler head; and
    c. Sprinkler failing to activate and therefore failing to limit the size of a fire.
10. The efficacy of the smoke detection and occupant warning system are taken into consideration with the following modes of operation:
    a. A fire being detected by an automatic fire detection system and therefore resulting in the occupant warning system being sounded.
    b. The automatic fire detection system failing and therefore occupants are relying on visual, audible or olfactory cues.
    c. Occupants activating the occupant warning system by pressing manual call points.

8 Risk Model

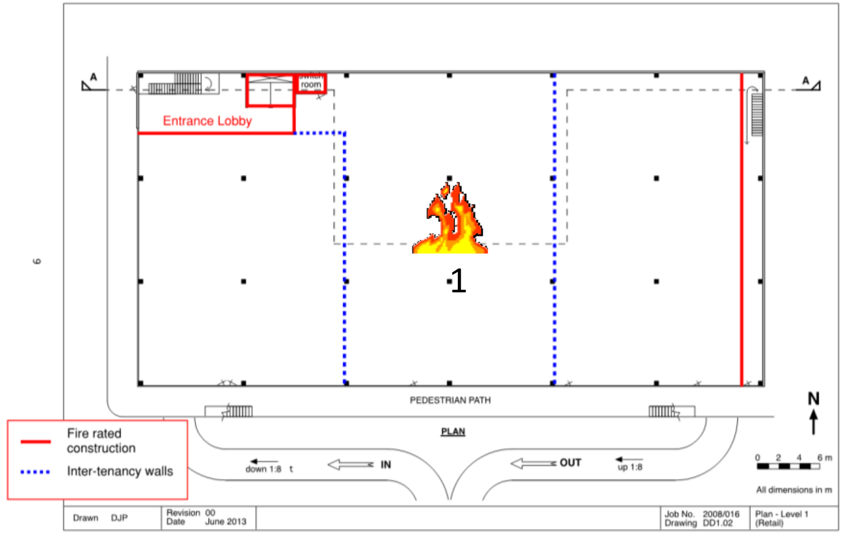
8.1 Event Tree Analysis

Separate event trees were constructed for fires starting in the (1) car park; (2) retail areas; (3) Level 2; and (4) Level 3-6. The event trees included the impact of both working and failing of fire safety systems (1) Natural smoke ventilation/control system; (2) Fire rated lobbies (glazing and drenchers); (3) Automatic smoke detection and occupant warning system; (4) Sprinklers; (5) Lifts; and

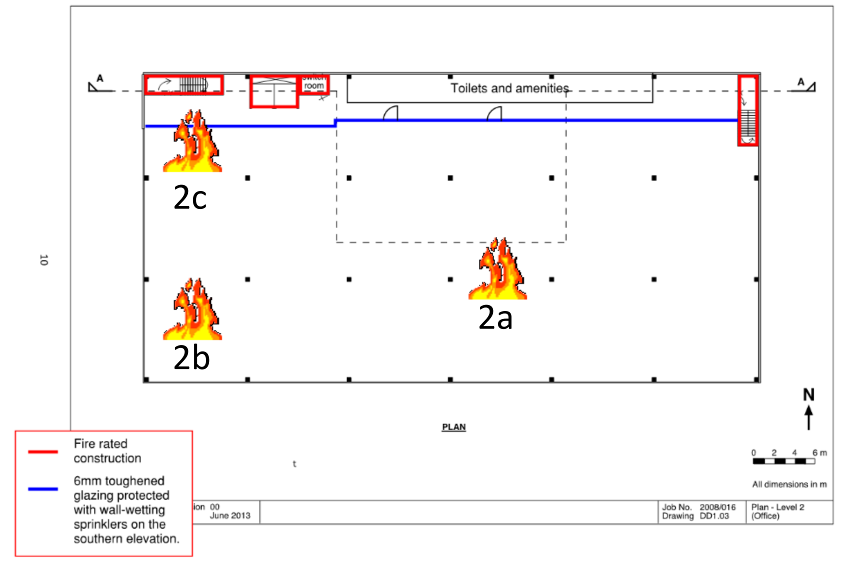
[1] A sheet metal product which can be laid as the formwork as well as to serve as an integral part of the structural component. The use of it reduces the concrete slab thickness requirement.



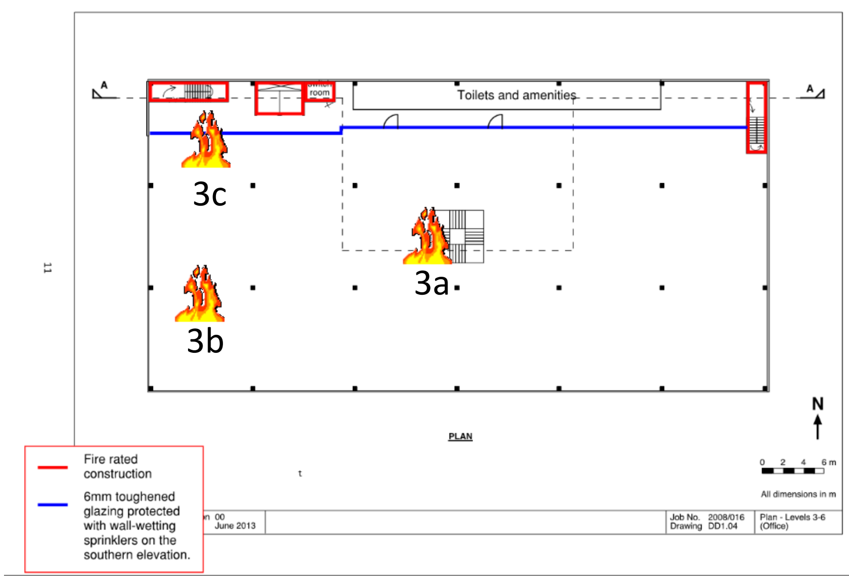
(a) Fire location for Scenario 4 (Car Park)



(b) Plan view of fire locations for Scenario 1 (Ground Level Retail)



(c) Fire locations for Scenario 2 (Level 2 Offices)



(d) Fire locations for Scenario 3 (Openly Connected Office Levels)

Figure 3. Floor Plans for various levels and fire locations for various scenario

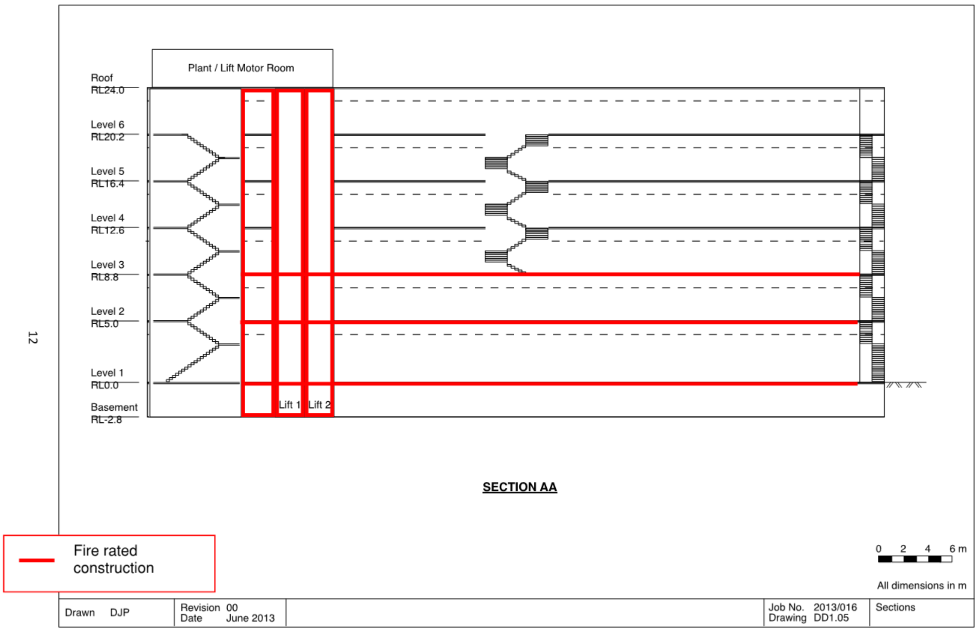


Figure 4 – Section A-A Showing Fire Compartments

(6) Management Strategy (for staged evacuation). The event trees were constructed with events occurring in a chronological order. As an example, the sequence of events was included in the event tree for Level 3-6 is Fire Ignition →Smouldering or flaming fires→Fire size less than or greater than 1m^2 in floor area→ Fire located in Location A (near stair), B (near far corner of the office) or C (in the office area near the lifts) →Sprinklers working or failing→Automatic smoke detection and occupant warning system working or failing→Natural smoke ventilation system working or failing→ Management Strategy working or not → Drenches to lobby glazing working or failing→Lobby glazing achieving the prescribed rating or not→Lifts working or failing.

This initially resulted in an event tree with in excess of 1,000 possible combinations of sub-systems working and/or failing. The size of the event tree however was significantly reduced due to the assumptions outlined in Section 7. The final event tree representing all scenarios is detailed in Section 9.1. The number of consequences for each of the remaining branches has been determined using ASET-RSET verification. Uncertainties have been taken into consideration for the ASET/RSET analysis by choosing either 80th of 90th percentile values for input parameters, using credible data sources and making conservative assumptions where required.

8.2 Acceptance criteria

As mentioned in Sections 2 and 6, the acceptance criteria is that the calculated value of risk will be less than the defined ERL Benchmark. The benchmark of acceptable risk to life with respect to fire was based on the principle of being equal to or better than current industry standards. Current industry standards are considered to include those buildings meeting the DtS provisions of the BCA and those with approved alternative solutions. Both types of buildings have demonstrated compliance with the performance requirements of the BCA and hence are deemed to pose an acceptable level of risk to life from fire. Based on this premise, the acceptable level of risk to life from fire posed by a building in Australia can be quantified by the number of deaths per 1000 fires for the applicable occupancy.

A comparison of NSW FB data and Australia-wide data in Dryne [41] shows that NSW provides a close representation of Australia in terms of fire statistics. The number of deaths per 1000 fires for the

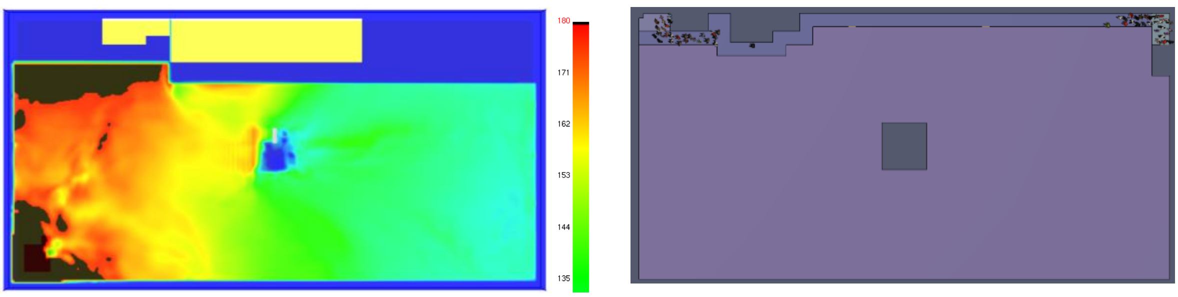
'Shop Store Office' occupancy is 1.36. The ERL benchmark for the Office Building development is based on 1.36 deaths/1000 fires or a probability of death from the fire of 1.36 x 10^{-3}.

In section 2, the steps to calculate the ERL are presented. At each branch of the event tree, the scenario has a probability (Figure 1b) and a design fire. To calculate the consequence of each possible outcome, the number of occupants in breach of the defined tenability limits is quantified as shown in Section 8.4.

8.3 Tenability Limits

The tenability criteria is as follows: occupants can make their way through the relatively clear air below the hot smoke layer; and the smoke layer is maintained above any openings between compartments, thus minimising the risk that smoke will migrate to other areas. The acceptance criteria with regard to enclosure tenability for occupant evacuation shall be as (1) when the smoke layer is above 2.1m, the smoke temperature is to be less than 200 °C (relating to an approximate heat flux on the floor of 2.5 kW/m^2) [42, 43], (2) When the smoke layer is below 2.1m, the tenability limit for smoke temperature is to be determined using the radiation heat flux intensity and tolerance time criteria stated in the SFPE Handbook, 3rd Edition, Table 2-6.19 [44] (a) <2.5 kW/m^2 >5min (b) 2.5 kW/m^2 30 sec (c) <2.5 kW/m^2 4 sec. (3) Visibility through the smoke layer is to be greater than 10 m in large open spaces and greater than 5 m for small enclosures / spaces. Where smoke layers deepens locally around any enclosing / bounding walls near exits, the application of 5m in these parts has been adopted in conjunction with the smoke layer temperature. (4) a Fractional Effective Dose (FED) of Carbon Monoxide (CO) is to be less than 0.3 [43].

The Metropolitan Fire & Emergency Services Board Guideline-17 [45] has been taken as a guide for the exposure limits for the fire brigade: (1) Routine conditions 25 min in maximum air temperature of 100°C (lower layer) and 1 kW/m^2 radiation heat flux; (2) Hazardous conditions: 10 min in maximum air temperature of 120°C (lower layer) and 3 kW/m^2 radiation heat flux; (3) Extreme conditions: 1 min in maximum air temperature of 160°C (lower layer), 280°C (upper layer) and 4-4.5 kW/m^2 radiation heat flux; (4) Critical conditions (not expected to operate, but may encounter): <1 min in maximum air temperature of >235°C (lower layer), 280°C (upper layer) and 10 kW/m^2 radiation heat flux.



(a) FDS Temperature Contour at t=520s

(b) Pathfinder Simulation showing Occupant position at t=520s

Figure 4. Fire model and evacuation model results

8.4 Determination of consequence

Each fire scenario is modelled with a fire model (with the design fire as an input) and an evacuation model. An example is shown in the below screen captures from CFD-based fire model Fire Dynamics Simulator (FDS)[46] (Figure 4a) and evacuation model, Pathfinder [47] (Figure 4b). FDS model was developed by National Institute of Standard and Technology (NIST) and is being used by both researchers [27, 48, 49] and fire safety engineers. Pathfinder can be used to calculate occupant movement time of occupants in a building and it has also been used by researchers [50] and fire safety engineers alike. The movement time of occupants has been calculated using Nelson and Mowrer method given in the SFPE handbook [51]. The results from the fire simulation and evacuation modelling were integrated to determine exposure of occupants to untenable conditions. Figure 4(a) shows the onset of untenable conditions (T=180°C) for one of the FDS simulations at t = 520 seconds. Figure 4(b) shows the location of occupants at the same time in the Pathfinder evacuation model.

FDS results show when and where tenability limits have been breached, and evacuation simulation results show how many occupants were exposed to untenable conditions from that time and therefore the number of casualties for a given scenario and consequence. This essentially an ASET/RSET analysis. A factor of safety of 1 was be applied to each ASET/RSET analysis. This is justified on the basis that the event-tree based approach quantifies the risk of occupants due to fire safety systems working and then separately when they have failed. Therefore, the event tree based approach intrinsically takes into account the risk to occupants from various fire safety systems either working as intended or failing to operate. Input data for ASET/RSET analysis took either the 80th of 90th percentile values (as appropriate) instead of mean values.

8.5 Trade-off tool

The overall ERL result is shown in Table 3. This table shows the QRPA trade-off tool which was developed to analyse the effectiveness of the trial design features in mitigating the risk to life. The tool was used to determine the preferred solution and its associated ERL based on the simulation results, and underpinned by statistical data.

Table 3 – Trade-off tool developed to assess trial design features with respect to ERL

Sector	System Component	On/Off	ERL
Levels 3-6 (Openly Connected Office)	Sprinklers	On	0.001014607
	Smoke Detection	On	
	Smoke Control	On	
	Glazing	On	
	Drenchers	On	
	Lifts	On	
Level 2 (Office)	Sprinklers	On	1.44358E-07
	Smoke Detection	On	
	Smoke Control	On	
	Glazing	On	
	Drenchers	On	
	Lifts	On	
Level 1 (Retail)	Sprinklers	On	0
	Smoke Detection	On	
	Smoke Control	On	
	Glazing	On	
	Drenchers	On	
	Lifts	On	
Basement (Carpark)	Sprinklers	On	0
	Smoke Detection	On	
	Smoke Control	On	
	Glazing	On	
	Drenchers	On	
	Lifts	On	
Building Total ERL		**0.001014751**	

9 Design Fire Scenarios and Modelling Results

9.1 Potential Fire Scenarios

As shown in Figure 1(a), data for ignition location and probability was collected. According to data included in the NSW Fire Brigades Annual Statistical Reports (ASR) [34-38], the most common areas

Table 4 Credible Fire Scenarios

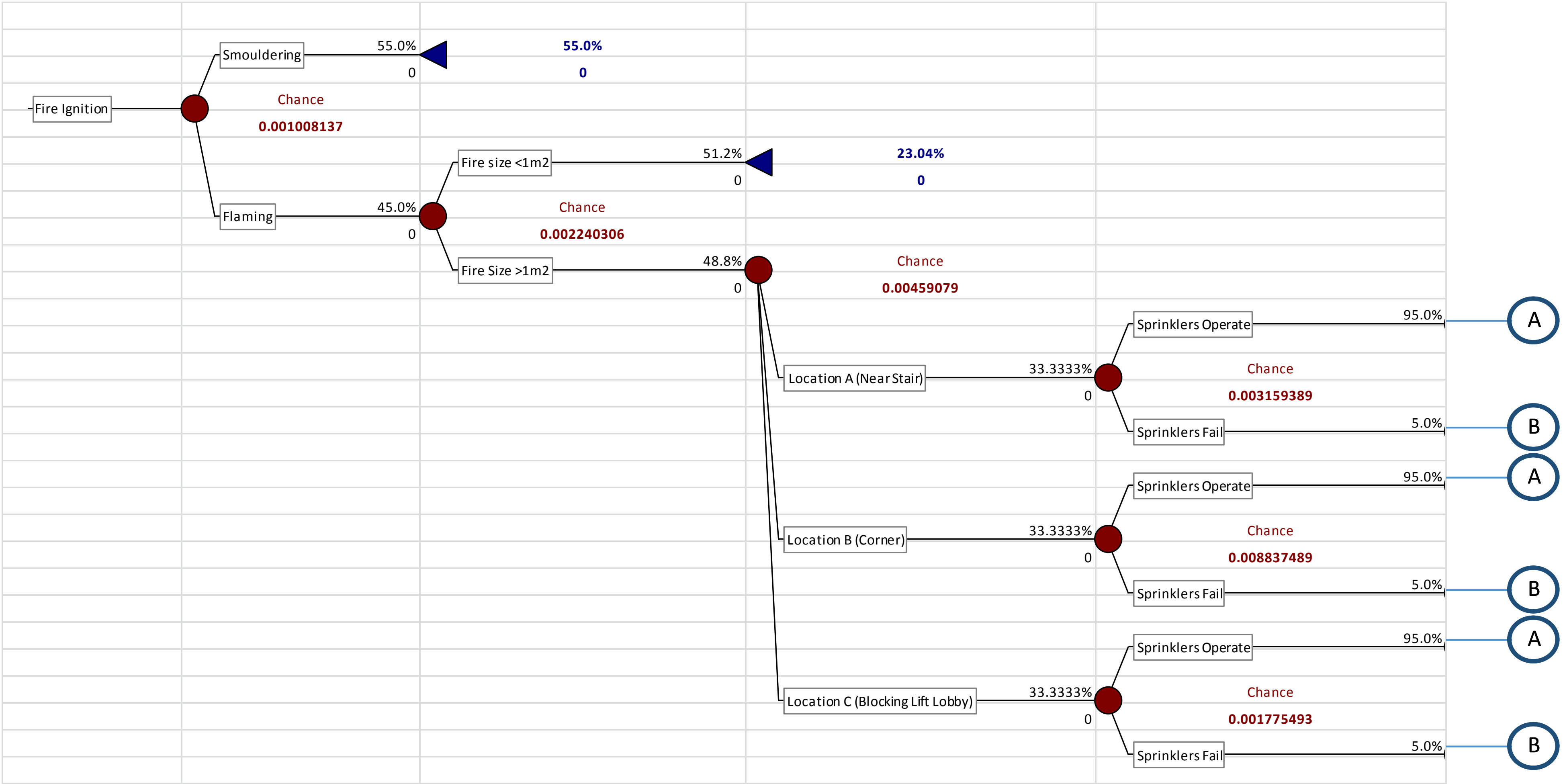
Storey of Fire Origin	Area of Fire Origin	Fire Type	Fire Size	Prob.	Relative Likelihood	Consequence	Comment	Risk Score
Open Office Levels 3-6	Kitchen, cooking area	Flaming	$>1m^2$	16.80%	Frequent	Catastrophic	Potential spread of smoke and flame to all 4 floors via open stair, potential for wide spread damage and multiple deaths.	20
Ground Level Retail	Kitchen, cooking area	Flaming	$>1m^2$	16.80%	Frequent	Catastrophic	High population of people, but multiple egress routes, death possible for those close to the fire.	20
Ground Level Retail	Storage areas (including garage and vehicle storage)	Flaming	$>1m^2$	15.30%	Frequent	Catastrophic	High population of people, but multiple egress routes. High/dense fuel load, potential for death and serious injury.	20
Office Level 2	Kitchen, cooking area	Flaming	$>1m^2$	16.80%	Frequent	Severe	Moderate population, potential for major property damage but death is unlikely.	15
Basement Carpark	Storage areas (including garage and vehicle storage)	Flaming	$>1m^2$	15.30%	Frequent	Severe	Low population, potential for major property loss, however deaths unlikely	15
Open Office Levels 3-6	Office	Flaming	$>1m^2$	6.72%	Occasional	Catastrophic	Potential spread of smoke and flame to all 4 floors via open stair, potential for wide spread damage and multiple deaths.	12
All levels	All locations	Flaming	$<1m^2$	-	Frequent	Major	Flaming fires of $<1m^2$ have the potential to cause only minor damage and serious injuries, but are unlikely to cause death.	10
Office Level 2	Means of egress (hallway/mall and lobby)	Flaming	$>1m^2$	7.08%	Occasional	Severe	Level 2 is within its own compartment, one stair to be used for evacuation on this level, but other floors unlikely to be impeded. Potential for major property loss, deaths unlikely.	9
Ground Level Retail	Means of egress (hallway/mall and lobby)	Flaming	>1m2	7.08%	Remote	Catastrophic	Creates a hazard to all those using the west side stair. Lifts unable to be used for evacuation, evacuation of all other floors at risk and likely to take much longer. All lobbies, lifts and refuges will be sterile and probability of fire start is unlikely.	8
Open Office Levels 3-6	Means of egress (hallway/mall and lobby)	Flaming	$>1m^2$	7.08%	Remote	Catastrophic	Potential spread of smoke and flame to all 4 floors via open stair. All lobbies, lifts and refuges will be sterile and probability of fire start is unlikely. Potential for wide spread damage and multiple deaths.	8
Roof	Service, equipment areas	Flash over	$>1m^2$	7.81%	Occasional	Major	Fire isolated service room on roof, loss of expensive plant and equipment is likely, injury or death is unlikely.	6
All levels	Service, equipment areas	Flash over	$>1m^2$	7.81%	Occasional	Major	Fire isolated service room on roof, loss of expensive plant and equipment is likely, injury or death is unlikely.	6
Basement Carpark	Means of egress (hallway/mall and lobby)	Flaming	$>1m^2$	7.08%	Occasional	Major	Low population, potential for major property loss, smoke lobby is not the primary means of evacuation in the basement car park, deaths unlikely	6
Office Level 2	Office	Flaming	$>1m^2$	6.72%	Occasional	Major	Moderate population, potential for major property damage but death is unlikely.	6
All levels	All locations	Smouldering	$<1m^2$	-	Frequent	Minor	Smouldering fires are unlikely to cause any injury and only minor damage.	5

for fires to start in office and retail buildings are kitchen, cooking area (16.80%); storage areas (including garage and vehicle storage) (15.30%); Sales, show-room area (10.44%); Service, equipment areas (7.81%); Means of egress (hallway/mall and lobby) (7.08%); and Office (6.72%). The same data set indicates the most common causes of fire start are Incendiary and suspicious (20.88%); Short-circuit and other electrical failure (17.34%); Unattended heat sources (5.22%); and Abandoned, discarded material (4.04%). The majority of fires are smouldering fires with 55% falling into this category [52]. The remaining 45% are flaming, of which 51.2% are less than one square metre in size (BSI PD-7974 2003, Table A.6, [53]).

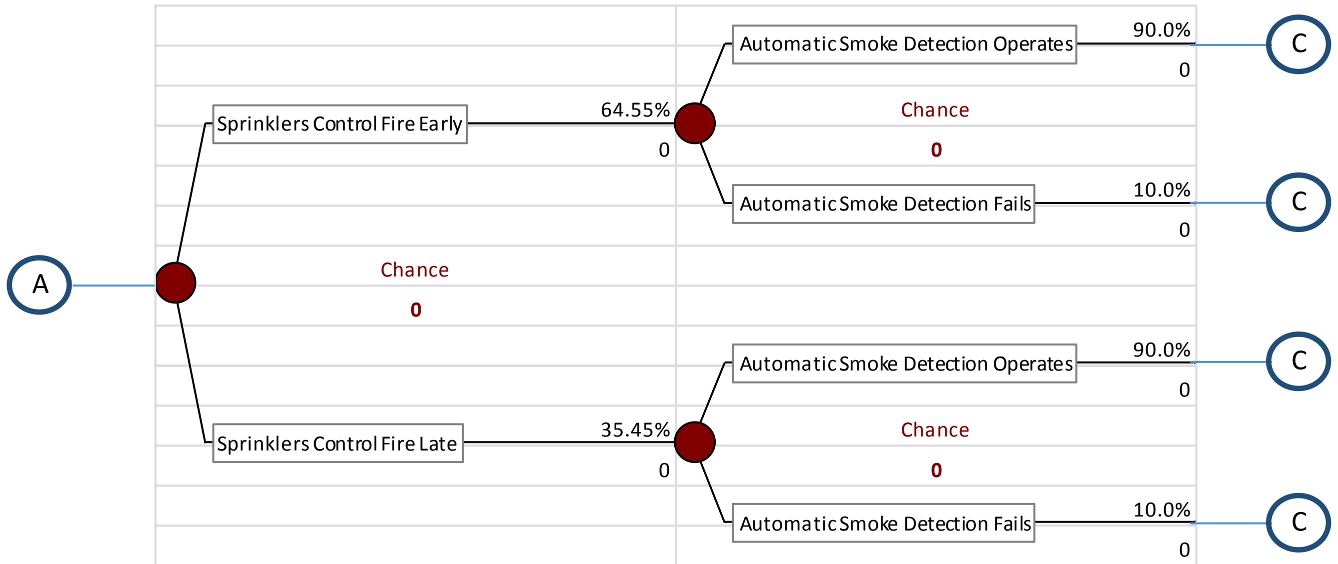
Based on this data and the layout of the building, the fire scenarios posing a credible risk are summarised in Table 4. A high-level qualitative risk analysis was conducted to identify these specific scenarios to be tested against the trial designs. The level of risk associated with the risk score and the applicable action are (a) red (extreme): Requires quantitative analysis (score 16-20); (b) yellow (high): Requires quantitative analysis (score 12-15); (c) blue (medium): considered only if unique to other fires in higher risk categories (score 7-11); and green (low): insignificant, no further analysis required (score 1-6) [54]. In Table 4, risk scores are allocated based on engineering judgement.

Table 5 – Design Fire Scenarios for Analysis

#	Description	Time of Day	Day	Occupant State	Ignition Source	Fuel Load		Design Fires	Location of Fire	Ventilation Conditions	HVAC
						Type	Density (MJ/m^2)				
1	Level 1, kitchen, cooking area or storage area	1300	Weekday	Awake, alert	Electrical fault, unattended heat source, abandoned/ discarded material	Shops	1100	4, 5, 6	Café area of retail tenancies, storage area	Well ventilated, fuel controlled	Dampers closed
2	Level 2, office and kitchen, cooking area	1300	Weekday	Awake, alert	Electrical fault, unattended heat source abandoned/ discarded material	Office, business	800	1, 2, 3	Desk or waste basket, communal kitchen	Well ventilated, fuel controlled	Dampers closed
3	Level 3, office and kitchen, cooking area	1500	Weekday	Awake, alert	Electrical fault, unattended heat source abandoned/ discarded material	Office, business	800	1, 2, 3	Desk or waste basket, communal kitchen	Well ventilated, fuel controlled	Dampers closed
4	Basement Carpark, storage area	1700	Weekday	Awake, alert	Electrical fault, abandoned/ discarded material	Underground garage, private	200	7, 8, 9	Garage storage area	Well ventilated, fuel controlled	Dampers closed



Fire Ignition
Smouldering
55.0%
0
55.0%
0
Chance
0.001008137
Fire size <1m2
51.2%
0
23.04%
0
Flaming
45.0%
0
Chance
0.002240306
Fire Size >1m2
48.8%
0
Chance
0.00459079
Location A (Near Stair)
33.3333%
0
Sprinklers Operate
95.0%
A
Chance
0.003159389
Sprinklers Fail
5.0%
B
Location B (Corner)
33.3333%
0
Sprinklers Operate
95.0%
A
Chance
0.008837489
Sprinklers Fail
5.0%
B
Location C (Blocking Lift Lobby)
33.3333%
0
Sprinklers Operate
95.0%
A
Chance
0.001775493
Sprinklers Fail
5.0%
B



A
Chance
0
Sprinklers Control Fire Early
64.55%
0
Automatic Smoke Detection Operates
90.0%
0
C
Chance
0
Automatic Smoke Detection Fails
10.0%
0
C
Sprinklers Control Fire Late
35.45%
0
Automatic Smoke Detection Operates
90.0%
0
C
Chance
0
Automatic Smoke Detection Fails
10.0%
0
C

Figure 5 – Office Building Fire Scenario Event Tree

Table 6 Event Tree Data and Assumptions

Probabilities – Office Building Event Tree				
Component	Description	Value	Reference	Comment
Probability of Fire Start	Based on data from the London Fire Brigade's Real Fire Library.	0.0017	Holborn et al. 2002, Table 12 [55]**Error! Reference source not found.**	The data used has been collected from the mid-1990s and is more applicable than other sources which utilise fire statistics dating back to the 1960s (e.g. North 1973). The main cause of fire in office buildings during that period was careless action with a naked flame (mainly smokers' materials) which is not applicable to office buildings in Australia today.
Probability of Flaming	Probability that the fire will be flaming.	0.45	Hall 2010 [52]	Based on statistical data.
Probability of fire size <1m2	Based on the number of fires of this size in office buildings without sprinklers.	0.512	BSI PD-7974 2003, Table A.6 [53]	Using data from office buildings without sprinklers accounts for those fires which start, but do not go on to develop into serious fires whether through self-extinguishment or otherwise (i.e. not through automatic suppression).
Sprinklers	Reliability of sprinkler system operation in response to flaming fires	0.95	Moinuddin and Thomas [56]	Australian data is most relevant. Moinuddin and Thomas [56] from fault tree analysis shows that the reliability of the sprinkler system in Australian high-rise building lies in between 89% and 98% when isolation valves are installed for each storey. The local fire brigade data shows ~95.5% reliability.
Sprinklers Early	Probability that one sprinkler head will bring the fire under control (achieving suppression earlier).	0.6455	HB-147, Table 6.3 [57]	Based on the percentage of fires brought under control by one sprinkler head.
Sprinklers Late	Probability that four sprinkler heads will bring the fire under control (achieving suppression later).	0.3545	HB-147, Table 6.3 [57]	Based on the percentage of fires brought under control by four or more sprinkler heads.
Automatic Smoke Detection	Reliability of commercial smoke detectors.	0.9	BSI PD -7974 2003, Table A.17 [53]	Most applicable data source. Many smoke detector reliability values include low grade and domestic (e.g. battery operated) smoke detectors. A commercial grade system is most representative of the system to be specified for this building.
Smoke Control System	Probability of smoke control system (automatic and manual) operating as designed	0.9	BSI PD-7974 2003, Table A.17 [53]	Most conservative of all credible data sources
Manual Detection	Based on the percentage of office fires discovered by occupants at ignition or in under 5 minutes	0.48	Holborn et al. 2004, Table 12 **Error! Reference source not found.**[58]	Relevant to occupancy and building type, is the most conservative of all credible data sources)
Lift Reliability	Reliability of lifts, minus the reliability impact of the fire itself.	0.99338	Sharma 2008, Chapter 6 [59]	Sharma 2008 references reliability of lifts from other studies and calculates additional reduction of reliability due to factors caused by fires (through Fault Tree Analysis)..
Drencher Reliability	Reliability of the drencher system (in parallel and separate to sprinkler system).	0.95	Moinuddin and Thomas [56]	Australian data is most relevant. Moinuddin and Thomas [56] from fault tree analysis shows that the reliability of the sprinkler system in Australian high-rise building lies in between 89% and 98% when isolation valves are installed for each storey. The local fire brigade data shows ~95.5% reliability.
Glazing Reliability	Probability that fire resisting structures (Glazing), will achieve at least 75% of the designated fire resistance standard	0.4	PD7974, Table A.17 [53]	Highly conservative value, given that in the majority of scenarios even achieving 30% of the rated value would be sufficient to provide protection to occupants.
Pr(Fire in Location A)	Probability that the fire is located near the stair.	0.33333	N/A	Given that the location of kitchens, office/retail areas, storage areas, etc. within the specified floor spaces is undefined, there is equal probability of the fire being anywhere outside of the designated lobby area.
Pr(Fire in Location B)	Probability that the fire is located in the far corner of the building.	0.33333	N/A	Given that the location of kitchens, office/retail areas, storage areas, etc. within the specified floor spaces is undefined, there is equal probability of the fire being anywhere outside of the designated lobby area.
Pr(Fire in Location C)	Probability that the fire is located near the lobby door leading to the lifts and western fire isolated exit.	0.33333	N/A	Given that the location of kitchens, office/retail areas, storage areas, etc. within the specified floor spaces is undefined, there is equal probability of the fire being anywhere outside of the designated lobby area.
Management Strategy	Reliability of the management strategy for staged evacuation on the openly connected office floors fails. Strategy is for all occupants not on the fire affected floor to move into the lobby and await further instruction - only the floor of fire origin evacuates through the fire isolated stair.	0.85	N/A	Conservative value chosen assuming 6 monthly (or more frequent) fire drills, fire warden system and robust induction program.
Number of MIPs per floor	The number of mobility impaired personnel on each floor.	6	N/A	As agreed with the Authorities Having Jurisdiction (AHJ)
Probabilities - Retail Fires Event Tree				
Component	Description	Value	Reference	Comment
Probability of Fire Start	Based on data from the London Fire Brigade's Real Fire Library.	0.003	Holborn et al. 2002, Table 12 [55]	The data used has been collected from the mid-1990s and is more applicable than other sources which utilise fire statistics dating back to the 1960s (e.g. North 1973)
Probability of fire size <1m2	Based on the number of fires of this size in retail buildings without sprinklers, 'Other areas'.	0.435	BSI PD-7974 2003, Table A.6 [53]	Using data from retail buildings without sprinklers accounts for those fires which start, but do not go on to develop into serious fires whether through self-extinguishment or otherwise (i.e. not through automatic suppression).
Probabilities - Carpark Fires Event Tree				
Component	Description	Value	Reference	Comment
Probability of Fire Start	Based on data from the London Fire Brigade's Real Fire Library.	0.003	Holborn et al. 2002, Table 12 [55]	The data used has been collected from the mid-1990s and is more applicable than other sources which utilise fire statistics dating back to the 1960s (e.g. North 1973)
Probability of fire size <1m2	Based on the number of fires of this size in retail buildings without sprinklers, 'Other areas'.	0.435	BSI PD-7974 2003, Table A.6 [53]	Using data from retail buildings without sprinklers accounts for those fires which start, but do not go on to develop into serious fires whether through self-extinguishment or otherwise (i.e. not through automatic suppression).

All fire scenarios with a risk rating of significant or higher (score ≥ 12), as shown in Table 4, were taken forward for further for quantitative risk analysis and testing against the trial designs. The design fire scenarios for analysis have been consolidated into a total of four scenarios as detailed in Table 5. Each scenario has three associated schematic design fires (one for each sprinkler suppression scenario and one for sprinklers fail). Three types of corresponding fuel loads (as per IFEG 2005, [22]) are considered across the scenarios: Office, business; Shops; and Underground garage, private. This gives rise to a total of nine schematic design fires as detailed in Table A.1 in Appendix A.

The main event tree has been split into a series of sub-event trees to aid documentation. The event tree has been formulated to quantify the probability associated with each possible response from the fire safety system to the fire scenarios detailed in Table 5. Smouldering fires and small flaming fires were discounted in the qualitative risk assessment and are not considered in the quantitative analysis. When further intervention from the fire safety system would have had no effect on the scenario outcomes, the event tree has been terminated. The event tree applicable to all office scenarios is shown in Figure 5.

Fuel load is based on the dominant fuel load in the affected area for each scenario. Day and time of day for each scenario is based on worst case scenario occupancy populations (i.e. during peak times). Occupant state is based on the class of building and associated building use. As a measure of conservatism, intervention by occupants with fire extinguishers was ignored.

Level 3 was selected as the floor of fire origin for the fire scenarios concerning the openly connected office spaces on the top four levels as this will result in the largest consequence. This preliminary assumption effectively assumes the worst-case scenario for any fire starting on levels 3 to 6 which are connected by the open stair through which fire and smoke may spread. Calculation of the ERL in this way is therefore inherently conservative.

The probability values and data sources for the event trees are summarized in Table 6.

9.2 Fire Locations and Design Fires

Given that the layout of each floor will remain flexible throughout the life of the building, a number of different fire start locations were considered for each scenario as shown below. With the exception of the service equipment areas, this approach inherently considers the remaining flaming fire scenarios that were discounted from further analysis by the risk assessment shown in Table 4.

The schematic design fire parameters did not vary with location; however, occupant response was varied and integrated into evacuation modelling as detailed in Section 10. The fire locations for each of the fire scenarios to be modelled and analysed are shown in Figure 2.

9.3 Fire Modelling Results

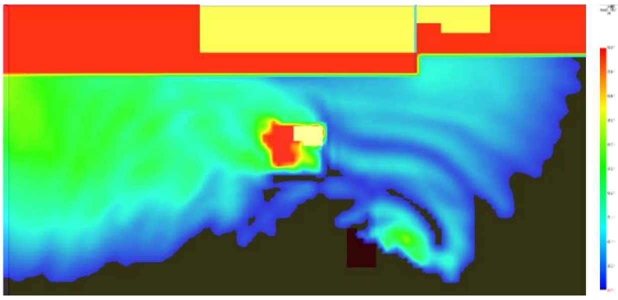
FDS was used to model the worst case scenario of a fire on Level 3 (this would affect a total of 4 levels) as shown in Figure 2(d) and the consequences from these scenarios effectively applied to other scenarios where fires occur on levels 4 to 6. Grid size of 0.25 m was used. The FDS simulations also incorporated opening of the lobby doors at the latest detection time and closure when the last person enters the lobby. By using the worst case times, this conservatively estimates worst case conditions reached inside the lobby for each simulation. These fire safety system responses were modelled for each fire location (1) Sprinklers control the fire early (with one active head); (2) Sprinklers control the fire late (with four active heads); (3) Sprinklers fail; (4) Smoke control system activates (skylight above open stair opens); and (5) Smoke control system fails.

Table 7 – Level 3 (Floor of Fire Origin) FDS Results

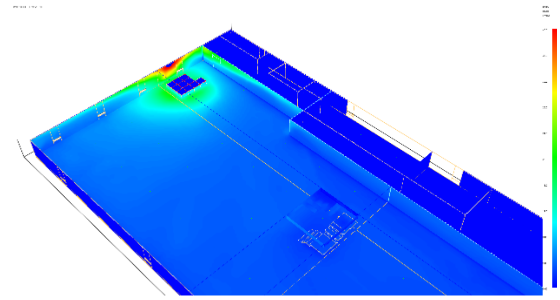
Simulation /Scenario	Design Fire	**Time Until Tenability Limit Reached (seconds)**													
		Onset of 10m visibility on floor	**10m across entire floor**	**Onset of 5m visibility on floor**	**5m across entire floor**	**Onset of 60°C on floor**	**60°C across entire floor**	**Onset of 100°C on floor**	**100°C across entire floor**	**Onset of 180°C on floor**	**Onset of 180°C on Occupants (East Side)**	**Onset of 180°C on Occupants (West Side/Lifts)**	**180°C across entire floor**	**ASET (East Side)**	**ASET (West Side/Lifts)**
Fire Location A, Smoke Control System activates, all other systems fail	3	96	193	181	252	218	367	333	484	477	587	587	660	587	587
Fire Location A, Sprinklers control fire early, all other systems fail	1	155	310	304	657	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf
Fire Location A, Sprinklers control fire early, Smoke Control System activates, all other systems fail	1	155	310	304	657	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf
Fire Location A, Sprinklers control fire late, all other systems fail	2	128	193	175	257	227	425	524	inf	inf	inf	inf	inf	inf	inf
Fire Location A, Sprinklers control fire late, Smoke Control System activates, all other systems fail	2	97	200	178	254	234	424	538	inf	inf	inf	inf	inf	inf	inf
Fire Location A, total failure – all systems fail	3	96	193	178	252	221	356	328	477	473	585	585	652	585	585
Fire Location B, Smoke Control System activates, all other systems fail	3	110	221	137	257	216	380	328	488	466	520	520	697	520	520
Fire Location B, Sprinklers control fire early, all other systems fail	1	112	304	230	743	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf
Fire Location B, Sprinklers control fire early, Smoke Control System activates, all other systems fail	1	112	304	225	741	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf
Fire Location B, Sprinklers control fire late, all other systems fail	2	111	221	137	254	212	463	440	inf	inf	1280	1280	inf	1280	1280
Fire Location B, Sprinklers control fire late, Smoke Control System activates, all other systems fail	2	111	221	139	254	212	461	475	inf	inf	1230	1230	inf	1230	1230
Fire Location B, total failure – all systems fail	3	111	221	137	257	212	380	326	488	464	520	520	693	520	520
Fire Location C, Smoke Control System activates, all other systems fail	3	49	228	65	260	119	175	175	266	266	695	480	691	695	480
Fire Location C, Sprinklers control fire early, all other systems fail	1	51	299	65	790	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf
Fire Location C, Sprinklers control fire early, Smoke Control System activates, all other systems fail	1	51	297	65	796	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf
Fire Location C, Sprinklers control fire late, all other systems fail	2	51	232	65	260	122	448	185	inf	inf	inf	inf	inf	inf	inf
Fire Location C, Sprinklers control fire late, Smoke Control System activates, all other systems fail	2	51	232	65	260	124	450	185	inf	inf	inf	inf	inf	inf	inf
Fire Location C, total failure – all systems fail	3	49	228	65	260	119	375	184	484	275	670	480	680	670	480

Each simulation was run for a total of 1800 seconds or 30 minutes, if a tenability limit was not reached by this time, the ASET was considered infinite for the purposes of the analysis. Make up air inlets for each floor were sized in accordance with CIBSE Guide E TM19 [42].

The FDS results for Level 3 are summarised in Table 7. There are similar results for Level 4-6 which are not presented due to the space constraints. Some sample results of visibility and heat flux are presented in Figure 6. It can be noted that in all cases, visibility was not deemed to affect the tenability limit due to the familiarity of the occupants with the building and their location relative to the exits at the time visibility limits were reached. In all cases, exposure to smoke temperatures of 180°C was the first tenability limit reached. Although occupants are able to be exposed at this temperature for up to a minute, to retain conservatism in the calculation of ASET values, the time at which 180°C was reached in the location of occupants was noted as the tenability limit.



(a) Visibility result



(b) Heat flux result

Figure 6. Contour plots from FDS simulation showing visibility and heat flux contours

Branzfire [60], a two zone model, was used to model all fires occurring in the basement carpark, Level 1 Retail and Level 2 Office. Similar to the FDS simulations, the relevant fire safety system responses were modelled (1) Sprinklers control the fire early (with one active head); (2) Sprinklers control the fire late (with four active heads); and (3) Sprinklers fail. The Branzfire simulation runs are summarised in Table 8. Again, it can be noted that in all cases, visibility was not deemed to affect the tenability limit due to the familiarity of the occupants with the building and their location relative to the exits at the time visibility limits were reached. In all cases, exposure to smoke temperatures of 180°C was the first tenability limit reached. Although occupants are able to be exposed at this temperature for up to a minute, to retain conservatism in the calculation of ASET values, the time at which 180°C was reached in the location of occupants was noted as the tenability limit.

Table 8. Branzfire results

Scenario	Design Fire	Visibility <10m across entire floor	180°C across entire floor	FED CO	ASET
Lv 1 Retail - Sprinkler Early	4	180	1800	697	697
Lv 1 Retail - Sprinkler Late	5	169	1800	486	486
Lv 1 Retail - Sprinkler Fail	6	169	680	383	383
Lv 2 Office - Sprinkler Early	1	509	1800	1433	1433
Lv 2 Office - Sprinkler Late	2	420	1800	1101	1101
Lv 2 Office - Sprinkler Fail	3	289	680	690	680
Carpark – Sprinklers Early	7	634	infinite	infinite	infinite
Carpark – Sprinklers Late	8	509	infinite	infinite	infinite
Carpark – Sprinklers Fail	9	361	967	infinite	967

10 Evacuation Modelling

10.1 Design Occupant Groups

The IFEG [22] states that: “To avoid excessive complexity only the most critical, relevant or significant characteristics should be considered for a given group”. In order to avoid complexity, design occupant groups have been developed as (1) Staff and Public for Basement “Carpark” (2) Mixed occupants (Public/Staff) for Ground (Level 1) “Shop” (3) Staff and Escorted Public for Level 2 “Office” (4) Staff and Escorted Public for Level 3 – to 6 “Office”. It is assumed that all occupants are awake, staff members are familiar with the building and trained, whilst the visitors/public are unfamiliar and untrained.

It is possible that a greater number of disabled and MIP may congregate on one floor level than noted in the design occupancy populations. This scenario is to be considered as part of the buildings emergency management procedures. Occupants on the ground floor (level 1) retail/shop will consist of both people from the general public and shop/retail staff and therefore are expected to be unfamiliar/familiar with the buildings exits, egress layouts, and are most likely to exit via the door through which they entered [32]. Occupants on all other levels are expected to be familiar with the buildings exits and egress layouts, or be escorted (except car park) by someone who is familiar.

10.2 RSET Calculation

The RSET includes several time components; these components are described in Chapter 2.8 of the IFEG [22] and are articulated as Cue period (Tc), Response period (T_r), Delay period (T_d), and Movement period (T_m). These components can combine to form evacuation phases and are articulated as Detection phase (Tc), Pre-movement phase (Tr + Td), Movement phase (T_m), and Evacuation phase (T_r + T_d + T_m). The RSET is then calculated by summing the following components/phases:

$$RSET = T_c + T_r + T_d + T_m$$

10.3 Detection and pre-movement time (T_c, T_r)

The calculation of the detection (phase) time, for automatic detection has been calculated by using Alpert correlation, taking into consideration the device type (i.e. smoke detector, sprinkler etc.), location and sensitivity. The calculation of the detection (phase) time, for manual detection has been derived on the basis of (1) At Ignition [58] OR (2) whichever occurs first of (a) 5 minutes after ignition [58]; or visibility at 2.1m reduced to 10 m. Values for pre-movement time for the given building usages are provided within table 4.5 of CIBSE Guide E [42]. Pre-movement times within the carpark are assumed to be similar in nature to the office levels due to having the same occupant design group characteristics, and hence a pre-movement time of 1 minute has been adopted. For retail/shop occupants it is considered 2 minutes.

10.4 Movement Phase (T_m)

To calculate the movement time, references have been consulted in order to provide travel speeds for the varying occupants [42, 44]. The effective travel speed will be greatly dependent upon the slowest member of a group (the MIP occupants). Studies by the Fire SERT Research group at the University of Ulster as referenced by the SFPE Handbook [44] have provided movement speeds for MIP occupants.

According to Jin [61] it can be expected that movement through smoke will affect the movement time of the occupants; however research conducted by Fridolf et al. [62] have quoted that “*when the visibility is higher than 2.5 m, it may be argued that visibility does not affect the walking speed*”. It has therefore been assumed that the occupant walking speed will not be affected before untenable conditions develop, for example visibility less than 10 or 5 m respectively.

Based on the above, the respective travel speeds proposed are 1.2 m/s for general public and 0.69[2] m/s for MIP occupants for all design group. A review by Thompson and Marchant [63] has summarised flow rate data from several resources and presents flow rates between 1.3 and 1.83 persons/m/s with a mean of 1.44 persons/m/s. For the purposes of the fire engineering assessment a flow rate of 1.36 persons/m/s was used (lower 95th percentile of [1.3, 1.44, 1.83]), however in accordance with the SFPE method, the flow speed through the door was dependent on the occupant density at the door. The buildings population numbers have been denoted in Section 4.1.

The movement time was calculated through evacuation modelling by using Pathfinder rather than simpler hand calculations to better understand the impact of having several floors being evacuated simultaneously.

The use of lifts as a means of evacuation has been considered as part of this study, for the purposes of the evacuation modelling it has been assumed that due to the implementation of the evacuation strategy all mobility impaired occupants will always evacuate via the lifts. This assumption is considered conservative given that if the use of lifts is compromised occupants may use the stairs with assistance of others. Evacuation modelling of occupants via lifts is proposed to follow the methodologies outlined by Klote and Milke [64] in their Appendix C.

Table 9 – Calculated Building ERL

	ERL for Initial Preferred Trial Design		Final Alternative Solution	
Sector	System Component	ERL	System Component	
Levels 3-6 (Openly Connected Office)	Al components of Table 3	0.001014607	Al components of Table 3 except smoke control	0.001014604
Level 2 (Office)	Al components of Table 3 except smoke control	1.44358E-07	Al components of Table 3 except smoke control	1.44358E-07
Level 1 (Retail)	Only Sprinklers, Smoke Detection	0	none	0
Basement (Carpark)	Only Sprinklers, Smoke Detection, Lifts	0	none	0
Building Total ERL		0.0010147512		**0.0010147487**
Acceptance Criteria		0.0013		0.0013
Building Total ERL / Acceptance Criteria		78.1%		78.1%

11 ERL Results, Final Design and Discussion

11.1 Occupant Life Safety – ERL

The ERL of the building is first calculated, as described in Section 8, incorporating all design features in the trial designs is shown in Table 3 and presented there. Note that Management Strategy was not included in further analysis, as it was deemed unnecessary. Additionally, it is an objective of the fire safety strategy not to be reliant on fire brigade or management in use requirements. Then some features of Trial Design of Table 3 are switched off as shown in columns 2 & 3 of Table 9. This is initial

[2] A movement speed of 0.69 m/s has been based on data supplied by the SERT Research Group for the mean manual wheelchair movement speed, SFPE Handbook Revision 3

preferred trial design. The results show that the calculated ERL is approximately 22% lower than the acceptable ERL.

A trade-off analysis has been conducted to determine the effectiveness of the design features in the trial designs. Event tree analysis has been used to determine the effect on the ERL when one or more of the design features is removed. Table 10 shows the factor of increase in ERL for the entire building if certain sub-systems were to be removed from specific areas of the building.

Table 10– Effect of Sub-systems on Building ERL

Sector	Removed System Component	Relative factor (multiple) of increase in ERL
Levels 2, 3-6 (Openly Connected Office)	Sprinklers	20
	Smoke Detection	4.2
	Smoke Control	0.0
	Toughened glazing	1.7
	Drenchers	20
	Lifts	2.2
Level 1 (Retail)	Sprinklers	0.0
	Smoke Detection	0.0
Basement (Carpark)	Sprinklers	0.0
	Smoke Detection	0.0
	Lifts	0.0

Several different combinations have been investigated to determine the design features necessary to achieve an acceptable ERL. The analysis shows that (1) Removing sprinklers and wall-wetting sprinklers from the trial design for Level 2, 3-6 will result in a 20-fold increase in the building wide ERL each, (2) Removing the smoke detection and occupant warning system from Level 2 and Level 3-6 will also result in the building wide ERL being increased by a factor of 4.2, (3) Removing lifts from Level 2, and 3-6 would result the building wide ERL being increased by a factor of 2.2 (4) Removing toughened glazing from the trial design for Level 2, 3-6 will result in a 1.7-fold increase in ERL. Therefore, the building solutions require all features which results in above 0 in Table 10 in order for the building-wide ERL to be acceptable.

The natural ventilation/smoke control system proposed for Level 3-6 was found to have minimal benefit to life safety and does not significantly change the ERL of the building. The same was found for sprinklers, automatic fire detection and occupant warning for the Basement Carpark and Level 1 Retail. The analysis also shows that lifts are not required in the Basement Carpark as the net increase in risk was negligible. Therefore, these features as proposed in the trial design are not required.

11.2 Required Fire Safety Measures

The fire safety measures that are required by the building to achieve an acceptable ERL are primarily the same as Table 3 except the features are deemed not required by the trade-off analysis. The differences are (1) Fire Rated Construction: the fire resistance levels to the Basement Carpark, Level 1 Retail and Level 3-6 Offices are permitted to achieve FRL 90/90/90 and to the Level 2 Offices are permitted to achieve FRL 60/60/60 which replaces "the ground floor lobby is to be separated from the rest of ground floor with fire rated construction achieving an FRL of 60 min", and (2) Smoke detection, Sprinkler and Occupant warning system: instead of the whole building, only Level 2 to Level 6 as per AS1670.1, AS2118.1 and AS1670.1, respectively. All other elements of the building design not listed in this table shall satisfy the requirements of the BCA DtS provisions. The ERL of the building with all required fire safety measures is shown in fourth and fifth column of Table 9. As it can be observed that the calculated ERL is approximately 22% lower than the acceptable ERL, this alternative solution is deemed to have met the applicable performance requirements of the BCA.

Although the analysis shows that sprinklers are only required on levels 2 to 6, the additional cost to provide sprinkler protection to the entire building will likely be largely or totally offset by the allowable reduction (if any) in structural Fire Resistance Levels (FRLs). This has not been explored further.

12 Conclusion

This case study has demonstrated the application of QPRA to determine a feasible alternative design that complies with the Performance Requirements of the BCA. A systematic approach was taken to identify the required fire safety measures of the alternative design and prove that the design will exceed the accepted benchmark for ERL whilst ensuring all claims are underpinned by a comprehensive body of evidence. An event tree was used as the framework for the risk model. Statistical data and analyses were utilised to calculate corresponding probabilities and various correlations were used to determine design fires. After initial semi-qualitative risk analysis, a number fire scenarios were selected for full quantitative analysis. For fire modelling, a CFD-based model, FDS for Level 3-6 office areas and a two-zone model, Branzfire for scenarios in the basement carpark, Level 1 Retail and Level 2 Office have been used. These provided ASET for each scenario. A three-dimensional evacuation model Pathfinder was used for determining RSET. At each end node of the event tree, consequences were calculated through ASET-RSET analysis. With cumulative consequences, an ERL was calculated. A trade-off analysis tool was developed which enabled exploration of the solution space in terms of potential fire safety measures which facilitated identification of an optimal solution. The final alternative design solution includes sprinklers, smoke detection, toughened glazing, drenchers (wall-wetting sprinklers) and lifts. Sprinklers and drenchers are found to the most crucial fire safety measures.

Overall, the case study presented in this paper shows how a QPRA approach can be used to achieve compliance of alternative design solutions, for buildings and other constructs, through sound application of engineering principles, scientific rigour and execution of the process outlined in the IFEG. For acceptance criteria, IFEG's ERL methodology was adopted. However, there are alternative methodology available to demonstrate achieving compliance of alternative design solutions.

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Appendix A: Quantified Design Fire

Design fires are expressed as t-squared fires where:

$$\dot{Q} = \alpha t^2$$

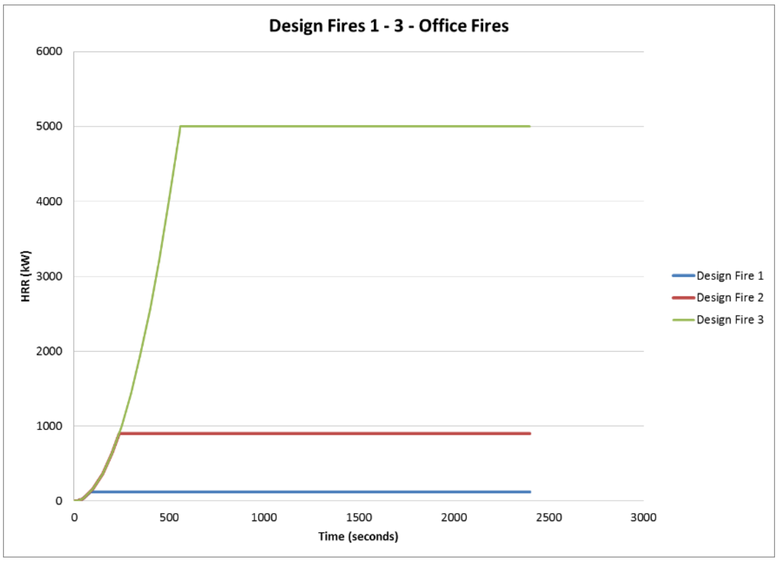
$$where, \dot{Q} = Heat\ Release\ Rate\ (kW), \alpha = Growth\ Rate\ \left(\frac{kW}{s^2}\right), t = time\ since\ ignition\ (seconds)$$

HRR is escalated over time according to the specified growth rate until sprinklers activate or until the peak HRR is reached. The HRR then remains constant until 80% of fuel has been consumed at which point the fire begins a t-squared decay until all available fuel has been combusted [65].

Sprinkler activation times have been calculated using FDS for design fires 1 and 2 (office fires), and using Alperts Correlation [66] for design fires 4 and 5 (retail fires) and 7 and 8 (carpark fires). To account for sprinkler efficacy in the scenarios where sprinklers activate, statistical data from Table 6.3 of HB-147 [57] was used to calculate the probability of two sub-scenarios (1) Only one sprinkler head is required to control the fire (sprinklers control fire early); and (2) Four sprinkler heads are required to control the fire (sprinklers control fire late).For Design Fires 1-6, 95th percentile fire growth rates taken from Table 17 of Holborn et al. [58] according to occupancy type.

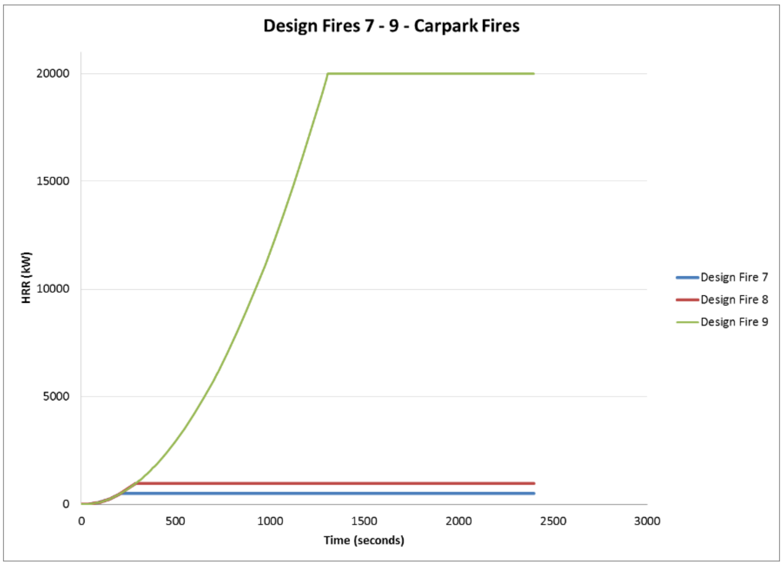
Peak HRR for Design Fires 1, 2, 4, 5, 7 and 8 are based on the assumption that HRR will remain constant once sprinklers have activated. Effectively it is assumed that sprinklers will control, but not suppress or extinguish the fire. Peak HRR for Design Fires 2 and 4 taken from Table 10.3 of Staffannson [65]. Peak HRR and growth rates for design fires 7-9 are taken from C/VM2 [43]. HRRPUA was taken from Table 10.4 of Staffannson [65] based on fuel load type. The HRR versus time curves for each of the design fires is shown in Figure A.1.

Fuel load density taken from IFEG 2005 [22], Tables 3.4.1a and 3.4.1b based on the most applicable occupancy type and most conservative value between 3.4.1a and the 90% fractile value from 3.4.1b. Fuel load based on the dominant fuel load in the affected area/floor for each scenario. Species yield and radiative fraction taken from C/VM2 [43] which is based on a mix of materials. However, modern materials contain a significantly greater mix of polyurethane, in particular for a modern office opting for a larger breakout space with soft seating. This uncertainty was accounted for by picking the worst case scenario or what would be the pessimistic extremity of any range capturing uncertainty. Given the associated peak HRR in the standard are in most cases higher than those prescribed above, the species yield and radiative fraction is considered conservative. Further, comparison with occupancy-specific recommended yields from Table 10.6 of Staffannson [65] shows that the values used above are conservative.



(a) HRR vs Time: Design Fires 1 - 3

(b) HRR vs Time: Design Fires 4 - 6



(c) - HRR vs Time: Design Fires 7 – 9

Figure A.1 - HRR vs Time curves for Design Fires

Table A.1 – Schematic Design Fires

Design Fire	Ignition Source	Sprinklers Control Fire	Sprinkler Activation Time (s)	Fire Growth Rate (kW/s^{-2})	Peak HRR (kW)	HRRPUA (kW/m^2)	Peak HRR Time (s)	Fuel Load		Radiative Fraction	Species				
								Type	Density (MJ/m^2)		Y_{soot} (kg/kg)	Y_{CO} (kg/kg)	ΔH_C (MJ/kg)	Y_{CO2} (kg/kg)	Y_{H2O} (kg/kg)
1	Electrical fault, unattended heat source, abandoned/discarded material	Early	86	0.016	118	250	86	Office, business	800	0.35	0.07	0.04	20	1.5	1.0
2	Electrical fault, unattended heat source, abandoned/discarded material	Late	237	0.016	899	250	237	Office, business	800	0.35	0.07	0.04	20	1.5	1.0
3	Electrical fault, unattended heat source, abandoned/discarded material	Fail	Fail	0.016	5000	250	559	Office, business	800	0.35	0.07	0.04	20	1.5	1.0
4	Electrical fault, unattended heat source, abandoned/discarded material	Early	126	0.101	1603	250	126	Shops	1100	0.35	0.07	0.04	20	1.5	1.0
5	Electrical fault, unattended heat source, abandoned/discarded material	Late	173	0.101	3023	250	173	Shops	1100	0.35	0.07	0.04	20	1.5	1.0
6	Electrical fault, unattended heat source, abandoned/discarded material	Fail	Fail	0.101	10000	250	315	Shops	1100	0.35	0.07	0.04	20	1.5	1.0
7	Electrical fault, abandoned/discarded material	Early	210	0.0117	516	250	210	Underground garage, private	200	0.35	0.07	0.04	20	1.5	1.0
8	Electrical fault, abandoned/discarded material	Late	288	0.0117	970	250	288	Underground garage, private	200	0.35	0.07	0.04	20	1.5	1.0
9	Electrical fault, abandoned/discarded material	Fail	Fail	0.0117	20000	250	1307	Underground garage, private	200	0.35	0.07	0.04	20	1.5	1.0