04

EXAMPLE TECHNICAL REPORT

LMDG

Fire Protection, Life Safety & Accessibility Solutions

Point Access Block

Single Exit Stair – Technical Report

LMDG File: 24-232
Issued: 2025-02-28
Revision: 4

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Document Revision History

Revision	Date Issued	Comments
0	2024-10-18	Draft for comment
1	2024-10-20	Updated from stakeholder engagement discussion
2	2024-12-30	Further stakeholder feedback updates
3	2025-02-13	Refinements and updates to risk analysis
4	2025-02-28	Final version issued

Report Validation

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Defined Terms

Acceptable Solution	Predetermined deemed-to-comply solution described in Division B of the NBC(AE)
Alternative Solution	Solution derived by designer that is considered to perform to an equivalent, if not enhanced, level of performance to that of the assigned objectives and functional statements of the identified acceptable solution(s)
Building Code Compliance	A design that either complies with the acceptable solutions described in Division B or is addressed through an alternative solution
Hazard	Defined as something that has the potential to cause harm
Registered Professional of Record	A registered professional retained to be responsible for the integrity and completeness of The design and field reviews of one or more of the following elements of a project: architectural, structural, mechanical, electrical, and geotechnical.
Risk	The combination of the frequency of an unwanted event and its consequence

Acronyms and Abbreviations

AHJ	Authority Having Jurisdiction
ASET	Available safe escape time
CRPD	Convention on the Rights of Persons with Disabilities
HVAC	Heating, ventilation, & air conditioning
NBC(AE)	National Building Code – 2023 Alberta Edition
NBCC	National Building Code of Canada 2020
NFC(AE)	National Fire Code – 2023 Alberta Edition
PAB	Point access block in which a single exit stair is provided within a building
RSET	Required safe escape time

Executive Summary

This report is intended to provide the technical basis that under pins the guidance provided within the City of Edmonton Point Access Block Alternative Solution and Design Guide. This report presents the technical rationale, methodology, and analysis for Point Access Block (PAB) design within the geographical locations in which the NBC(AE) is enforced. The purpose of such being to inform project stakeholders as to how alternative solutions could be developed including indicative risk mitigation measures.

The basis for an alternative solution is derived from the acceptable solution identified for departure. For PAB buildings, the applicable acceptable solution is NBC(AE) Sentence 3.4.2.1.(1) that includes the below functional and objective statements. In summary, these state that building occupants (persons and emergency responders) and the building are not to be subject to an unacceptable level of risk of injury or damage by fire spread beyond the point of origin or hazards delaying egress to a place of safety in an emergency.

Acceptable Solution	Functional Statements	Objectives
	F10, F12, F05, F06	OS3.7
3.4.2.1.(1)	F12, F06	OS1.2
	F12, F06	OP1.2

The historical basis for the above acceptable solution has been researched and illustrated that:

- The basis for the implementation of the number of exits is derived anecdotally by consensus at committee level prior to the commencement of World War 2.
- The exit stair provisions were solely focused on facilitating escape for occupants during a fire incident. No firefighting tactics or incidents beyond fire were contemplated.
- Area limits were assigned based upon a perceived view of a 'small' building.
- Originally three-storey buildings were permitted to contain single exit stairs.

Multiple latent assumptions and expectations underpin the number of exit stairs required for a building that is evaluated in relation to building occupants (including mobility challenged occupants) and firefighters. The resulting conclusion is a problem definition that forms the basis for alternative solution development and subsequent risk mitigation measures.

What would cause a single stair to fail?

The methodology employed to evaluate risk, as related to the above problem definition, involves the use of event trees, fault trees, and reliability diagrams.

- Event trees allow sequential events to be identified and quantified that illustrates the potential outcomes and quantified likelihood. The tree is illustrated horizontally commencing with a trigger event followed by intervening events until the outcomes are reached.
- Fault trees start with a failure point and proceed to identify failure modes until root causes are established. The root causes can subsequently be mitigated to improve overall reliability.
- Reliability diagrams visually illustrate fault trees as horizontal network paths that identify cut sets and failure paths.

Fundamentally the development of the fault tree identified that three concurrent failures are required to occur that include:

1. the presence of smoke within the corridor,
2. a means for smoke to flow into the stair (coloured green), and
3. an impetus for smoke movement (diffusion or pressure differential).

Fault trees were subsequently evaluated for single vs two stair scenarios for those that are subject and not subject to high building measures. The scenarios involved quantified reliability values that are established probabilistically via fire statistics and engineering judgement. The resultant reliability values indicatively facilitate a benchmark for a PAB design to demonstrate an equivalent level of reliability.

Design study 2 was utilised as an exemplar model to assess a proposed PAB design for a four-storey residential building with 16 units. The single stair is protected by a vestibule that is a risk mitigation measure above the minimum requirement of the acceptable solutions of the building code. The evaluation demonstrated that the introduction of a vestibule was able to provide an equivalent level of resilience to that of a 'code compliant' two stair design. A subsequent list of indicative risk mitigation measures has been derived that may, when appropriately assessed, support a PAB alternative solution. Each risk mitigation measure may be used in isolation or collectively.

PAB buildings up to six storeys (no high building measures)

1. Compartmentation / vestibule
2. Exterior passageway
3. Smoke management via pressurisation or ventilation

1 Introduction

1.1 Overview

LMDG Building Code Consultants Ltd (LMDG) has been retained by Dub Architects to collaborate on the production of a Point Access Block (PAB) guide for the City of Edmonton, Alberta. The guide is intended to inform project stakeholders of how PAB buildings may be designed and constructed beyond the prescriptive limitations of the applicable 'acceptable solutions' listed in Part 3 of the National Building Code – 2023 Alberta Edition (NBC(AE)) [1].

This report forms the technical basis for the content of the PAB guide.

1.2 Scope and Objectives

The scope of this report is to present the technical rationale, methodology, and analysis for PAB design within the geographical locations in which the NBC(AE) is enforced. The intent is to facilitate an equivalent level of performance as Part 3 of the NBC(AE) through alternative solutions. The analysis presented is intended to provide fire and life safety guidance on the use of PAB building design only. It does not address or contemplate other requirements. The only contemplated code variance is number of exits; any additional variances would require additional analysis that is not captured within this report. Although developed as standalone, this report is intended as a complimentary document to the PAB guide.

The objectives of this report are to:

1. Identify and articulate a robust problem definition for PAB design
2. Rationalise the key stakeholders and users of PAB buildings
3. Outline the framework and methodology of PAB performance analysis
4. Quantify a level of performance for a 'code compliant' design to which an alternative solution may be benchmarked against
5. Detail the risk analysis, assumptions, inputs, and uncertainty
6. Rationalise potential risk proportionate mitigation measures for use by project stakeholders in PAB design

1.3 Intended Audience

The intended audience for this report is as follows:

- Property developers
- Design professionals
- Authority Having Jurisdiction (AHJ)
- Fire departments
- Researchers

1.4 Scope of Building Types

The building types for which this report is intended are multi-storey multi-unit residential buildings. The risk analysis does not constrain building height, building area, or construction materials; however, exemplar building types of up to six-storeys are presented in the accompanying Design Guide. Each exemplar building shows single exit stair conditions serving floor areas containing only a Group C major occupancy, specifically dwelling units. If other major occupancies are present, they are to comply with the applicable acceptable solutions for exit design and do not communicate directly with the Group C major occupancy.

It is considered that the multi-storey residential building meets the constraints of the applicable construction article for the building risk profile (i.e., height, area, & use) and is not subject to further alternative solutions.

1.5 Disclaimer

This report is intended to be impartial and **does not advocate for or against the use of PAB buildings**. This report sets out the technical basis for a specific problem statement based upon the information made available at the time of production. The report is bound by the framework of the NBC(AE) in relation to alternative solution development and acceptance.

1.6 Report Structure

The structure of the report is intended to lead the reader through a logical path of risk identification, evaluation, and conclusions.

Chapter 2 Regulatory Framework

This chapter explores the construct of the NBC(AE) in respect to expectations and the structure of alternative solutions. The Chapter further seeks to identify and rationalise the acceptable solution(s) that are sought for departure for a PAB. Intent and performance expectations are derived from the acceptable solution(s) to be used as the benchmark for risk evaluation.

Chapter 3 Problem Definition

This chapter seeks to arrive at a problem definition that will form the basis of an alternative solution. Any risk mitigation measures proposed for PAB design would directly correlate to the problem definition and, as such, is critical to PAB design. The chapter explores in detail the implicit assumptions and expectations of exit stairs including who is at risk, NBC(AE) implicit assumptions, and performance-based design approaches.

Chapter 4 Risk Assessment

This chapter details the risk assessment process, methodology, inputs, and conclusions. The risk assessment is initiated by the problem definition and utilises event trees, fault trees, and reliability diagrams to identify and evaluate failure modes and vulnerabilities of PAB design. Risk is quantified for multiple generic scenarios that serve as a comparative benchmark for alternative solution acceptance.

Chapter 5 Alternative Solutions

This chapter identifies and describes potential alternative solution risk mitigation measures extrapolated from the problem definition and failure modes of the risk assessment process.

2 Regulatory Framework

This chapter explores the construct of the NBC(AE) in respect to expectations and structure of alternative solutions. The Chapter further seeks to identify and rationalise the acceptable solution(s) that form a single exit stair alternative solution. Intent and performance expectations are derived from the acceptable solution(s) to be used as the benchmark for risk evaluation.

2.1 Structure of the Building Code

Within the province of Alberta, the Safety Codes Act is the legislative instrument that governs the development and implementation of safety documents, including the Building Code. Within this framework, the representative provincial body has elected to adopt the latest edition of the National Building Code of Canada (NBCC 2020) with alterations to the content to reflect provincial specific requirements. The subsequent current applicable Building Code, at the time of report development, is the National Building Code – 2023 Alberta Edition (NBC(AE)).

The NBC(AE) is made up of three major divisions - Division A, Division B, & Division C. Division A presents paths to compliance (acceptable or alternative solutions), the objectives that the Code addresses, and the functional requirements (in qualitative terms) that solutions must satisfy. Division B presents deemed-to-comply solutions that are subdivided into ten parts with Part 3 outlining Fire Protection, Occupant Safety and Accessibility. Division C provides administrative and informative provisions & expectations.

The Building Code is an objective-based code with the following five targeted objectives:

- Safety
- Health
- Accessibility
- Fire and Structural Protection of Buildings
- Environment

Compliance with the NBC(AE) is demonstrated via satisfying the objectives and associated functional statements. The acceptable solutions outlined in each part are deemed-to-comply solutions, which if adopted demonstrate that the applicable objectives and functional statements have been met. Alternative solutions present a parallel path to compliance through meeting the applicable objectives and functional statements by alternate means [2].

2.2 Alternative Solutions

The NBC(AE) is developed as a panacea document that is envisioned to capture most common building types and configurations. As buildings become more complex, the application of Division B Part 3 'acceptable solutions' can lead to unintended consequences and 'grey' areas for which best practice and sound engineering judgement is a latent requisite to maintain safety. The preface of the NBC(AE) speaks to this directly:

> *The NBC(AE) is not a textbook on building design or construction. The design of a technically sound building depends upon many factors beyond simple compliance with building regulations. Such factors include the availability of knowledgeable practitioners who have received appropriate education, training and experience and who have some degree of familiarity with the principles of good building practice and experience using textbooks, reference manuals and technical guides.*

Compliance with the NBC(AE) can be demonstrated through:

1. complying with the applicable acceptable solutions in Division B, or
2. developing and submitting alternative solutions that will achieve at least the minimum level of performance required by Division B in the areas defined by the objectives and functional statements attributed to the applicable acceptable solutions.

However, the NBC(AE) does not provide specific performance criteria relative to achieving the objectives of the Code. The performance of alternative solutions in general is described in Division A, Notes to Part 1 Clause A-1.2.1.1.(1)(b), which states that:

> *An effort must be made to demonstrate that an alternative solution will perform as well as a design that would satisfy the applicable acceptable solutions in Division B – not "well enough" but "as well as".*

The latent construct of generic building codes is presented in **Figure 2-1** [3]. The very nature of applying a risk-based approach to a building code is that 'safety' is very challenging to define. Building occupants and subsequent human behaviour is highly unpredictable with fire incidents stochastic in nature [4]. It is imperative for society to recognise that occupants are knowingly or unknowingly exposed to an amount of risk when they occupy premises. The risk tolerance of individuals is highly skewed by individual experiences and perception with the NBC(AE), and all building codes / building by-laws in Canada, representing the collective level of societal tolerable risk. Owing to the building code review and update process, the latent risk tolerance is perpetually behind current risk tolerance levels. Such a divergence of risk tolerability is driven by national and international large scale fire events and, as such, alternative solutions are an essential mechanism to manage emerging or recently evolved threats to the built environment.

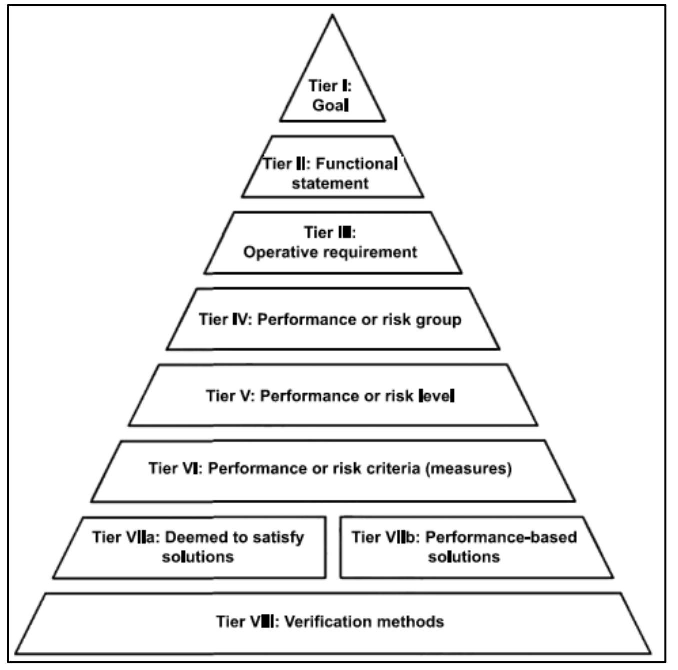

Figure 2-1: Performance-Based Building Regulatory System Hierarchy

Of importance when developing an alternative solution is the acknowledgement of liability. When a departure from a deemed-to-comply acceptable solution is contemplated, a greater level of liability is absorbed by the Registered Professional(s) of record. Although alternative solutions are benchmarked against applicable acceptable solutions, the burden for sufficiently demonstrating compliance and the appropriateness of the alternative solution(s) falls on the design Professional.

Such burden is complicated by latent implicit risk presented by the defined acceptable solutions that are generically ambiguous and subjective.

2.3 Implicit Risk

The anchoring of alternative solutions to the level of performance of one or more acceptable solutions constrains the means in which risk can be demonstrated to a comparative basis. Such a provision inhibits the evaluation of some alternative solutions where emerging hazards (materials, technologies, behavioural characteristics, etc.) are presented beyond what is contemplated in the NBC(AE). Current examples of this include mass timber construction and lithium-ion technologies. For such risk types, alternative methods for expressing risk may be more appropriate.

Risk is typically expressed through three methods as presented in **Figure 2-2** [5]**.**

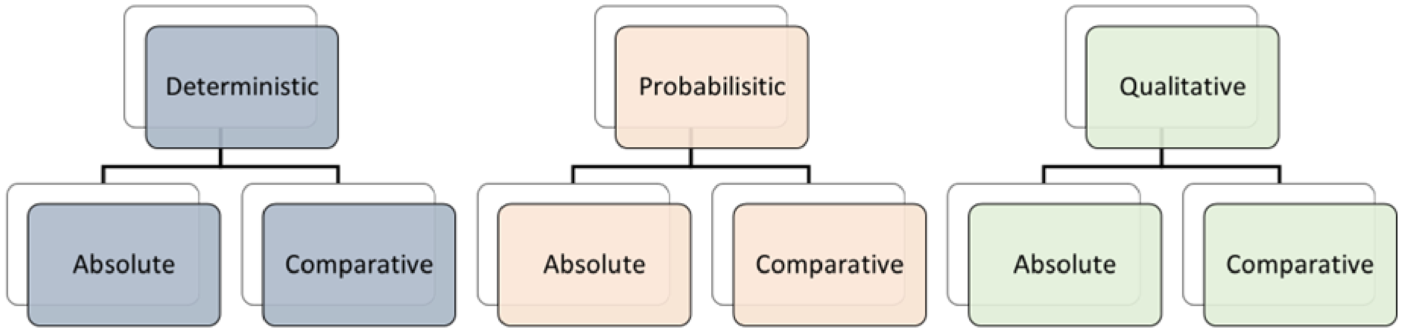

Figure 2-2: Demonstrable Risk

As an overview:

- Deterministic – A quantitative approach that establishes a defined set of conditions that are envisioned to occur
- Probabilistic – A quantitative approach that establishes the probability of events or outcomes occurring
- Qualitative –A non-numerical examination utilising experience, knowledge, and engineering judgement alone

Absolute and comparative approaches assert the rationale within each approach in isolation or using comparison with an acceptable solution as the benchmark for tolerability. When put in a practical sense, the use of comparative assessment can be very limiting as the approach fundamentally relies upon a limited number of variances between selected scenarios, and assumes risk characteristics that have been predefined by the acceptable solutions. A base scenario is established that aligns with the requirements of one or more acceptable solutions. Subsequent scenarios should be identified that ideally contain a very limited number of variants from the base solution. The more variants between the solutions, the less meaningful a comparison is.

It is also appropriate to highlight that comparative assessment can potentially be used inappropriately to highlight the inadequacies of prescriptive guidance. A code compliant scenario could be established that contemplates undefined limits that creates skewed outcomes to compare against. The results ultimately conclude that the prescriptive approach can include undesirable scenarios as opposed to demonstrating that the proposed design solution is 'safe'.

2.4 Acceptable Solution(s) Forming Basis of Alternative Solution

For buildings where PAB are contemplated, the applicable acceptable solution is:

NBC(AE) Division B, Part 3, Sentence 3.4.2.1.(1) Minimum number of exits

> *Except as permitted by Sentences (2) to (4), every floor area intended for occupancy shall be served by at least 2 exits.*

For clarity, sentences 2 – 4 referenced above relate to specific exemptions that permit PAB buildings. This includes buildings up to two storeys in height with limitations on occupant loads, floor areas, and travel distance as well as exemptions for occupancy specific relaxations.

The objective and functional attributions of **NBC(AE) Sentence 3.4.2.1.(1)** are listed below:

Table 2-1: Functional and Objective Statements

Acceptable Solution	Functional Statements	Objectives
3.4.2.1.(1)	F10, F12, F05, F06	OS3.7
	F12, F06	OS1.2
	F12, F06	OP1.2

OS Safety

OS1 Fire Safety

OS1.2 An objective of this Code is to limit the probability that, as a result of

a) the design or construction of the building,
b) activities related to the construction, use or demolition of the building,
c) the condition of specific elements of the building,
d) the design or construction of specific elements of the building related to certain hazards, or
e) inadequate built-in protective measures for the current or intended use of the building,

a **person** in or adjacent to the building will be exposed to an **unacceptable risk of injury** due to **fire**. The risks of injury due to fire addressed in this Code are those caused by **fire or explosion** impacting areas **beyond its point of origin**.

Intent Statement:

To limit the probability that emergency responders will not have a choice of an alternative exit in the case of one exit being blocked or obstructed in a fire situation, which could lead to emergency responders being delayed in gaining access to a floor area, which could lead to delays or ineffectiveness in emergency response operations, which could lead to the spread of fire, which could lead to harm to persons.

OS3 Safety in use

OS3.7 An objective of this Code is to limit the probability that, as a result of

a) the design or construction of the building,
b) activities related to the construction, use or demolition of the building,
c) the condition of specific elements of the building,
d) the design or construction of specific elements of the building related to certain hazards, or
e) inadequate built-in protective measures for the current or intended use of the building,

a **person** in or adjacent to the building will be exposed to an **unacceptable risk of injury** due to **hazards**. The risks of injury due to hazards addressed in this Code are those caused by persons being **delayed in or impeded** from moving to a safe place **during an emergency**.

Intent Statement:

Intent 1:

To limit the probability that persons will not have a choice of an alternative exit in the event that one exit is blocked or obstructed in an emergency situation, which could lead to delays in the evacuation or movement of persons to a safe place, which could lead to harm to persons.

Intent 2:

To limit the probability that emergency responders will not have a choice of an alternative exit in the event that one exit is blocked or obstructed in an emergency situation, which could lead to emergency responders being delayed in gaining access to a floor area, which could lead to delays or ineffectiveness in emergency response operations, which could lead to delays in the evacuation or movement of persons to a safe place, which could lead to harm to persons.

OP **Fire and Structural Protection of Buildings**

OP1 **Fire Protection of the Building**

OP1.2 An objective of this Code is to limit the probability that, as a result of

a) the design or construction of the building,
b) activities related to the construction, use or demolition of the building,
c) the condition of specific elements of the building,
d) the design or construction of specific elements of the building related to certain hazards, or
e) inadequate built-in protective measures for the current or intended use of the building,

the **building** will be exposed to an **unacceptable risk of damage** due to **fire**. The risks of damage due to fire addressed in this Code are those caused by **fire or explosion** impacting areas **beyond its point of origin**.

Intent Statement:

To limit the probability that emergency responders will not have a choice of an alternative exit in the event that one exit is blocked or obstructed in a fire situation, which could lead to emergency responders being delayed in gaining access to a floor area, which could lead to delays or ineffectiveness in emergency response operations, which could lead to the spread of fire, which could lead to damage to the building.

F05 To retard the effects of fire on emergency egress facilities.

F06 To retard the effects of fire on facilities for notification, suppression and emergency response.

F10 To facilitate the timely movement of persons to a safe place in an emergency.

F12 To facilitate emergency response.

2.4.1 Acceptable Solution Discussion

The acceptable solutions within the NBC(AE) should be considered as complimentary in nature that provide overlapping levels of resilience for fire & life safety. There are multiple acceptable solutions that assume at least two exit stairs are provided within a building. These include, but are not limited to:

- Exit separation
- Exit discharge
- Crossover floor provisions

Strictly speaking, these are not departed from within a PAB design however, the intent of what they are trying to achieve should be considered.

2.5 Methodology

The NBC(AE) is silent on the appropriate methodology for which an alternative solution should be expressed. Guidance on administrative provisions is provided in Division C of the NBC(AE) however, expression of risk and structure is absent. **Figure 2-3** [6] presents a generic method that is typically adopted for the submission of performance-based design solutions. The framework is considered best practice when proposing performance-based design approaches. The incorporation of such a process is highly influenced by the complexity of the solution proposed, familiarity of the process by the design professional, and appropriateness of the process for the proposed solution.

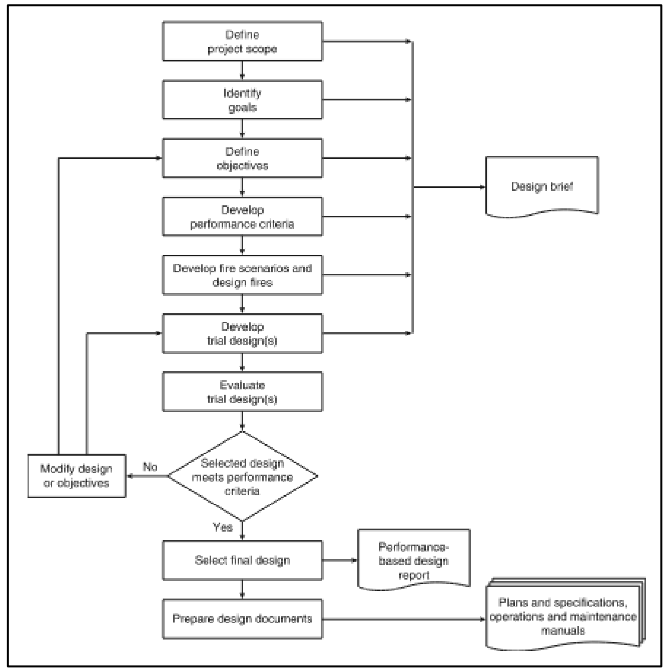

Figure 2-3: Performance-Based Design Process

2.6 Summary

To summarise, an alternative solution is required to be submitted for a PAB building where a departure from acceptable solution Sentence 3.4.2.1.(1) occurs. The solution is required to be benchmarked against the objectives and functional statements of Sentence 3.4.2.1.(1) such that building occupants (persons and emergency responders) and the building are not subject to an unacceptable level of risk of injury or damage by fire spread beyond the point of origin or hazards, delaying egress to a place of safety in an emergency.

3 Problem Definition

This chapter seeks to arrive at a problem definition that will form the basis of an alternative solution. Any risk mitigation measures proposed for a PAB design would directly correlate to the problem definition and as such is critical to PAB design. The chapter explores in detail the implicit assumptions and expectations of exit stairs including who is at risk, NBC(AE) implicit assumptions, and performance-based design approaches.

3.1 Historical Basis for Exit Stair Provisions

The definitive origins of building code provisions are rarely able to be identified with 100% certainty & clarity. Acceptable solutions are typically drawn from historic committee decisions and rationalisation viewed through a contemporary societal lens that does not translate well to the modern built environment. The number of exit stairs for building design is no exception. One of the earliest discovered documents to which the number of exit stairs was discussed was the *Proceedings of the Thirty-Sixth Annual Meeting of the National Fire Protection Association* [7] from May 1932. A synopsis of the talking points and the merit of single vs multiple stair design is contemplated.

> *There is quite a little sentiment in favor of the thought that a* ***single stairway is sufficient or is as far as we can reasonably go in view of economic conditions****. It is recognized that these very high buildings present a difficult problem in respect to safety to life, but it is one which will be there even though any number of stairways are provided.*
>
> *Another school of thought is that* ***we are not sure that one stairway will assure safety****; we know from experience that fire doors on stairway enclosures are all too often blocked open, and the stairway which is designed and constructed as an ideal fire escape, in effect becomes a potential flue to spread the fire and smoke from any lower floor to the entire structure. We can conceive of a condition where a fire in the contents of a lower floor could spread fire and smoke throughout such a fire resistive building and create a panic condition with a large loss of life. From that viewpoint, if we had a second stairway down which people could. pass, we would have a safe condition, and there are members of the committee who feel that the N.F.P.A. should not take the responsibility of* ***any compromise with the principle of fire safety as expressed in the requirement for two means of egress***
>
> *The particular point on which I am anxious to secure information is not particularly the question of the smokeproof tower, but the principle of* ***whether a single stairway could be permissible in the small area building****. We had in mind making the maximum area which might be served by one stairway in an office building six thousand square feet, gross, which is a tower approximately seventy by eighty feet.*
>
> *We did not go into the question of area specifically, but our general feeling is that unless the tower is extremely small, so that there is practically one small office and very few people on the floor, there should be two stairways.*

The manifestation of the above committee rationalisations are the below acceptable solutions outlined within the first National Building Code of Canada issued in November 1941.

4.6.5.2.(c) From floor-areas not on the ground floor – Every such floor-area shall have direct access to at least two independent exits, except that in the following cases one exit shall be sufficient:

i. Floor-areas of 3000 square feet or less in buildings of Type 1A, 1B, or 1C construction not over **three storeys** in height whose occupancies are included in Division 3 or 4 of Group C, commercial and industrial, or in Group D, Residential, or in Group E accessory.
ii. Floor-areas of 3000 square feet or less in buildings in any type of construction not over **two storeys** in height whose occupancies are included in Division 3 or 4 of Group C, commercial and industrial, or in Group E accessory.

It is further noted that Sentence 4.6.5.2.(d) predicates that a minimum of four exits are required for assembly occupancies with occupant loads exceeding 1,000 people.

The introduction of the National Building Code 1953 saw the exit requirements become more stringent.

Sentence 3.20.7.3.(b) – Every floor area in every storey with an area of 1000 square feet or more, or an occupancy in excess of sixty persons shall have at least two exits.

It was not until the National Building Code 1970 was issued that building height was reintroduced for exit provisions which allowed a single exit for a Group A occupancy with occupant loads constrained to <60 people, floor area <2,000 square feet (186 m²), and travel distance limited to 15.2 m. With the implementation of the 1977 National Building Code, the above provisions had been extended to all floor areas, with the exception of dwelling units, with occupancy specific floor areas and travel distances reflective of the current edition of the NBC(AE). By the 1980 edition of the National Building Code, reference to requiring more than two exits in any occupancy had been removed.

To summarise the historical context:

- The basis for the implementation of the number of exits is derived anecdotally by consensus at committee level prior to the commencement of World War 2.
- The exit stair provisions were solely focused on facilitating escape for occupants during a fire incident. No firefighting tactics or incidents beyond fire were contemplated.
- Area limits were assigned based upon a perceived view of a 'small' building.
- Originally three-storey buildings were permitted to contain single exit stairs.
- A minimum of four exits was required until 1980 for assembly buildings with more than 1,000 occupants

The assumptions derived from the evaluation of the historical building code development serves to illustrate the basis for the current day PAB prescriptive provisions that informs what the building code intended to achieve by limiting PAB buildings to two storeys.

3.2 Who is at Risk

A significant component of a risk informed approach is the identification of who is at risk and the associated characteristics. **Section 2.4** identifies the groups with which exit stair provisions are intended:

1. Persons in or adjacent to the building
2. Emergency responders

Each of these groups are explored in the following sections.

3.2.1 Persons in or Adjacent to the Building

Within a residential environment, a plethora of occupant types may occupy apartments that rely upon the exit stair(s). The occupants can include any demographic, gender, age, cognitive ability, culture, religion, dependency, etc. that will inform their response to fire cues, pre-evacuation actions, exit strategy, and willingness to use facilities. The compartment fire dynamics and propensity for fire development and spread is difficult to predict owing to the freedom enjoyed by residential building occupants in maintaining their apartments and the fiscal responsibility on building owners to maintain fire safety systems over the life span of the building.

The grouping of generic occupant characteristics informs the risk profile of a building and subsequent risk mitigation measures. **Table 3-1** illustrates the characteristics that serves to predict human behaviour and response [8]. The categories include occupant alertness levels that relates to their ability to respond to signals for evacuation or fire queues and familiarity with the building that addresses wayfinding and building complexity.

Table 3-1: Occupant Characteristics

Awake & familiar with building	Asleep & familiar with building
Awake & unfamiliar with building	Asleep & unfamiliar with building

The occupants of a muti-storey residential building would be classified as asleep and familiar with the building. To explore further, although the occupants are likely to be extremely diverse by nature, it is considered that they would generally be familiar with at least a primary access and egress route to their individual dwelling in a non-complex geometry. It is acknowledged that people unfamiliar with the building may be present during a fire incident however, they would be in the minority and are likely to be more vigilant to evacuation signals due to a heightened awareness or will be in the presence of a person familiar with the building layout.

With respect to people with disabilities, the United Nations Convention on the Rights of Persons with Disabilities (CRPD) is the basic international framework addressing the rights of people with disabilities. It aims to promote, protect, and ensure the equal enjoyment of all human rights and fundamental freedoms by persons with disabilities.

To effectively capture and quantify the proportion of the building population that may have a disability, information from Statistics Canada [9] has been assessed. Specifically, the focus was on disabilities that would inhibit a person from self-evacuating from the building, both by requiring assistance from others or requiring extended time or space to evacuate.

The results indicated that approximately 10% of building occupants may exhibit a disability with a further subset of 10% (i.e., 1% of the building occupants) representing "more severe" disabilities that include:

- Mobility issues which will include those using mobilities devices (scooters, wheelchairs, etc.) and other assistive devices like walkers
- Visual challenges (visual acuity worse than 6/60 to 3/60) and blindness (visual acuity worse than 3/60)
- Hearing challenges

With respect to the above, it is feasible that a multi-storey residential building could be inhabited by at least one person that has a form of disability that may inhibit their ability to evacuate the building. They may also be located anywhere within the building. Within the context of this analysis, and when considered on an alternative solution basis, the benchmark level of performance is that of a 'code compliant' design in which two stairs are present. In this context, and the current iteration of the NBC(AE), design principles and risk mitigation measures relating to evacuation for persons with disabilities are in the process of improvement.

On a comparative basis within a two-stair multi-storey building, no provisions for refuge are provided (within a sprinklered building) nor are there means to evacuate down exit stairs. A PAB building offers no reduction in this performance with the exception of a potential alternative stair that provides no refuge or means to transport an occupant. It is feasible that evacuation of a person with mobility challenges may occur whilst emergency responders are entering the building and utilising the PAB. This is directly comparable to a two-stair building where the same eventuality may occur.

The designated 'Principal' entrance serves as the predictor for stair use that supports the likelihood of such an occurrence.

3.2.2 Emergency Responders

Emergency responders is an umbrella term that captures multiple highly trained groups of people that could access the building during emergency scenarios. In relation to PAB design, the number, size, and construction of stairs within a building is directly related to maintaining safety during a fire incident. The evidence to support such a claim is obvious considering the following:

1. Exit stairs are constructed as fire separations such as to retard the ingress of fire and smoke
2. The width of stairs was historically derived from anthropometric studies and anticipated movement [10]. An implicit escape time is levied upon exit width that anticipates when a loss of tenability may occur

Accordingly, despite the direct obligation set out in the NBC(AE) to capture emergency responders, the analysis will solely focus on firefighters and associated personnel. The rationale to support this is predominantly driven by the counter intuitive nature of another emergency responder type accessing a PAB during a fire incident. This is not a likely nor safe scenario. It is acknowledged that emergency responders would utilise a PAB during a non-fire emergency for access however, such scenarios are derived anecdotally and not reflected within the historical or contemporary application of the NBC(AE) for PAB design.

The Notes to Part 3 of the NBC(AE) offer the following in relation to provisions for firefighting:

The requirements of this Part are based on the assumption that firefighting capabilities are available in the event of a fire emergency. These firefighting capabilities may take the form of a paid or volunteer public fire department or in some cases a private fire brigade. If these firefighting capabilities are not available, additional fire safety measures may be required.

Firefighting capability can vary from municipality to municipality. Generally, larger municipalities have greater firefighting capability than smaller ones. Similarly, older, well-established municipalities may have better firefighting facilities than newly formed or rapidly growing ones. The level of municipal fire protection considered to be adequate will normally depend on both the size of the municipality (i.e., the number of buildings to be protected) and the size of buildings within that municipality. Since larger buildings tend to be located in larger municipalities, they are generally, but not always, favoured with a higher level of municipal protection.

Although it is reasonable to consider that some level of municipal firefighting capability was assumed in developing the fire safety provisions in Part 3, this was not done on a consistent or defined basis. The requirements in the Code, while developed in the light of commonly prevailing municipal fire protection levels, do not attempt to relate the size of building to the level of municipal protection. The responsibility for controlling the maximum size of building to be permitted in a municipality in relation to local firefighting capability rests with the municipality. If a proposed building is too large, either in terms of floor area or building height, to receive reasonable protection from the municipal fire department, fire protection requirements in addition to those prescribed in this Code, may be necessary to compensate for this deficiency. Automatic sprinkler protection may be one option to be considered.

Alternatively, the municipality may, in light of its firefighting capability, elect to introduce zoning restrictions to ensure that the maximum building size is related to available municipal fire protection facilities. This is, by necessity, a somewhat arbitrary decision and should be made in consultation with the local firefighting service, who should have an appreciation of their capability to fight fires.

Also of note is the User's Guide to the NBC 1995 that provides the below assertion [10].

> *In most buildings, at least two separate exits are required. This provides redundancy, in case one exit is blocked, and a route for fire fighters to reach a fire floor, while allowing one exit to be used for the continuing evacuation of occupants.*

It is regrettable that such information is not represented in the NBC(AE) with the purpose of omission unknown. It is the Author's opinion that the predication of the access and egress of two exit stairs for occupants and firefighters is logical but likely derived as a function of the provision of two exit stairs as opposed to the requirement for two exit stairs. The execution of such a strategy is also beyond the acceptable solutions of the NBC(AE). The means to how occupants would be made aware of the requirement to utilise a specific stair for evacuation and how that is managed during a dynamic fire incident is not apparent.

3.2.3 Fire Department Operations

The preceding notes from the NBC(AE) and 1995 Users Guide denotes that beyond very limited features relating to vehicular access, access to water supplies, and internal firefighting features (i.e. standpipe provisions), no design implications are levied upon the number of exit stairs nor their use for firefighting tactics (i.e. hose deployment tactics etc.). As such, a design professional contemplating a PAB design is not empowered with firefighting knowledge and tactics beyond what is outlined in Part 3 of the NBC(AE).

Supporting reference guidance is however provided within NFPA 1710 [11] that informs career fire department incident response size, times, and objectives. Although not completely transferable to the provisions of the NBC(AE), NFPA 1710 would predicate the following for a structure fire in a municipality equivalent to Edmonton (the below should be considered indicative and confirmed by Edmonton Fire Department):

- Full alarm assignment capacity of either
  - 27 strong response force (3-storey apartment building including typical apartment size of 111 m²)
  - 42 strong response force (high building with support to sprinkler & standpipe facilities)
- Alarm answering time – 40 seconds (99th centile)
- Alarm processing time – 106 seconds (95% centile)
- Turnout time – 80 seconds (90% centile)
- Travel time (1st engine company) – 240 seconds (4 min) (90% centile)
- Travel time (2nd engine company) – 360 seconds (6 min) (90% centile)
- Travel time (full alarm resources non-high rise) – 480 seconds (8 min) (90% centile)
- Travel time (full alarm resources high rise) – 610 seconds (10 min, 10 secs) (90% centile)

The above performance benchmarks allow certain assumptions to be substantiated in response to PAB design. From the moment of alarm notification to the fire department, firefighters are likely to be in attendance within 466 seconds (7 mins 46 secs) with the full alarm resource consignment within 836 seconds (13 mins 56 secs) (assumed worst-case high-rise incident). It is considered probable that evacuation of occupants may still be occurring during this time frame and that fire department resources are deployed internal to the building for the purpose of firefighting or rescue operations.

Firefighting tactics and equipment deployment within the structures are dynamic in nature and beyond the NBC(AE) and NFPA 1710.

For example, it is not known if the fire dept would establish an attack hose line and reserve hose line in the same stair or separate stairs, which floor levels these would be initiated from, establishment of bridge heads, dynamic risk assessment of floor levels beyond the established fire floor, resource assignments to each floor at each stair entry to manage stair use during an incident, etc. All such factors would influence stair design that should be captured within an alternative solution. Further input is required from the Fire Department to inform single stair vs multiple stair tactics that influence alternative solutions.

3.3 Number of Stairs

3.3.1 Prescriptive Application

An appropriate degree of fire safety is achieved through a selection of complementary and harmonized fire precautions that inform a fire strategy and offer sufficient resilience to the building occupants. From this perspective, the extension of a PAB building requires a holistic approach to fire safety lest the impact of the change be trivialised, or salient factors overlooked. At its core, and assuming adequate fire precautions such as a fire-resistance rating for the structure, firefighter provisions, etc. are included, adequate exiting is comprised of two main components: diversity of exits and escape time. Exit diversity is simply promoting the likelihood that a minimum number of exits are available, at the commencement of the evacuation period, and that a single fire event being of sufficient size to overcome the exit separation distance is acceptable. The subcomponents to exit diversity are reflected in the NBC(AE)'s requirements for minimum number of exits (Article 3.4.2.1.) and minimum separation distance between exits serving a floor (Article 3.4.2.3.).

Evacuation time is the duration in which escaping occupants may be exposed to the products of combustion or untenable conditions. Within the NBC(AE), escape time is a function of travel distance (distance from a remote location to a point of egress) and exit capacity (mm per person). To take this further, travel distance is a unit of length intended to measure time. If a nominal walking speed is assigned, then the time to reach an egress component can be quantified. Exit width denotes a flow rate in which the width facilitates the flow of occupants with an implicit duration. When these components and subcomponents are combined and prescriptively met, the NBC(AE) considers the risk of exposure for escaping occupants to be tolerable. The components are illustrated in **Figure 3-1**.

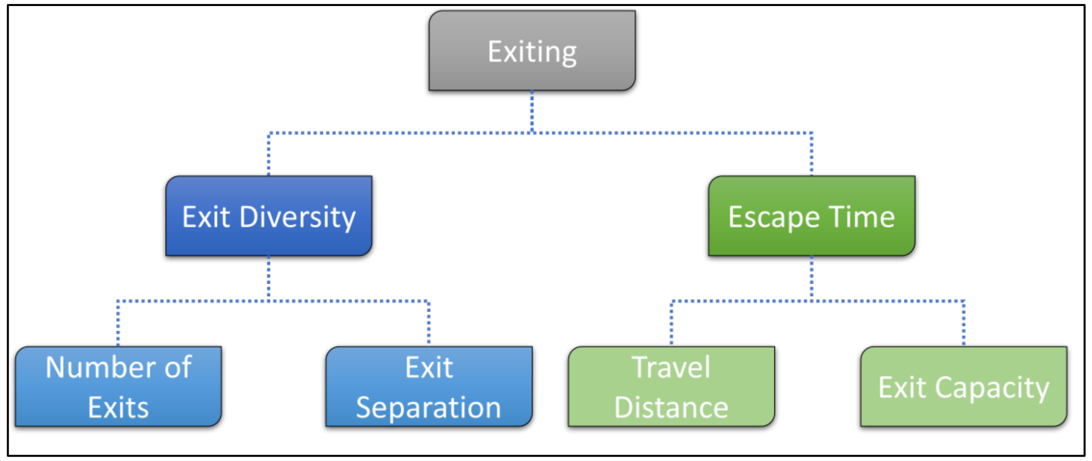

Figure 3-1: Exiting Components

To summarise, a PAB removes the resilience afforded by exit diversity and thus has a greater reliance on evacuation time components to maintain a proportionate level of fire safety. When an alternative solution contemplates an evacuation time component, a divergence occurs between performance-based design and prescriptive approaches. These are explored in the following sections.

3.3.2 Evacuation Fundamentals

The method of analysis for a performance-based design timed-evacuation study encompasses the following two-time stages:

- ASET – Available safe evacuation time
- RSET – Required safe evacuation time

A trial design is considered successful when ASET is greater than RSET. The premise of the framework is that an ASET limit is calculated that determines when a pre-determined set of tenability criteria are exceeded. The RSET value signifies the time at which occupants enter a place of relative safety, which relates to the escape time. As such, the combination of the ASET and RSET analyses will inform whether the occupants can safely evacuate the analysis area within the duration of tenable limits. The time variance between ASET and RSET for a particular design fire scenario provides the safety margin.

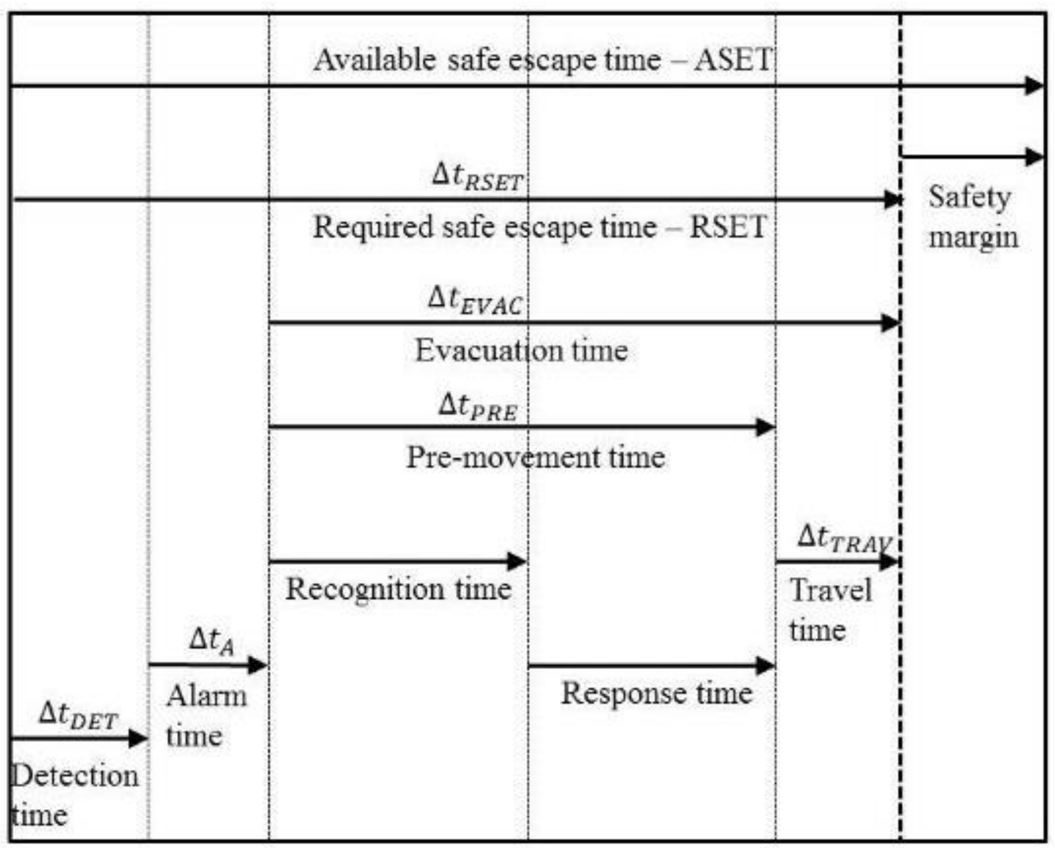

Figure 3-2: ASET vs RSET

The required safe evacuation time (RSET) is a time-based calculation of how long it would take building occupants to reach a place of relative or ultimate safety. RSET is composed of two main areas: the occupant profiles and evacuation calculations.

Occupant profiles define how many occupants are at risk, behavioural traits, physical and cognitive abilities, and anthropometric measurements. The salient factors that inform the evacuation calculations are visually portrayed in **Figure 3-2** and reproduced below:

$$T_{RSET} = \Delta t_{det} + \Delta t_{al} + \Delta t_{pre} + \Delta t_{trav}$$

Where:

$T_{RSET} = Required\ Safe\ Evavuation\ Time$

$\Delta t_{det} = Detection\ time$

$\Delta t_{al} = Alarm\ time$

$\Delta t_{pre} = Premovement\ time$

$\Delta t_{trav} = Travel\ time$

The subcomponents of the evacuation analysis inform how long it takes for occupants to be notified of a fire condition, how long it would take for occupants to recognise and respond to the fire / alarm queues, and how long it would take to traverse the various egress constraints to reach relative or ultimate safety. Each subcomponent is explained further below:

- Detection time denotes the period of time in which a potential fire event is initiated until the point at which it is detected. It is the reference time at which a conflagration is typically simplified to the point at which flaming combustion occurs. There can be a significant incipient stage prior to flaming combustion that encompasses the heating of a fuel source. This is typically ignored as a measure of conservatism.
- Alarm time is associated with a delay between detection and the initiation of a building-wide fire alarm.
- Premovement time comprises recognition and response times and is typically the most challenging value in exiting to accurately quantify. Recognition represents the time at which a building occupant is in receipt of a fire queue (signal or visual) and recognizes that queue as a trigger to commence evacuation. Response time is the time at which an occupant recognizes the requirement to evacuate and actually commences movement towards an exit.
- Travel time encompasses the physical movement of occupants to an exit and the flow through the exit component.

Cross mapping of **Figure 3-1** and **Figure 3-2** illustrates that a transparent path for exit design is not readily identifiable. Both paths are intended to achieve the same goal but offer varying overt metrics to achieve this. **Figure 3-2** does not overtly identify exit diversity as a metric but is implicitly captured as exit availability within ASET and flow time within Δt_{trav}. Further observations are explored in the following section.

3.3.3 Implicit Assumptions and Expectations

It can be denoted from the previous sections that the prescriptive approach to exiting and that of a first principles evaluation do not easily correlate. These and other implicit assumptions are outlined below.

- *Escape time* – As detailed in **Section 3.3.1** , the NBC(AE) limits travel distance and exit width as a means to limit escape time. The actual acceptable escape time is not quantified and is challenging to reverse engineer. The NBC Users Guide 1995 offers a range of potential escape times; however, they are not conclusive. [10] The intricacies of human behavior and route selection are simplified within the building code with only the closest stair counted in respect to travel distance thus skewing escape time.
- *Tenability* – The point at which a stair is considered untenable is not well defined within the NBC(AE). Predominantly, a value of 1% by volume of contaminated air from the fire floor is assigned. In an idealized scenario, exit components would be maintained contamination free. From a first principles perspective,

visibility is the preeminent means to determine tenability. Generally, this is applied to floor area locations that are exposed to fire conditions with values of 10 m to 5 m depending upon wayfinding requirements. [12]

- *Exit integrity* – The NBC(AE) assumes that once an occupant reaches and flows into an exit component (i.e., an exit stair), they have reached a place of relative safety. This is acknowledged by the termination of travel distance to this location as the occupants are no longer considered to be exposed to products of combustion. Fundamentally, exit integrity assumes that there is an acceptably low probability that fires will originate within exit stairs. In reality, fires have been recorded as originating within stairs through deliberate malicious activities collected through fire incident data (refer to **Section 4.7**). Despite these provisions & observations, it is predicated that the NBC(AE) does not include arson as a credible fire scenario. The justification for this is that no building or number of stairs could be designated as adequately protected to combat a motivated person intent on arson.
- *Other emergency types* – As stated previously, it is considered that the use of exit stairs and the pursuit of a PAB is purely driven by fire incident scenarios. It is feasible that an emergency situation could occur that requires the use of stairs or the number of stairs is an actor in an adverse event (i.e., active shooter scenarios in which exit discharge locations are utilized to inflict maximum damage). This is true for any stair type in a building however, it is asserted that the number of exit stairs is solely driven by a fire incident.
- *Number of fires* – The premise of the NBC(AE) is that a given fire scenario is accidental in nature with only a single seat of fire contemplated. Arson / deliberate fire scenarios (including multiple seated scenarios) are not able to be fully mitigated against due to the intent behind their initiation. Fire spread from a single room as it pertains to contemporary compartment fire dynamics is contemplated and forms a significant basis for acceptable solutions and prescriptive risk mitigation measures.
- *External fires* – External fires as they relate to PAB design are not currently captured in the NBC(AE) in a meaningful way. Exit discharge distances attempt to alleviate an external fire risk however, connectivity as to what would initiate building evacuation for an external fire has not been well documented.
- *Occupant flow splits* – The distribution of occupants for exit stairs is often simplified. The choice of exit route for an occupant that is familiar with the building is typically driven by convenience, distance, and familiarity with that route. [8] In a PAB vs two stair scenario, it is entirely feasible that the main entrance stair (if also an exit stair) will be the exit route of choice for occupants. The second stair may remain either completely unused or under utilised in an actual fire incident.
- *Counterflow on stairs* – Premovement time for occupants during a fire incident scenario varies greatly owing to the diverse nature of the occupants and variance in cognitive awareness. This is reflected by the quantified premovement values that extend from 5 minutes up to greater than 40 minutes. [12] It can be concluded that firefighters may have attended and been actively engaged in firefighting and rescue activities whilst occupants were attempting escape. Flow management of stairs by firefighters is not documented in the NBC(AE) but may form part of a Municipal standard operating procedure. The number of occupants within a stair will likely be low during firefighting operations considering the implicit low occupant density of residential buildings. The minimum width of 1.1 m applied at an exit stair was originally rationalised by the bi-deltoid width (22 inch or 550 mm each) [10] of two occupants flowing side-by-side down a flight of stairs. It has not been documented or evidenced that this width would be insufficient for temporary bidirectional occupant & firefighter flow.

3.4 Summary and Discussion

A review of the contents of this Chapter indicates that the movement from a multiple exit stair design to a PAB relates to resilience. The underlying assumption being that if one or more exit stairs are provided in a building, at least one will remain to support evacuation and firefighting operations. For a PAB building, if the risk of failure of a PAB was sufficiently low (within comparative tolerable limits), then equivalency could be considered to meet with a multiple stair design. Accordingly, the risk assessment process seeks to answer:

What would cause a single stair to fail?

Although previously mentioned within **Section 3.3.3** , the most significant threat to a single stair becoming untenable during evacuation or firefighting operations is a fire within the stair itself. As mentioned in the previous section, it is fully acknowledged that this is a possibility and does occur in reality (as fire incident data suggests within **Section 4.7**). The risk, however, is considered low and the NBC(AE) implicitly absorbs this risk.

As detailed in the following risk assessment chapter, a single stair does not constitute a single point of failure. Multiple cascading events are required to occur to for a fire to initiate in a stair or other discrete location. Fire detection and suppression are located within the stair(s) to act as risk mitigation measures and the fabric of the NBC(AE) would need to be altered to consider exit failure. For clarity, travel distances would not terminate at exit stairs and stairs would be discounted from exit capacity calculations to acknowledge potential failure.

The subsequent analysis and evaluation within this report does not consider a fire originating within an exit stair as credible in recognition of the low probability of occurrence.

4 Risk Assessment

This chapter details the risk assessment process, methodology, inputs, and conclusions. The risk assessment is initiated by the problem definition and utilises event trees, fault trees, and reliability diagrams to identify and evaluate failure modes and vulnerabilities of PAB design. Risk is quantified for multiple generic scenarios that serves as a comparative benchmark for alternative solution acceptance.

4.1 Overview

Fire risk assessment is a fundamental practice that underpins safety and helps to establish tolerable risk. In a broad sense, risk assessment involves the process of identifying hazards, rationalizing frequency of occurrence, and evaluating potential consequence. [13]

The basis of this risk assessment is to quantify and evaluate the reliability of a two-exit stair residential building against a PAB residential building. The two-stair building will serve as the benchmark for tolerable risk such that an alternative solution supporting a PAB building will be appropriately mitigated to provide an equivalent, if not enhanced, level of performance.

4.2 Risk Assessment Methodology

In assessing what failure modes could cause a single stair in either scenario to fail, the root causes can be appropriately mitigated such that a level of equivalence can be established to support an alternative solution approach.

The methodology employed to evaluate risk involves the use of event trees, fault trees, and reliability diagrams.

- Event trees allow sequential events to be identified and quantified that illustrates the potential outcomes and quantified likelihood. The tree is illustrated horizontally, commencing with a trigger event followed by intervening events until the outcomes are reached.
- Fault trees start with a failure point and proceed to identify failure modes until root causes are established. The root causes can subsequently be mitigated to improve overall reliability.
- Reliability diagrams visually illustrate fault trees as horizontal network paths that identify cut sets and failure paths.

The methodology includes:

1. Develop one or more event trees to 'map' the fault process between a PAB and two stair condition.
2. Develop one or more fault trees that further define the event tree 'gates' for PAB vs two stair conditions.
3. Quantify reliability values for identified root causes that are informed by statistical analysis, research, and engineering judgement.
4. Establish reliability values for PAB condition.
5. Convert fault tree(s) to reliability diagram(s).
6. Develop fault trees for two stair conditions with minimum allowable fire precautions.
7. Provide quantified values to root causes informed by statistical analysis and research.
8. Establish reliability values for code compliant multiple stair condition.
9. Convert fault tree(s) to reliability diagram(s).
10. Compare reliability for PAB vs multiple stair designs to facilitate identification of mitigation measures.
11. Quantify impact of mitigation measures in modified fault trees to inform alternative solutions.

The outcome is to provide risk proportionate mitigation measures within alternative solutions to allow building developers / designers to propose PAB buildings.

4.3 Acceptance Criteria

Failure in the context of this analysis is defined as:

A loss of tenability within the stair for occupants and firefighters.

Tenability could be defined in multiple ways. The NBC(AE) implicitly acknowledges that the applicable acceptable solutions would allow smoke ingress into exit stairs. The volume of smoke is intended to be restricted however, smoke contamination cannot be ruled out. Subsequently, how much smoke could be permissible within a stair should be determined.

It is considered that for the purpose of this risk assessment evaluation, no smoke contamination within the exit stair(s), beyond leakage values, is the benchmark for tolerable risk. The benefit of this simplified approach is to limit subjective discussion on smoke contamination that detracts from the prominent purpose of the risk analysis. Accordingly, a quantified performance value for smoke contamination is not provided to support this analysis.

4.4 Event Tree Analysis

Figure 4-1 presents an event tree of multiple cascading events that are required to occur for a stair to fail. What the tree illustrates is a critical path of sequential events or occurrences that are required to transpire for a reasonable likelihood of stair contamination occurring. One in seven outcomes identified stair contamination as a possibility.

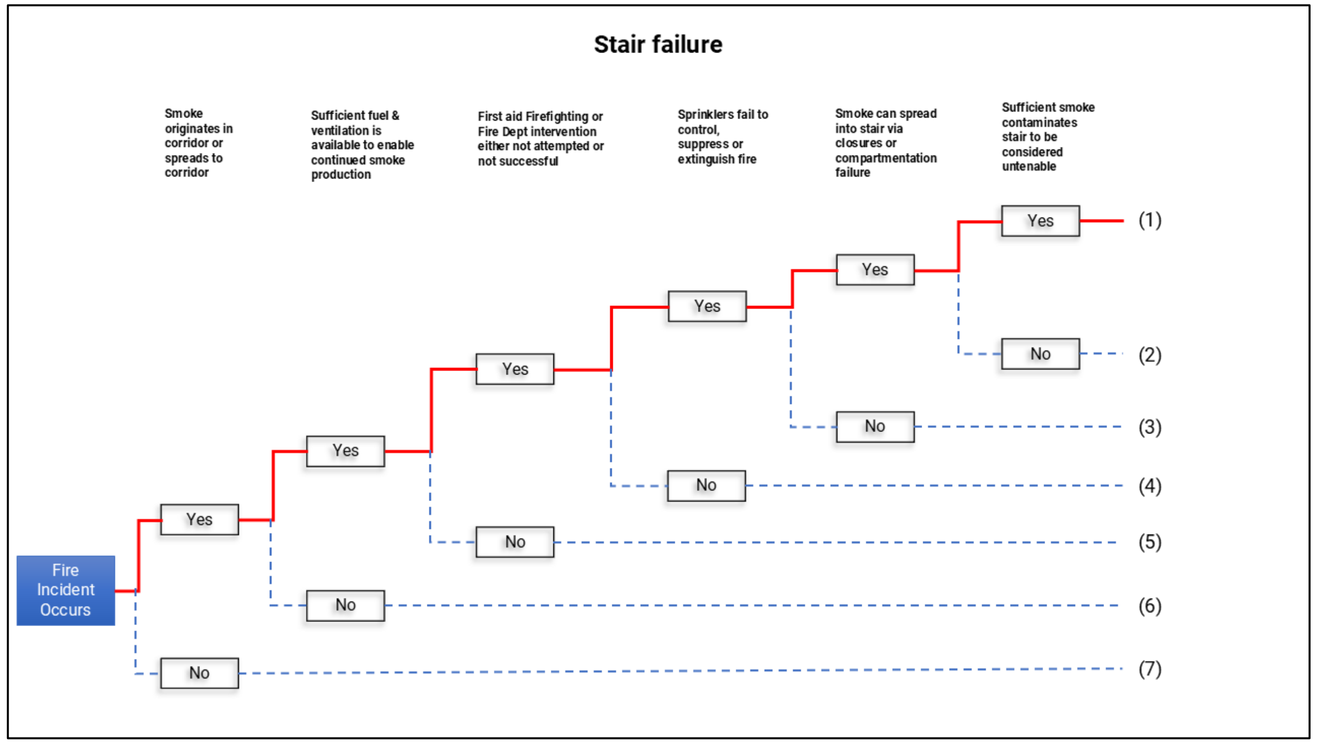

Figure 4-1: Event Tree - Stair Failure

Interrogation of the event tree quickly indicates that:

- Insufficient resolution is provided to locate key root causes
- The sequence of events is applicable to both single and multiple exit stair scenarios

Further refined analysis has subsequently been conducted with fault trees.

4.5 Fault Tree Analysis

Figure 4-2 presents a single stair fault tree that advances the logic utilised within the event tree.

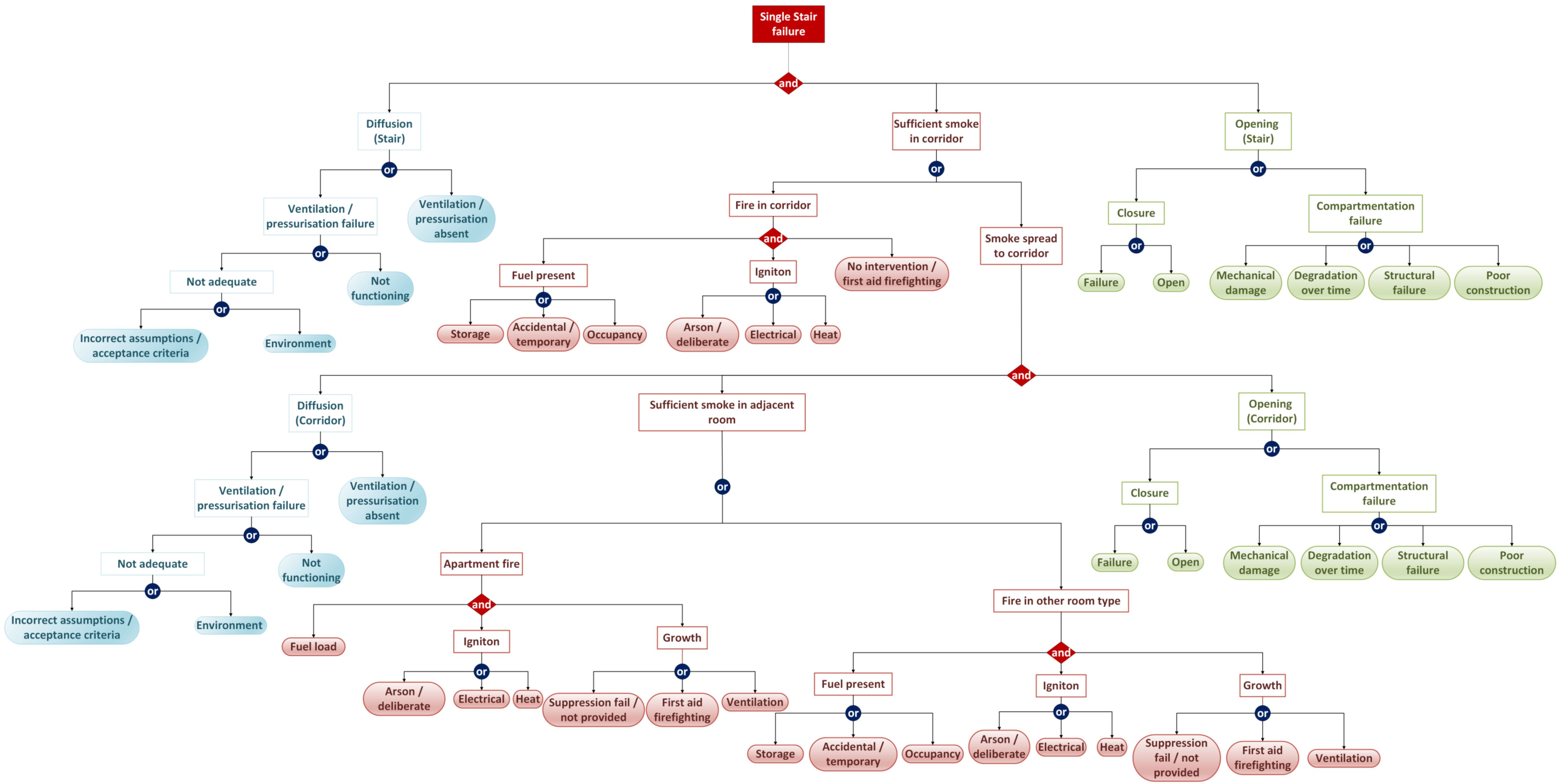

Figure 4-2: Single Stair Fault Tree

The logic of a fault tree is that a failure mode is placed at the top with a series or gates defining underlying causes. Multiple gate types are available for analysis however only 'and' or 'or' gates are utilised for stair evaluation. The 'and' gate represents concurrent activities that are required to occur whereas 'or' gates provide an option of a particular failure type. [14]

Development of the fault tree identified three concurrent ('and' gate) failures that are required to occur. They include:

1. the presence of smoke within the corridor (coloured red),
2. a means for smoke to flow into the stair (coloured green), and
3. an impetus for smoke movement (diffusion or pressure differential) (coloured blue).

4.5.1 Presence of Smoke in the Corridor

The relevance of smoke in the corridor is that this is the primary path for smoke contamination of the stair. It is considered unlikely that smoke could spread to a stair via an intervening wall due to the failure modes required for this to occur. The presumption is that a fire does not occur within the stair (as discussed in the previous chapter) and fires external to the building are discounted. External fires are ruled out as credible fire scenarios owing to a lack of mandated or reliable detection features that would initiate evacuation of a building. An exit through lobby condition also has the potential to contaminate a stair and, for the purpose of this analysis, is considered equivalent to a corridor.

The presence of smoke is contingent upon a fire being located either in the corridor (or lobby) or an adjacent room. Any adjacent room being either an apartment or ancillary space (i.e. storage room, amenity room, etc.). A fire requires the presence of fuel, oxygen, and heat for a deflagration to commence.

- Fuel would be location specific. In an apartment, fuel would be considered an absolute certainty. In an adjacent room or corridor, fuel could be present as storage, temporary / accidental placement, or if an occupancy is present.
- Ignition would manifest as deliberate / arson, electrical, or another heat source.
- Oxygen would be from the surrounding air without the need for further ventilation paths to be present.

A final factor would be the omission of intervention which could manifest as:

- First aid firefighting by occupants
- Firefighting activities
- Failure of an automatic suppression system

To summarise, smoke requires being present in the corridor due to a fire in the corridor or if smoke spreads to the corridor. If smoke requires being spread to the corridor, then further failures, such as apartment doors, are required to occur to enable smoke spread.

4.5.2 A Means for Smoke to Flow into the Stair

A means for smoke flow is quite simplistic. Smoke flow is enabled through a closure or via the compartmentation (assembly). The most likely opportunity for smoke flow is via a closure that is either open (temporarily or held open) or a failure of a closure. The less likely scenario is smoke transport via finished compartment assembly. The requirements being:

- Mechanical damage
- Degradation over time
- Structural failure
- Poor construction

Should the smoke originate from the corridor, only one opening is required (opening to the stair). If smoke requires travel to the corridor, then to the stair, at least two openings (opening to the corridor and opening to the stair) would be required to permit smoke transport.

4.5.3 Impetus for Smoke Movement

The means for which smoke would transit into the stair enclosure is also a factor. In the absence of a means to create a positive pressure differential between the stair and intervening space, smoke would flow from the corridor to the stair via diffusion or a pressure imbalance. This same logic applies where a fire occurs remote to the stair where an impetus exists for smoke flow first into the corridor then to the stair.

4.5.4 Comparison to Two Stair Scenario

Within a comparable two-stair scenario, as illustrated in **Figure 4-3**, the below observations are made.

- The primary difference between the PAB and two stair conditions is that **both of the two stair openings are required to fail as opposed to just one**.

Pressure imbalance and air flow has relatively low impact for shorter buildings. This does become a factor for buildings classified as 'high buildings' where environmental forces are more prominent and 'limits to smoke movement' mitigation measures are prescriptively imposed on the design.

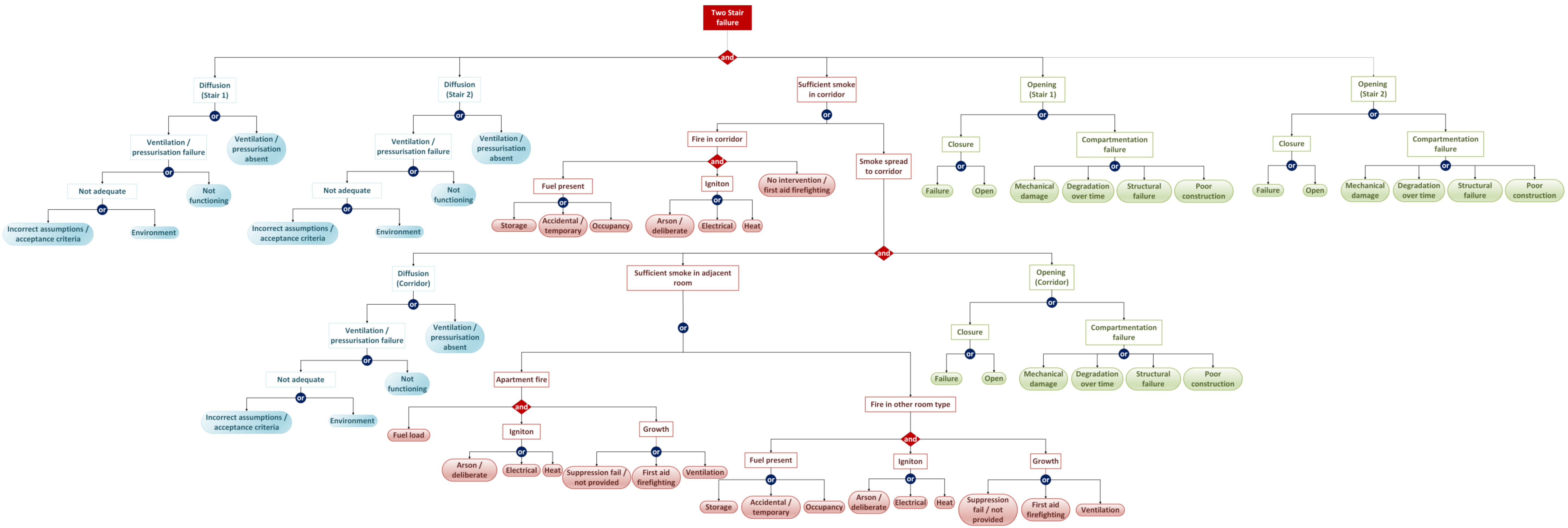

Figure 4-3: Two Stair Fault Tree

To illustrate the reliability implicit with the comparable fault trees, reliability diagrams are presented.

4.6 Reliability Diagrams

Another way to visualise the fault trees is through reliability diagrams as presented in **Figure 4-4** and **Figure 4-5**. The diagrams illustrate reliability through network paths from left to right. 'And' gates are illustrated as parallel paths whereas 'or' gates are illustrated in series. The diagrams have been colour coded in respect to the three primary failure modes.

1. Red squares – The presence of smoke within the corridor,
2. Blue squares – A means for smoke to flow into the stair, and
3. Green squares – An impetus for smoke movement (diffusion or pressure differential)

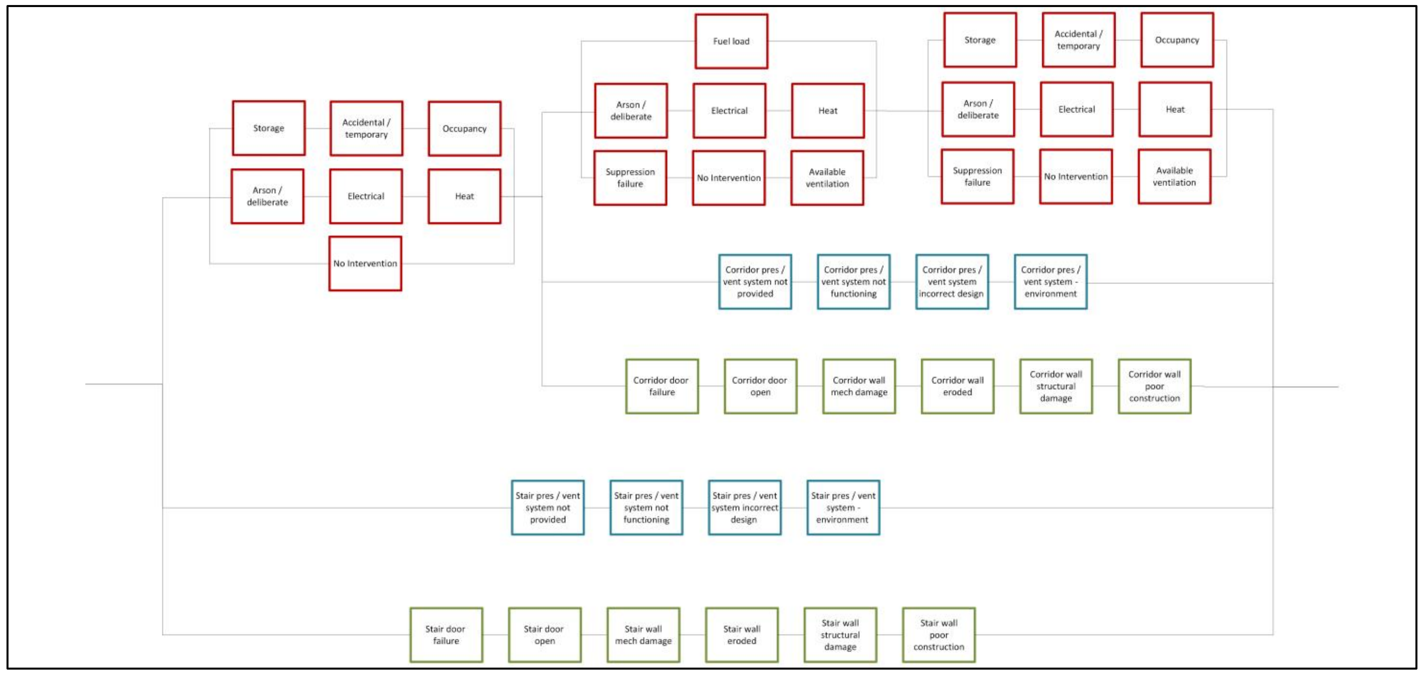

Figure 4-4: Reliability Diagram - Single Stair

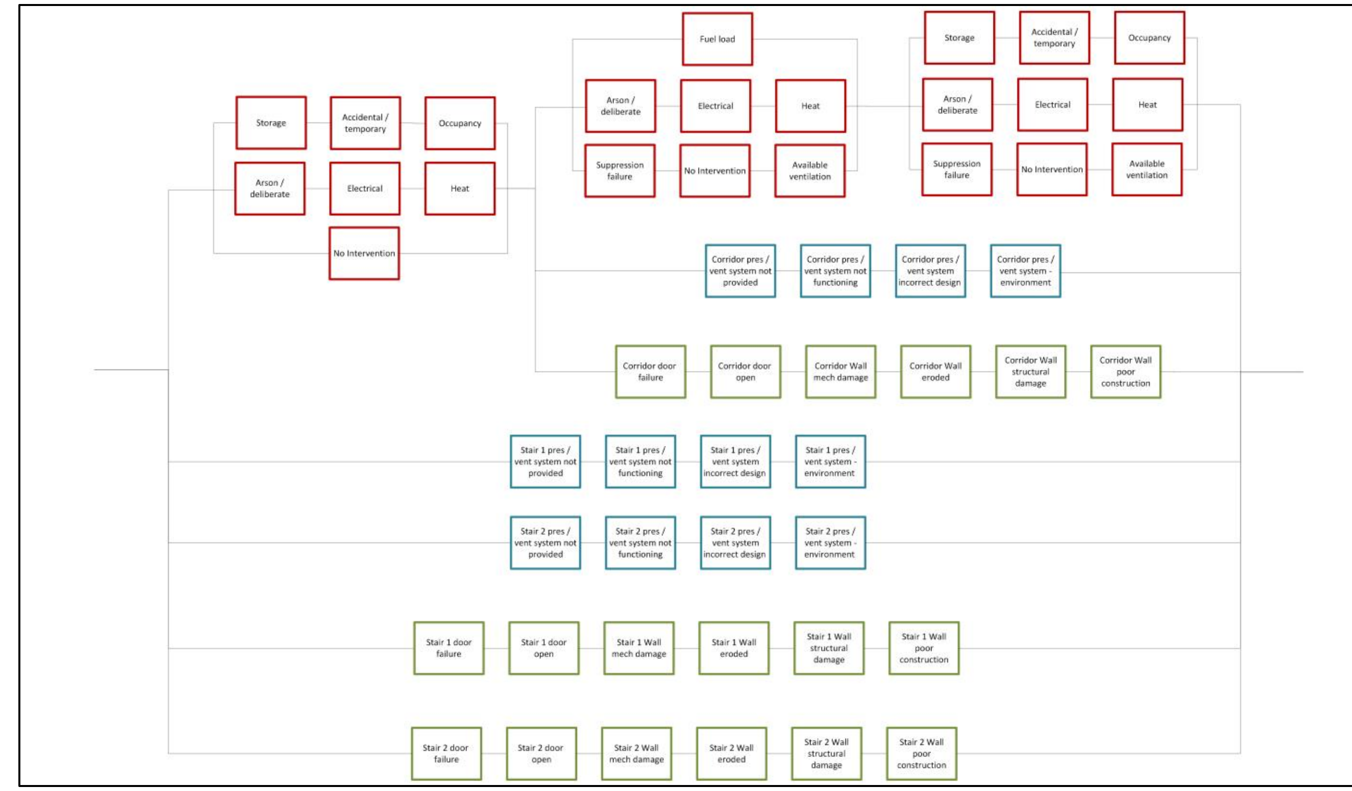

Figure 4-5: Reliability Diagram - Two Stairs

Review of the reliability diagrams present the below observations:

1. A single stair condition requires a minimum of five concurrent failures
2. A two-stair condition requires a minimum of seven concurrent failures
3. If smoke does not originate within the intervening corridor, a minimum of seven and nine concurrent failures are required for the single and two stairs respectively.
3. Smoke originating within the corridor presents the least reliable event.
4. Overall, the likelihood of one or more stairs becoming untenable is a very low likelihood event.

4.7 Risk Quantification

The outcomes of the fault tree analysis and reliability diagrams have facilitated the identification of root causes for failure and the need to evolve the analysis to capture buildings subject to 'high building' requirements and those that don't. Four subsequent fault trees have been developed to include PAB vs two stair conditions for above storeys and up to and including six storeys in height (six storeys acting as a trigger for 'high building' requirements).

Quantified values for reliability have been provided for each of the root causes. Red values on the fault trees indicate input values with blue values indicating calculated values. Calculated values are governed by the below equations:

'And' gate = $P(A) \times P(B)$

'or' gate = $P(A) + P(B) - P(A) \times P(B)$

The input values presented in **Figure 4-6**, **Figure 4-7**, **Figure 4-8**, and **Figure 4-9** indicate a considered likelihood of failure between 0 (no failure likely to occur) and 1 (failure certain to occur). The values are explored individually in the following sections.

Of note with the values utilised within the four fault trees is that the comparative nature of the risk analysis removes the dependence on specific values. To explain, if the value for the failure of a closure was considered contentious, the value could be altered with no impact on the resulting reliability. This is because the value change would apply to both PAB and two stair scenarios. As such, the actual reliability value listed in **Table 4-1** is not as important as the difference between the PAB and two stair scenarios.

The Author fully acknowledges that any attempt to quantify risk invites scrutiny with the values open to subjective interpretation. Fire incidents by their nature are low frequency events with data either not directly relatable to a specific failure mode or skewed in some respect. **Focus should be applied to the differences between the fault trees values and not individual values applicable to a two stair and PAB scenario**.

4.7.1 Presence of Smoke in the Corridor

Fire statistics indicate that between 2005 to 2015, an average of 2237 fires occurred in residential apartment buildings across Canada. Of those fires, 9% occurred in the building's means of egress (43% of those within corridors or hallways and 27% within stairways). 11 deaths and 2009 injuries occurred in residential building fires during this time period. [15]

Unfortunately, the above statistics lack the appropriate resolution to draw significant conclusions from. Pertinent questions would include:

- Age and location of the buildings?
- What were the fire sizes and propagation characteristics?
- What constitutes an injury? i.e., directly related to products of combustion or trips and falls when evacuating?
- What is the scale of the injury? i.e., provided with oxygen on scene or hospital attendance?
- Were the stairways all exit stairs?

Within the fault trees, three components govern the propagation of a fire that includes presence of a fuel load, ignition source, and ability to grow.

- Fuel load – Within the apartment fire scenario, the presence of a fuel load is considered as 1 (absolute certainty). Within the corridor or other room type, the presence of fuel is less certain and is considered as being present from either storage of combustibles, accidental / temporary storage of combustibles or if an occupancy is present.
- Ignition sources – Within the three fire locations, it is considered that arson / deliberate ignition is likely to occur with the most likely location being within an apartment. 39% of residential fires were reported as being started by smokers' materials with electrical distribution contributing 3.3% and other electrical equipment 3.2% [15]. Within the fault trees, these are represented as electrical and heat sources. It should also be borne in mind that the statistical data set is largely absent of emerging threats such as lithium-ion battery fires that has been more prevalent of recent years.
- Growth – Growth is characterized as the environmental ability to grow and the absence of an active suppression system or first aid firefighting. 35% of residential apartment fires were extinguished by occupants (first aid firefighting), 38% by the fire department, and 18.1% burned out. [15] Of note is that there will be an unquantified number of fires that have occurred in residential buildings that were extinguished by occupants that were never reported to the fire department. Automatic fire suppression operated in 2.7% of the residential apartment fires with 7.3% not operating as the fire was too small to activate the system. These statistics speak to the general ability for a fire to develop and propagate and interaction by building users.

  In respect to sprinkler reliability, many documents offer reliability values for sprinkler systems. 92% reliability is offered for US based failures from 2007 to 2011 [16] with New Zealand offering expected performance of 90% [17]

4.7.2 Means for Smoke to Flow into the Stair

The means for smoke to flow either into the stair or intervening corridor is contingent upon a means of failure manifesting as either a closure failure or a breach of compartmentation. The fault trees capture the flow opening as failure of a closure (open or not functioning) and compartmentation (mechanical damage, degradation over time, structural failure, and poor construction).

Statistics are not available to meaningfully track compartmentation or closure failures to the resolution applicable to dynamic stages of a fire incident. I.e., was a door propped open at some stage during the fire? At the start? Fully or partially open? Did firefighting operations lead to the doors being propped open?

What can be stated is that failure of a closure or compartmentation is plausible with the fault trees identifying that multiple failures would be required if the fire does not originate in the corridor. The probabilistic values within the fault trees are informed by engineering judgement that are applicable to a PAB and two stair design.

4.7.3 Impetus for Smoke Movement

The impetus for smoke movement becomes more complicated as the building height increases. For 6 storeys and below, prescriptive limits to smoke movement are not levied on residential buildings (assuming that this is the threshold for which a high building classification is triggered for a given building (floor level > 18m above grade)). As such, there are no risk mitigation measures prescriptively levied on the building relating to creating a pressure differential or flow path to prevent smoke ingress into a stair or corridor. It should be noted also that there is a common misconception that residential corridors are prescriptively provided with pressurization systems. Such systems are not imposed by the acceptable solutions of Part 3 and therefore, if provided, are not intended to support fire and life safety. It is understood that such systems are provided by mechanical engineers for the purpose of counter balancing stack effect within the building and as an odor suppressant to the corridor. The fault trees capture this with a likelihood of failure of 1.

For buildings above 6 storeys, limits to smoke movement are provided for stairs serving above the lowest exit level. Corridors are not provided with such measures. The NBC(AE) permits natural pressurization to be used as a smoke management mitigation measure for stair cores serving floors above the lowest exit level within 'high' buildings. A predominant supporting rationale behind the natural pressurization method is the cold weather experienced within Canada during the winter months. Considering the impact of climate change, impact of climatic and construction variables, and drive for thermally efficient buildings, the efficacy of pressurization to perform to a minimum standard is questionable. For clarity, natural pressurization is a system designed to create an overpressure within a designated volumetric space relative to adjacent spaces for the purpose of containing or limiting smoke movement. Except for HVAC systems for regulating and maintaining internal building temperatures, no mechanical or other means of pressurization are adopted beyond atmospheric conditions.

The fault trees capture the challenges presented by a natural pressurization system through:

- Failure of one or more components (doors to external not being propped open)
- Inadequate system design caused by environmental factors (prevailing winds, warm temperatures, etc.)
- Incorrect assumptions or input criteria (a 12 Pa pressure differential is not mandated by this approach)

4.8 Reliability Assessment

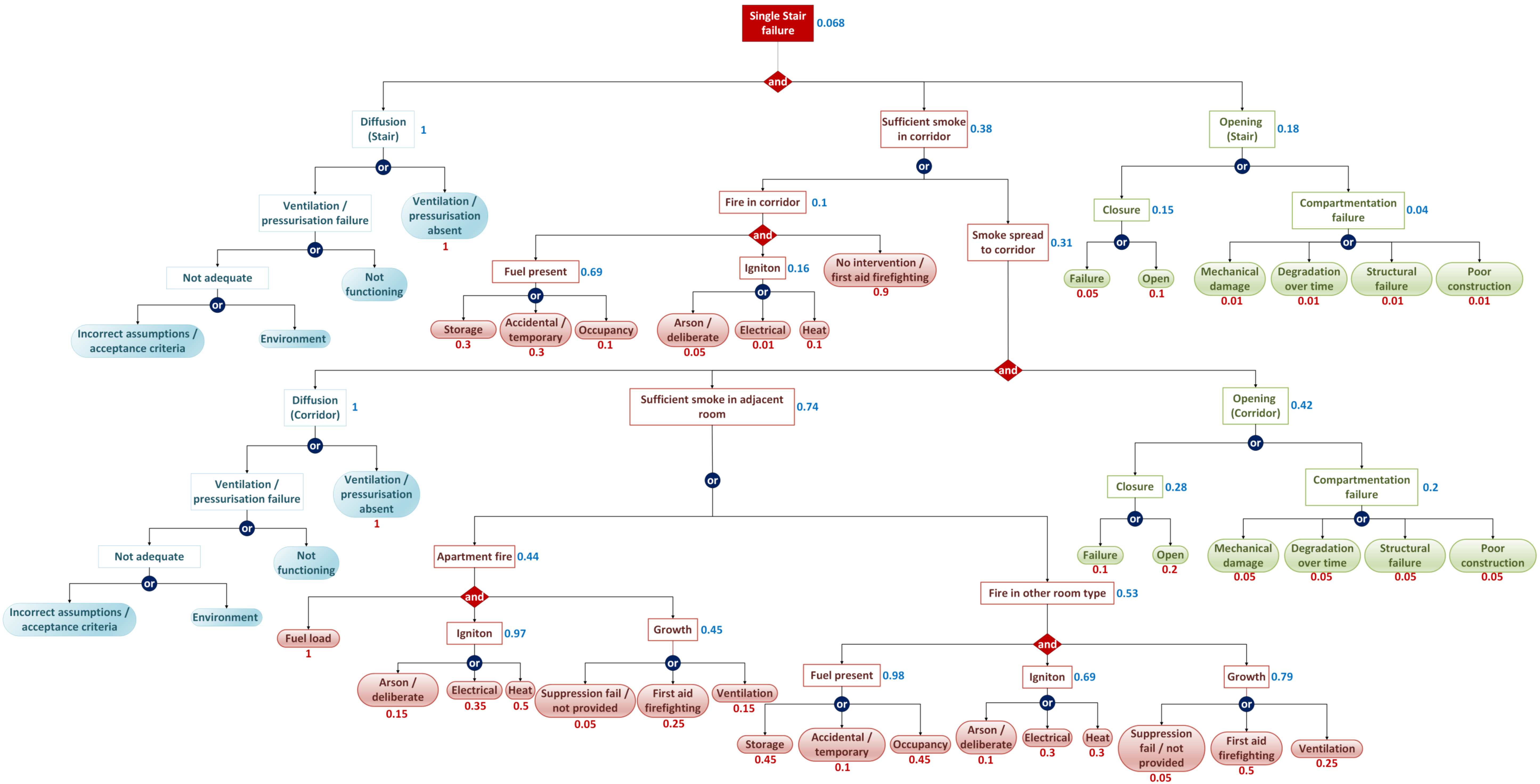

Figure 4-6: Single Stair Fault Tree - Up to 6 Storeys

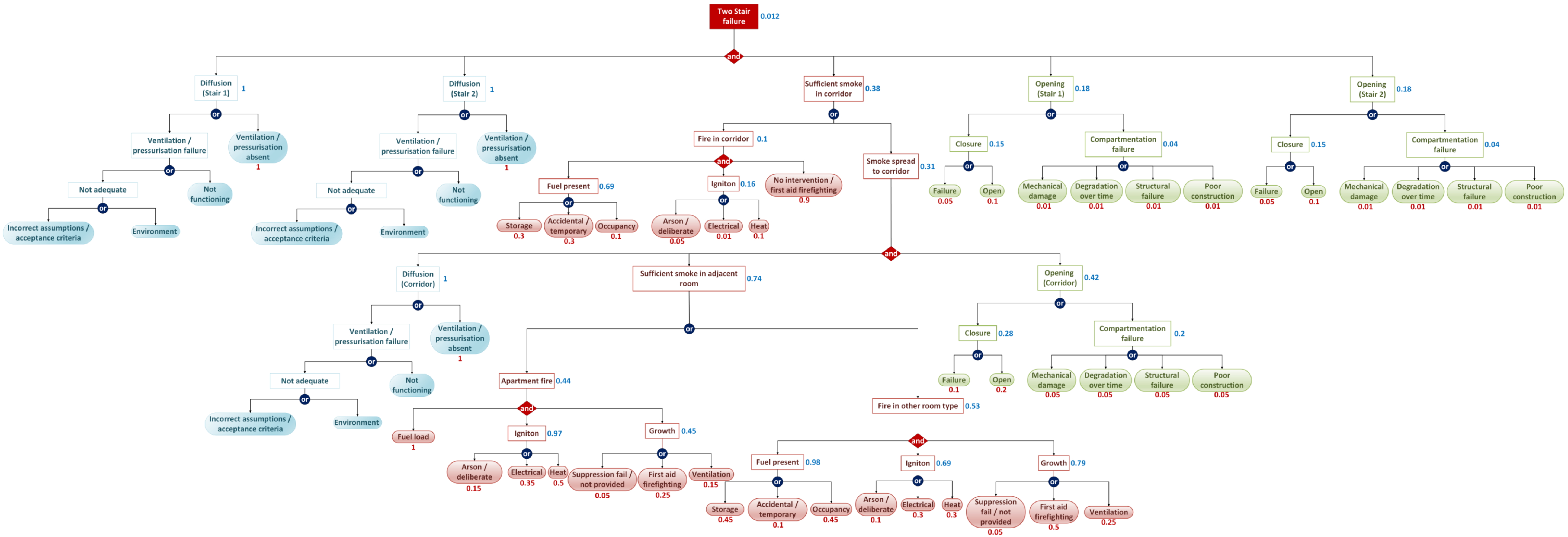

Figure 4-7: Two Stair Fault Tree - Up to 6 Storeys

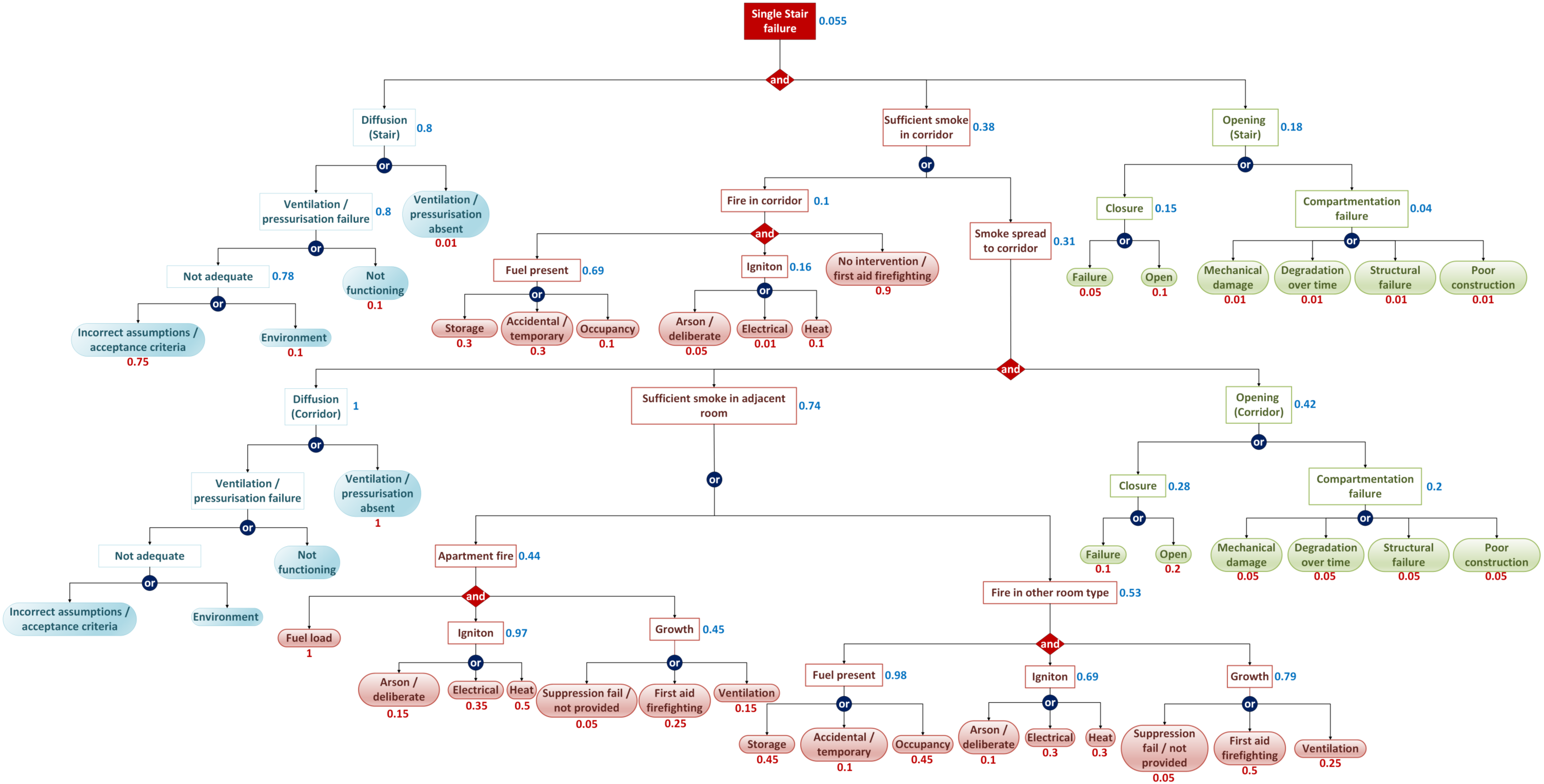

Figure 4-8: Single Stair Fault Tree - Above 6 Storeys

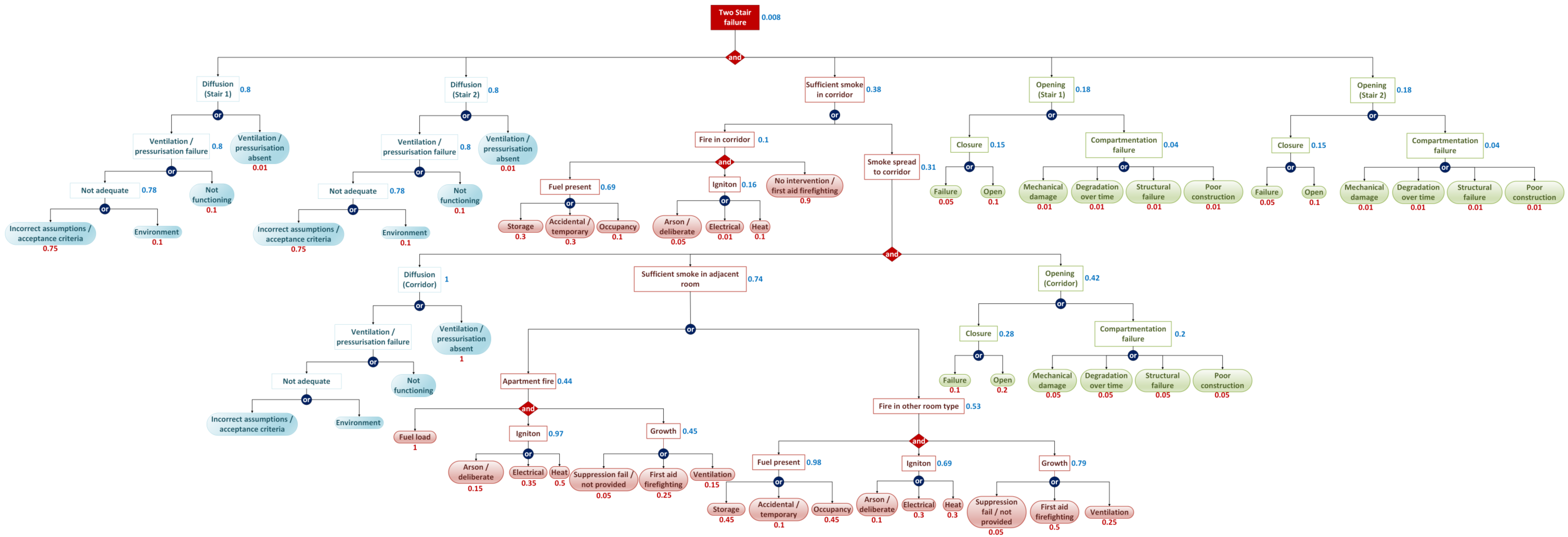

Figure 4-9: Two Stair Fault Tree - Above 6 Storeys

4.9 Reliability Discussion

As denoted in **Section 4.7** , the values assigned within the four fault trees are subjective and indicative. Reliable statistical data is not available to fully inform the root causes for each of the fault trees. The above values should be considered purely as indicative and not representative of a specific scenario or as a panacea for PAB design. The values can represent the efficacy of the methodology for which an alternative solution can be derived and benchmarked. When used for a specific design scenario, the input values should capture building geometry and salient design features that directly influence PAB design. For the generic examples outlined in the above fault trees, the resultant quantified reliability levels for each scenario are presented in **Table 4-1** below.

Table 4-1: Indicative Reliability Values

No of stairs	Up to 6 storeys	Above 6 storeys
Single stair	93.2%	94.5%
Two stairs	98.8%	99.2%

The values indicate that there is a reliability difference presented by a PAB and two-stair design. The resolution of the reliability values is not important as they are simply a function of the nature of the input values, i.e. decimal places vs whole numbers. What is critical is that when a PAB design is contemplated, the reliability value (to whichever resolution that is calculated) is increased to at least the level to which a minimum performing two-stair design would function.

Any quantification or a reference design should include geometric provisions and a building risk profile (height and area) as they pertain to a difference between a PAB and two-stair design.

4.10 Summary

The analysis conducted within this Chapter includes the risk assessment analysis to evaluate the problem definition and identify root causes that enable risk mitigation measures to be identified.

Four fault trees were established that differentiate between residential buildings classified as 'high building' as those that aren't for PAB and two-stair scenarios. Each fault tree was provided with quantified input values for the purpose of evaluating predicted indicative reliability values that substantiate the methodology for alternative solution development.

5 Alternative Solutions

This chapter identifies and describes potential alternative solution risk mitigation measures extrapolated from the problem definition and failure modes of the risk assessment process.

5.1 Structure of Alternative Solutions

As outlined in **Section 2.2** , an alternative solution as predicated within the NBC(AE) requires a comparative benchmark to govern acceptability. With the provision of a quantified performance benchmark of single and two stair scenarios, alternative solutions can be developed and presented for consideration. What an alternative solution is mandated to present are reliability values for a PAB design that are equivalent or exceed the reliability of the benchmark two stair performance.

5.2 Alternative Solution Exemplar

The production of an alternative solution to support a PAB building would be required to provide risk mitigation measures that can be directly attributed to the problem definition.

What would cause a single stair to fail?

Or to place in the context of an alternative solution:

Will the PAB building provide an equivalent level of resilience to the exit stair as a code compliant two-stair building?

If an alternative solution is able to address and appropriately mitigate the potential loss of a PAB, then the objectives and functional statements would be considered to be satisfied. The risk assessment, and particularly the reliability diagrams, illustrate the concurrent failure modes required to occur for a two-stair or PAB failure to be realised. To reiterate, the three main components that could lead to stair failure include:

1. the presence of smoke within the corridor,
2. a means for smoke to flow into the stair, and
3. an impetus for smoke movement (diffusion or pressure differential).

In relation to bullet point 1, mitigation measures exist that could reduce the likelihood of smoke occurrence in the corridor. These could include fuel load management and maintenance of equipment and infrastructure. In reality, these are difficult to effectively manage throughout the life cycle of a building and should in fact be captured implicitly within a well-maintained PAB or two-stair building. As the NBC(AE) assumes that a fire will occur, the aforementioned risk mitigation measures cannot be completely relied upon and should not form the basis for an alternative solution regarding PAB design.

The remaining bullet points (items 2 & 3) relate to compartmentation and smoke management that are considered to directly influence and affect the reliability of a PAB design.

To illustrate the risk assessment process in practice with a realistic design, design study 2 from the design guide has been selected. Design study 2 is a four-storey residential building with 16 units. The single stair is protected by a vestibule that is a risk mitigation measure above the minimum requirement of the acceptable solutions of the NBC(AE). The vestibule would act as an additional layer of compartmentation that would be required to fail for smoke to ingress the stair. It is not considered that a fire would or could occur within the vestibule.

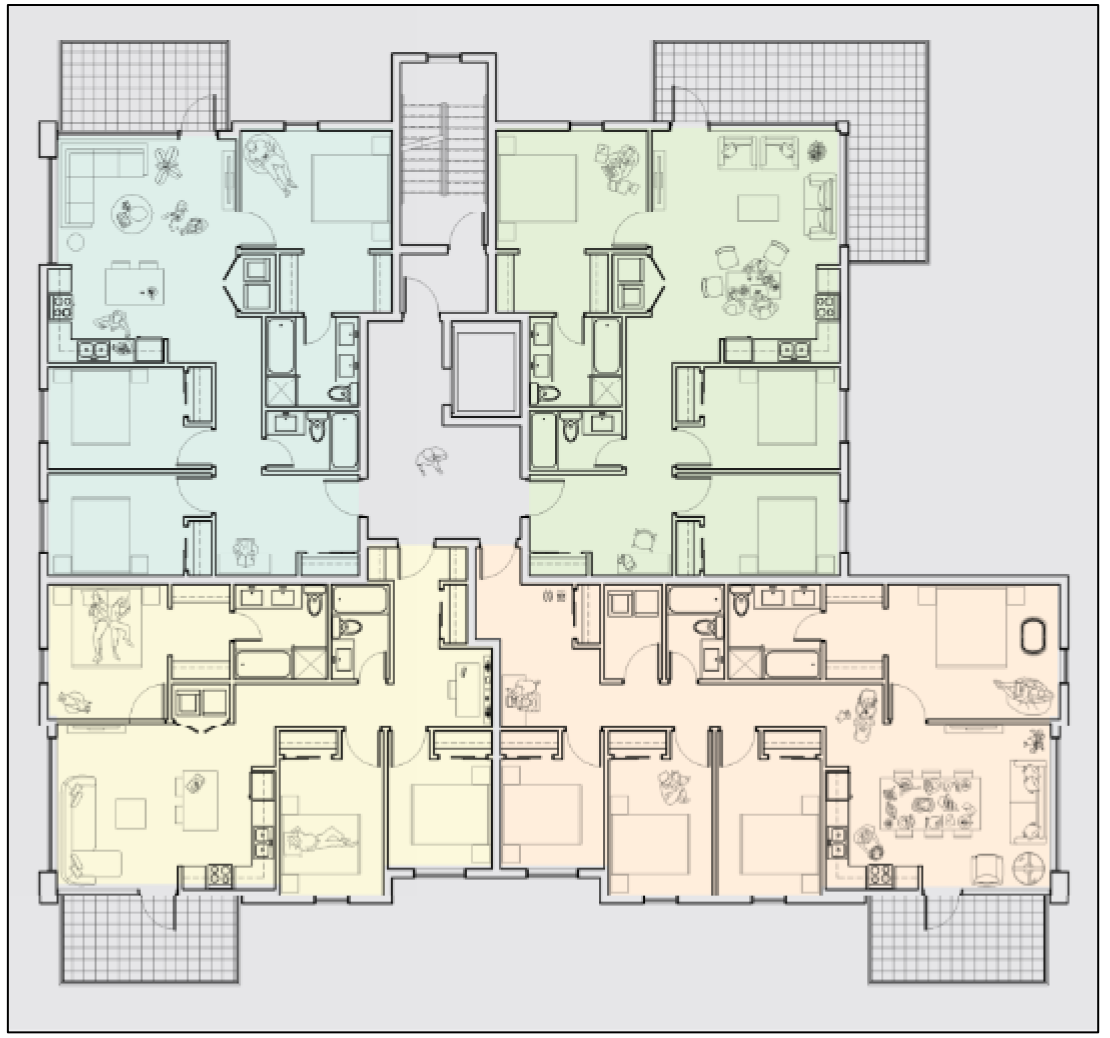

Figure 5-1: Design Study 2

Although the design exhibits characteristics that warrant amendment to the input values, the base line reliability value for a code compliant equivalent (similar design with two stairs) has been adopted from **Table 4-1** and **Figure 4-6** of 98.8% (0.012). **Figure A-1** within the appendices demonstrates the impact that a vestibule has on the reliability of the single stair with an increase from 93.2 % to 98.8%. The increase in reliability demonstrates an equivalent level of performance and thus satisfies the NBC(AE) requirement for an alternative solution.

Although not quantified within this technical report, the below risk mitigation measures may be considered that would likely provide a sufficient level of resilience to a PAB building (subject to an appropriate level of review and assessment).

PAB buildings up to six storeys (no high building measures)

1. Compartmentation / vestibule – An example being the provision of an intervening fire sterile vestibule within the corridor adjacent to the stair door. This directly compensates for the single opening failure presented by a single stair opening as demonstrated within the above example, or
2. Exterior passageway – Such a provision enables smoke disbursement directly to external and away from the exit stair, or

3. Smoke management – An example is the provision of a smoke control system that actively prevents smoke from entering the PAB. Pressurization of the PAB potentially inhibits smoke spread into the PAB or alternatively the corridor could be negatively pressurized by means of a smoke extraction system located in the corridor remote from the PAB. Smoke would be extracted from the corridor with makeup air provided via the PAB, thus actively preventing smoke contamination of the PAB.

The analysis contained within this report does not directly relate to building height. In theory, the methodology could be adopted for buildings of any height. The exemplar designs within the design guide are limited to 6-storeys thus risk mitigation measures are not contemplated further. Should PAB buildings seek to apply for greater building heights (above six storeys) then a robust smoke management system would likely be the anchor for such a solution.

Numerous key themes and vulnerabilities can be extracted from the risk analysis outlined in this report. Accordingly, the above lists should not be considered exhaustive with scope for innovation available and encouraged.

5.3 Summary

Alternative solution development that includes risk proportionate mitigation measures are offered for PAB buildings. Such solutions may be simplistic in nature and are required to address the actual risk presented as well as directly correlating back to the problem definition as presented in Chapter 3.

6 Conclusion

The scope of this report is to present the technical rationale, methodology, and analysis for PAB design within the geographical locations in which the NBC(AE) is enforced. Although developed as standalone, this report is intended as a complimentary document to the PAB guide.

The objectives of this report are to:

1. Identify and articulate a robust problem definition for PAB design
2. Rationalise the key stakeholders and users of PAB buildings
3. Outline the framework and methodology of PAB analysis
4. Quantify a level of performance for a 'code compliant' design to which an alternative solution may be benchmarked against
5. Detail the risk analysis, assumptions, inputs, and uncertainty
6. Rationalise potential alternative solutions for use by project stakeholders in PAB design

Upon evaluating the regulatory framework and acceptable solutions sought for departure, a problem definition was derived that spoke to the resiliency of a PAB building. It is considered that for an alternative solution to be contemplated that would provide an equivalent, if not enhanced, level of performance than that of a minimum performing code compliant design (two stairs), that enhanced resilience would be required to be afforded to the PAB design.

The risk assessment process identified that residential buildings should be rationalised for those classified as high building and those that aren't with risk mitigation measures applied to limit / reduce the likelihood that the PAB would become compromised. This philosophy would be applied to any residential building irrespective of height and area, provided that a higher level of reliability is provided than that of a code compliant design.

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Appendix

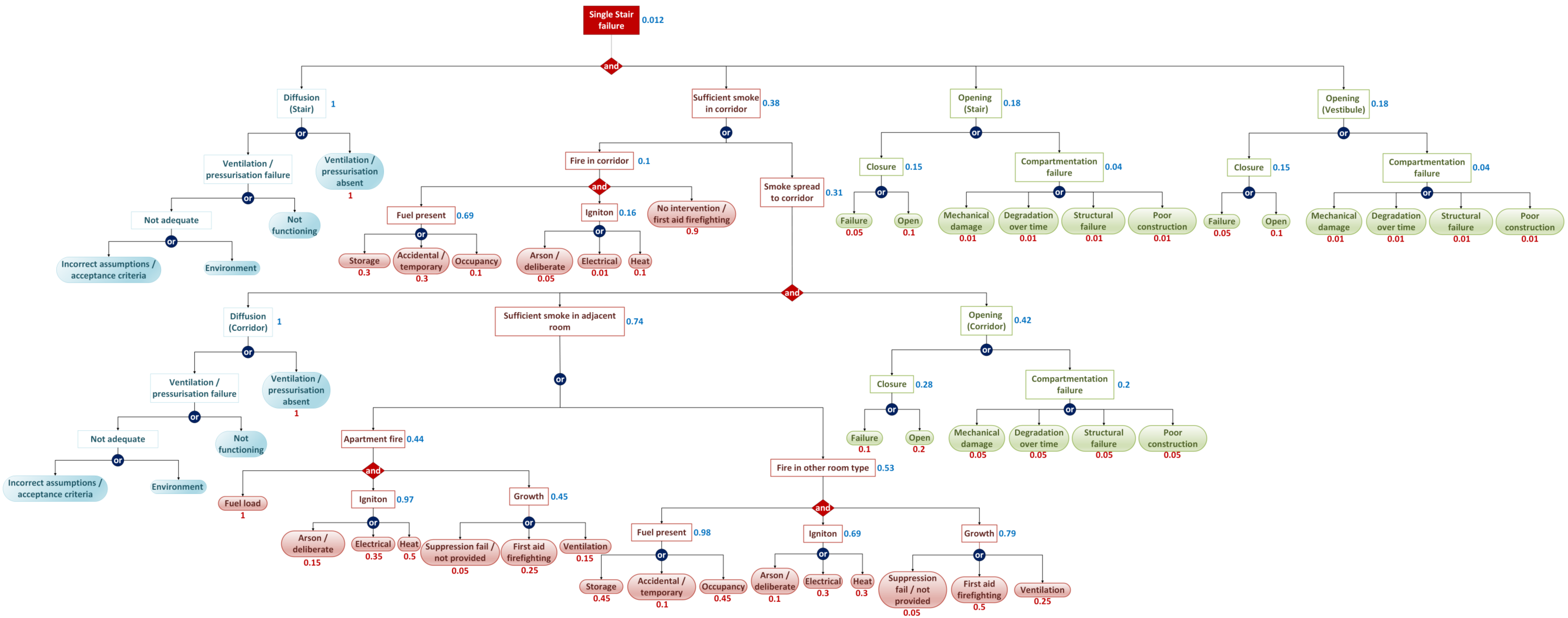

Figure A-1: Design Study 2 Fault Tree