A Dynamic, Probabilistic Fire Risk Model incorporating Technical, Human and Organizational Risks for High-rise Residential Buildings

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Abstract

Fire events in high-rise residential buildings pose threats to both property and human life and upon investigation it is frequently revealed that the cause of a fire event is not simply due to technical errors. Often these investigations uncover human and organizational errors (HOEs) that contribute to fire risk and fire events. Many human factors identified in fire risk environments can be minimized through employee training and development while organizational factors, such as safety culture, can be changed over time through transformational interventions that shift existing mindsets. Probabilistic risk analysis (PRA) methods are modeling tools that allow fire risk professionals to estimate risk by computing several scenarios of what can go wrong, the likelihood of events occurring, and the consequences of the events. PRA often takes a fixed value of events occurring likelihood over the building design period, whereas it may change due to aging of a fire safety measure. PRA is an explicit methodology for complying with performance requirements of building codes, but existing PRA methods may underestimate safety risk levels by ignoring HOEs while focusing solely on technical risks and errors as well as not taking into account reliability changes over the time.

In this work, a systematic review identifies HOEs that can potentially affect risk estimates in fire safety modelling of high-rise buildings. The importance and uniqueness of high-rise buildings is mainly due to the special nature of buildings where fire-fighting techniques require different safety measures than in other industries. In addition, the height of high-rise buildings and the increased number of occupants result in longer evacuation times than other types of buildings or industrial plants. Evacuation times are increased further when the number of stairways in these buildings is limited. A wide range of HOEs have been identified as impacting risk in various industries such as offshore oil production and nuclear plants, but not all these identified HOEs will be appropriate for high-rise buildings. Important factors are those that emerge consistently from different published sources supported by quantitative case studies of events such as the Grenfell Tower fire in London and the fire in the Lacrosse building fire in Melbourne. The linking of published HOEs with errors identified from high-rise building fire case studies uncover HOEs likely to

influence risk estimates. Quantifications of the impact of HOEs on risk estimates in other industries indeed justify additional research and inclusion of HOEs for risk estimates in high-rise buildings. This work uniquely connects HOEs from various industries to likely HOEs associated with risks in high-rise buildings to address an important gap in the literature. The research provides empirical quantitative studies, theoretical framework, and guidelines demonstrating how HOEs risks can be distilled to improve PRAs of fires in high-rise buildings.

To further address the gap, this work proposes a comprehensive Technical-Human-Organizational Risk (T-H-O-Risk) methodology to enhance existing PRA approaches by quantifying human and organizational risks. The methodology incorporates Bayesian Network (BN) analysis of HOEs and System Dynamics (SD) modeling for dynamic characterization of risk variations over time in high-rise residential buildings. Most current approaches assume that the relationships among HOEs are independent and current methods do not explain the interactions among these variables. An integrated T-H-O-Risk model overcomes this limitation by measuring causal relationships among variables and quantifying HOEs such as staff training, fire drill practices, safety culture and building maintenance. The model addresses the underestimation of risk resulting from not following the proper practices and regulations. Issues of selecting fire safety measures needed to reduce risk to an acceptable level are examined while evaluating the efficacy of active systems that are sensitive to HOEs. The methodology utilizes the "as low as reasonably practicable" (ALARP) principle in comparing risk acceptance for different case studies demonstrating the model's value related to risk reduction with respect to initial designs of high-rise residential buildings.

By incorporating both BN and SD techniques, the T-H-O-Risk model developed in this research evaluates HOEs dynamically in an innovative and integrated quantitative risk framework. This is possible by incorporating factors that vary with time since event tree/fault tree (ET/FT) and BN alone cannot deal with dynamic characteristics of the process variables and HOEs. The model includes risk variation over time which is significantly better than contemporary methods that only provide static values of risks. Initially three case studies are conducted with limited number of scenarios for the purpose of validation to demonstrate the

application of this comprehensive approach to the designs of various high-rise residential buildings ranging from 18 to 24 stories. Societal risks are represented in F-N curves. Results show that in general, fire safety designs that do not consider HOEs underestimate the overall risks significantly which can reach 40% in some extreme cases. Furthermore, risks over time due to HOEs vary by as much as 30% over 10 years. A sensitivity analysis indicates that deficient training, poor safety culture and ineffective emergency plans have significant impact on overall risk.

Subsequently, the application of the T-H-O-Risk methodology was expanded to seven designs of high-rise residential buildings (including earlier three) with 16 different technical solutions to quantify the impact of HOEs on different fire safety systems. The active systems considered are sprinklers, building occupant warning systems, smoke detectors, and smoke control systems. The results indicate that HOEs impact risks in active systems by approximately 20%, however, HOEs have a limited impact on passive fire protection systems. Large variations are observed in the reliability of active systems due to HOEs over time.

Finally, sensitivity and uncertainty analyses of HOEs were carried out on three selected buildings from the above seven. The sensitivity analysis again indicates that deficient training, poor safety culture and ineffective emergency plans have significant impact on overall risk. The model also identifies multiple cases where tenable conditions are breached. A detailed uncertainty analysis is carried out using a Monte Carlo approach to isolate critical parameters affecting the risk levels.

This research has developed a novel approach to enhance fire risk assessment methods using a holistic quantification of technical, human, and organizational risks for high-rise residential buildings which ultimately benefits future risk assessments providing more precise estimates. A significant contribution of this research involves the systematic identification of HOEs and their associated risks for consideration in future PRAs. By studying various trial designs, the impact of HOEs on fire safety systems is analyzed while demonstrating the robustness of the T-H-O-Risk methodology for high-rise buildings. The research lays foundations for next-generation building codes and risk assessment methods.

Student Declaration

"I , Samson Boon Hua Tan, declare that the PhD thesis by Publication entitled *A dynamic probabilistic fire risk model incorporating technical, human and organizational risks for high-rise residential buildings* is no more than 100,000 words in length including quotes, and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work".

Signature: Date: 17-Mar-2021

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PUBLICATIONS

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2. Tan S, Weinert D, Joseph P, Moinuddin K. (2020). Incorporation of technical, human and organizational risks in a dynamic probabilistic fire risk model for high-rise residential buildings. Fire and Materials Journal fam.2872. https://doi.org/10.1002/fam.2872.
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CONFERENCE PROCEEDINGS AND OTHER PAPERS

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PART A:

DETAILS OF INCLUDED PAPERS: THESIS BY PUBLICATION

Please list details of each Paper included in the thesis submission. Copies of published Papers and submitted and/or final draft Paper manuscripts should also be included in the thesis submission

Item/ Chapter No.	**Paper Title**	**Publication Status** (e.g. published, accepted for publication, to be revised and resubmitted, currently under review, unsubmitted but proposed to be submitted)	**Publication Title and Details** (e.g. date published, impact factor etc.)
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List of Abbreviation

ABCB	Australian Building Code Board
ALARP	As Low As Reasonably Practicable
Alt	Alternative Solution
AOF	Apartment of Fire
ASET	Available Safe Egress Time
BBN	Bayesian Belief Network
BCA	Building Code of Australia
BE	Blocked Exit
BN	Bayesian Network
BOWS	Building Occupant Warning Systems
BRS	Building Regulatory Systems
CBA	Cost Benefit Analysis
CF	Challenging Fire
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPT	Conditional Probability Table
CS	Concealed Space
DAG	Directed Acyclic Graph
DETECT	Smoke Detection in the Apartment of Fire
DFG	Design Fire Generator
DN	Scenarios with Detection System Not Working
DTS	Deemed-To-Satisfy
DY	Scenarios with Detection System Working
EGRESS	Egress Protection System
EN	Scenarios with Egress Protection System Not Working
ERL	Expected Risk to Life
ET	Event Tree
ETA	Event Tree Analysis
EY	Scenarios with Egress Protection System Working
FED	Fractional Effective Dose
FI	Fire Brigade Intervention

FN	Fire No
F-N	Frequency-Number of Death
FSVM	Fire Safety Verification Methods
FT	Fault Tree
FTA	Fault Tree Analysis
FY	Scenarios with a Fire Ignited
FYDN	Fire Yes–Detection No
FYDY	Fire Yes–Detection Yes
HE	Human Error
HEP	Human Error Probabilities
HFACS	Human Factors Analysis and Classification System
HOE	Human and Organizational Error
HOF	Human and Organizational Factors
HRR	Heat Release Rate
IR	Individual Risk
IS	Internal Surfaces
MCP	Manual Call Point
NCC	National Construction Code
NFPA	National Fire Protection Association
NN	Scenarios with Detection and Notification System Not Working
NoC	Number of Checks
NOTIFY	Notification System on the Floor
OE	Organisational Errors
PBD	Performance-Based Design
PRA	Probabilistic Risk Assessment
PSF	Performance Shaping Factors
QRA	Quantitative Risk Assessment
RC	Robustness Check
RC1	Robustness Check - Failure of Detection
RC2	Robustness Check - Failure of Sprinklers
RC3	Robustness Check - Failure of Building Alarm
RoC	Rate of Change
RP	Risk Probability
RSET	Required Safe Egress Time

RTI	Smoke Detector Response Time Index
SC	Smoke Control Systems
SD	System Dynamics
SF	Smouldering Fire
SOU	Sole-Occupancy Unit
SpN	Scenarios with Fire and Smoke Not Spreading Outside the Room/Floor of Fire Origin
SPREAD	Smoke Spreading Beyond the Dwelling Unit
Sprk	Sprinklers
SpY	Scenarios with Fire and Smoke Spreading Outside Room/Floor of Fire Origin
SR	Societal Risk
STS	Socio-Technical System
SuN	Scenarios with Suppression System Not Working
SUPPRESS	Sprinkler System that Suppresses Fire
SuY	Scenarios with Suppression System Working
T-H-O-Risk	Technical-Human-Organizational Risk
UF	Unexpected Catastrophic Failure
UT	Fire in a normally Unoccupied Room Threatens occupants of other Rooms
VM	Verification Methods
VC_i	Variation Coefficient

Chapter 1

Introduction

1. 1 Background

A fire event in a high-rise building could potentially cause great loss of property and human life, as happened at the Grenfell Towers tragedy in London where there were over 72 fatalities [1]. In Australia, buildings exceeding 25 metres in height are deemed as high-rise buildings [2,3]. Similarly, in the US, the National Fire Protection Association (NFPA) defines high-rise buildings as greater than 23 metres in habitable height [4]. Australia has over 325 buildings of 30 storeys or more, primarily in Melbourne and Sydney [5].

In recent years, fires in high-rise buildings have attracted extensive attention globally. While most fires occurring in high-rise offices or other building types have resulted in little or no fatalities, there have been some serious high-rise residential fires that resulted in catastrophic loss of human lives and properties such as the Grenfell Tower fire in London in 2017. Table 1 lists some recent fires in high-rise residential buildings around the world. Fire data from the National Fire Protection Association (NFPA) indicate that from 2009-2013, an estimated 14,500 structure fires per year in high-rise buildings resulted in associated losses of 40 civilian fire deaths, 520 civilian fire injuries, $154 million in direct property damage [6]. More than three out of five (62%) in high-rise fires were residential fires with 26 fatalities (64% of all fatalities) between 2009-2013. Fire data from China indicate that from 2007-2010, there were 54,800 high-rise residential fires per year (39.1% of all fires) which resulted in 967 deaths each year (69.6% of all deaths) [7]. In Australia, similar to other countries, residential fires cause significant burden. Between 2012-2019, there were 16,500 fires per year across Australia and 9,500 (57%) were due to fires in residential buildings [8]. Coronial records from the Australian National Coronial Information System (NCIS) database indicate at least 900 deaths (average 64 deaths per year) due to residential fires from 2003 to 2017 [9]. Meanwhile, recent accident data from India report an average of 13,248 deaths per year between 2017 -2018 as a result of fires in residential buildings [10]. Residential fires account for 58% of all fire fatalities in India. There are a number of important issues concerning these catastrophic high-rise residential fires that need to be addressed and while it is unlikely that these failures were caused by just one systemic failure, but a host of contributory causes arising from failures across complex systems, it is the goal of this thesis to focus on the root causes of these failures in high-rise residential buildings rather than other types of high-rise buildings. There are a number of important issues concerning these catastrophic high-rise residential fires that need to be addressed and while it is unlikely that these failures were caused by just one systemic failure, but a host of contributory causes arising from failures across complex systems, it is the goal of this thesis to focus on the root cause of these failures in high-rise residential buildings over other types of high-rise buildings.

SN	Building	City	Country	Deaths	Injuries	Date
1	Parque Central Complex East Tower	Caracas	Venezuela	0	25	October 17, 2004
2	Harrow Court	Hertfordshire	United Kingdom	3	0	February 2, 2005
3	Treskowstrasse Pankow Flats	Berlin	Germany	2	3	April 21, 2005
4	Tohid Town Residential	Tehran	Iran	128	132	December 6, 2005
5	Belaire Apartments	New York City	United States	2	1	October 11, 2006
6	Lakanal House fire	London	UK	6	20	July 3, 2009
7	Kozepszer Street Flats	Miskolc	Hungary	3	n/a	August 15, 2009
8	Wooshin Golden Suites	Busan	S. Korea	0	5	September 1, 2010
9	4 Rue du Lac Flats	Dijon	France	7	11	November 14, 2010
10	Jiaozhou Rd Apartment, No 1 Alley 718 Jing'an	Shanghai	China	58	71	November 15, 2010
11	Dynasty Wanxin Complex Towers B Apartments	Shenyang	China	0	0	February 3, 2011
12	Al Tayer Tower	Sharjah	UAE	0	0	April 28, 2012
13	Polat Tower	Istanbul	Turkey	0	0	July 17, 2012
14	Saif Belhasa Building	Dubai	UAE	0	2	October 6, 2012
15	Tamweel Tower	Dubai	UAE	0	0	November 18, 2012
16	Al Hafeet Tower 2	Sharjah	UAE	0	n/a	April 22, 2013
17	Jianye Mansion	Guangzhou	China	0	0	December 15, 2013
18	The Strand	New York City	United States	1	20	January 5, 2014
19	One57	New York City	United States	0	0	March 15, 2014
20	Krasnoyarsk Apartments	Krasnoyarsk	Russia	0	n/a	September 21, 2014
21	Lacrosse Building	Melbourne	Australia	0	0	November 25, 2014
22	Wedgwood Apartments	Castle Hills, Texas	United States	5	10	December 28, 2014
23	The Marina Torch	Dubai	UAE	0	7	February 21, 2015
24	Baku Residential Flats	Baku	Azerbaijan	16	63	May 19, 2015
25	Al Nasser Tower	Sharjah	UAE	0	40	October 1, 2015
26	The Address Downtown Dubai	Dubai	UAE	1	15	December 31, 2015
27	Ajman One Complex	Ajman	UAE	0	n/a	March 28, 2016

28	Sulafa Tower	Dubai	UAE	0	n/a	July 20, 2016
29	Shepherds Court	London	UK	0	1	August 19, 2016
30	Al Bandary Tower B	Sharjah	UAE	0	4	December 1, 2016
31	Oceana Adriatic Building	Dubai	UAE	0	0	December 13, 2016
32	Grenfell Tower fire	London	UK	72	80	June 14, 2017
33	Marco Polo Apartments	Honolulu	United States	4	13	July 14, 2017
34	The Marina Torch	Dubai	UAE	0	0	August 4, 2017
35	Zen Tower	Dubai	UAE	0	0	May 15, 2018
36	Paramis Building	Tehran	Iran	0	87	July 22, 2018
37	FR Tower	Dhaka	Bangladesh	26	70	March 28, 2019
38	The Cube Student Housing	Bolton	UK	0	2	November 16, 2019
39	Abbco Tower	Sharjah	UAE	1	25	May 5, 2020
40	Nerudova Street Apartment	Czech Republic	Czech Republic	11	0	August 9, 2020
41	Ulsan Samhwan Art Nouveau Apartments	South Korea	South Korea	0	0	October 8, 2020

Table 1 – Some recent high-rise residential building fires

Fatal fires are disastrous events and the investigations that follow often reveal causes related to both technical and human errors. Human errors are sometimes linked to processes rooted in the organizational culture that impact accidents occurring at the individual level. For example, an organization may implement a rigorous safety culture that encourages attitudes and behaviours of management and staff to focus on and be continuously aware of organizational safety practices. The level of awareness of safety issues can also vary over time, and perhaps if an organization becomes lax in its safety culture there may be an increase in accidents or decrease in the quality of building maintenance operations. During a fire event in a high-rise building, interactions between the building, the environment, the safety measures, and humans can influence the eventual outcome.

Previous fire safety research has primarily focused on technical issues yet ignored the human and organizational factors (HOFs) that contribute to risk. Researchers describe HOFs as the interaction between individuals and machines, but the expanded definition now encompasses the effects of individual, group and organizational factors involved in the life-cycle of an engineered system. HOFs include external, internal, or sociological factors [11]. The Health and Safety Executive [12] refers to HOFs as "environmental, organizational and job factors, and human and individual characteristics that influence behaviour at work in a way that can affect health and safety." HOFs exist in the operation and maintenance of engineered systems including high-rise buildings. In the case of catastrophic events and large fires, often the cause of the event is the result of a technical factor or a combination of technical factors. In many cases, human errors (HE) that are overlooked in the risk assessment contribute significantly to the event.

Human errors are departures from acceptable or desirable practices by an individual which can lead to an undesirable outcome [13]. Organizational errors (OE) relate to activities involving regulation, compliance, policies and planning. They represent departures from acceptable or desirable practices by a group of individuals which result in unacceptable or undesirable quality. Bea [13] asserts that organizational errors have a pervasive influence on human errors. Human and organizational errors (HOEs) are a subset of HOFs, are not easily measurable, and they vary with time. HOFs can influence the quality and reliability of systems which can result in HOEs. Teams or individuals can be influenced to make errors by organizations, procedures, and systems. HOEs are therefore outcomes, not causes. Stoelsnes et al. [14] argue that understanding HOFs can reduce the prevalence and development of HOEs.

Several industries including offshore plants and nuclear plants have studied the effects of HOEs on risk however, no studies regarding these factors in high-rise buildings exist. The importance and uniqueness of high-rise buildings focuses on the special nature of buildings where fire-fighting techniques require different safety measures than in other industries. In addition, the height of high-rise buildings and the increased number of occupants result in longer evacuation times than other structures or industrial plants. Evacuation times are increased further when these buildings have limited stairways or blocked stairways due to use them as storage space. The complexity of including the different interactions between the different parameters is one of the main reasons HOEs have been ignored in previous studies related to fire risk in high-rise buildings. This oversight likely contributes to an underestimation of fire risk. Fire risk in residential high-rise buildings is complex and depends upon multiple factors which should be evaluated by detailed and holistic fire risk assessment methods and models. The risk models should ideally consider human errors of omission and commission that increase the likelihood of a fire, the probability of loss, or harm to human life. Apart from failures in building technical systems, it is important to evaluate possible human and organizational failures to provide an inclusive fire safety design that incorporates such errors when faced with potentially life-threatening scenarios.

While infrequent, when fires occur in high-rise residential buildings, sometimes there are no casualties, such as the fire at the Lacrosse building in Melbourne[1], and sometimes evacuations, injuries and death are involved, such as the fire at

[1] http://www.abc.net.au/news/2014-11-25/residents-evacuated-after-fire-in-melbourne-cbd-apartment-build/5914978

the Parkview Towers in Pittsburgh[2], or the tragic fire at Grenfell Tower in London[3]. In the first case, the fire started on the second floor, people *"evacuated calmly"* and the fire commander commented that they were fortunate and that *"this is a fairly new high-rise building so it's sprinkler-protected."* At the Parkview Towers, the building was occupied by many senior citizens and *"some have disabilities."* Some fire hydrants froze but the main hydrants worked, and the fire chief thought it was helpful that they *"train in the building every couple of years and try to do a walk-through at least once a year."* At the Grenfell Tower, a "stay put" policy was in place that requested residents to stay in their apartments when there was a fire so residents would not hinder firefighters.

The Lacrosse building and the Grenfell Tower were similar in some ways, where the buildings had approximately the same number of storeys, the cladding and cores were similar, the fires began while residents were asleep, and firefighters responded in minutes[4]. There were 72 fatalities at the Grenfell Tower fire, where an evacuation was ordered almost two hours after firefighters arrived; however, there were no fatalities at the Lacrosse building fire, where an evacuation was ordered within minutes of the firefighters arriving at the scene. The Lacrosse building had two sets of stairs for emergencies, sprinkler protection and a building-wide alarm system, while the Grenfell Tower had one set of stairs with no sprinkler protection, or building-wide alarm system. A comparison of the Grenfell Tower and Lacrosse building is shown in Table 2. While the Grenfell Tower failure is largely a consequence of technical failures, in general terms, emergency plan failure and technical design errors are HOEs that contribute to risk resulting in failure.

Building, occupant and fire safety systems	**Grenfell Tower, London (2017)**	**Lacrosse Melbourne (2014)**
Type	High-rise residential	High-rise residential
Floors	24	23
State of occupants	Asleep	Asleep

[2] http://www.post-gazette.com/local/south/2016/12/16/apartment-building-fire-in-Munhall-pittsburgh/stories/201612160178?pgpageversion=pgevoke
[3] http://www.bbc.com/news/uk-40301289
[4] https://www.linkedin.com/pulse/thoughts-grenfell-tower-fire-when-colour-grey-post-6-parts-ed-galea

Fire brigade	Within minutes	Within minutes
Fire safety measures	No sprinklers, No building-wide alarm	Sprinklers Building-wide alarm
Façade system	Combustible cladding	Combustible cladding
Exit stairs	1	2
Evacuation strategy	*'Stay put'*	*Immediate*
Fatality	*71*	*0*

Table 2: Comparison of fires - Grenfell London vs Lacrosse Melbourne

The Grenfell Tower fire event indicates that policy decisions made at the building level can have a significant impact. The "stay-put" policy in place may have unfortunately contributed to loss of life. Maintaining building facilities in preparation for an emergency and executing well-constructed emergency plans reflect the building safety culture and are examples of HOEs that increased risk at Grenfell Tower. The Grenfell Tower fire resulted in a high number of fatalities while fires in buildings where a safety culture was stressed, have exhibited more fortunate outcomes. The building policies, culture, and their relationships to the occupants of a building during a fire event are a complicated system as well, and an understanding of these risks in different scenarios promotes a more holistic approach to fire safety. Table 3 provides a list of possible technical and human failures at the Grenfell Tower.

Technical failures	Human and organizational failures
Fire/Smoke Spread – cladding failure	Is **"stay put'** principle correct?
Smoke control failure	**Inadequate** training
Barrier failure	**Deficient** maintenance
Egress system failure	**Deficient** emergency plan
	Ineffective safety checks
	Incorrect risk assessment
	Poor safety culture

Table 3: What caused the Grenfell failure?

1.2 Overall Aim and Research Questions

The Building Code of Australia (BCA) and the Australian Building Codes Board (ABCB) provide directions for fire engineers to carry out designs and assessments for fire safety in buildings [15]. The numerous complex high-rise buildings in

Australia make it imperative to evaluate fire risks dynamically for the control and prevention of fires to minimize the possibility of large damages. This research is limited to high-rise residential buildings and explores existing methodologies for fire risk assessment and proposes enhancements to incorporate technical, human, and organizational risks.

There are growing concerns that deterministic, performance-based fire engineering designs may underestimate safety levels when compared with prescriptive designs (prescribing explicit requirements that are assumed to achieve implicit objectives) and may lead to inaccurate fire safety levels. Even in most probabilistic fire risk models, failures of technical systems are modelled while there is a paucity in the literature when it comes to analyzing the impact of HOEs. These models rarely consider the variation of occurrence probability in relation to time and have limited dynamic flexibility. Bayesian Network (BN) and System Dynamics (SD) tools incorporate an infinite number of states and consider the response of a system to effects from other systems [16]. BN and SD models provide both probabilistic and dynamic features making them useful for fire risk modelling; however, such research documentation is scarce. Concerns regarding the underestimation of risk in performance-based fire engineering designs and the gap in the existing literature base led to the following research question:

Research Question – *What human and organizational errors are relevant to probabilistic fire risk analysis of high-rise residential buildings?*

To perform realistic and detailed analyses to quantify overall fire risks specifically associated with high-rise residential buildings and simulate consequences under various scenarios, probabilistic scenarios involving HOEs must be identified. The sub-research questions are as follows:

Sub-research question I – *What are the quantitative impacts of human and organizational errors on probabilistic risk analysis of high-rise residential buildings?*

Sub-research question II – *How is risk modelling improved when incorporating Bayesian Network and System Dynamics methodologies into existing probabilistic fire risk analysis of high-rise residential buildings?*

The research questions lead to the overarching research aim as follows:

"To develop an enhanced fire risk model that incorporates technical, human and organizational risks for high-rise residential buildings."

An enhanced model which integrates technical, human and organizational risks (T-H-O-Risk model) and is evaluated to compare risk levels of existing models that focus only on technical risks. It is then possible to quantify the risk contribution of human and organizational errors to overall risk levels in high-rise residential buildings.

1.3 Supporting Literature and Terminology

The existing literature provides a foundation for model development in this research and points to gaps in the literature that this project proposes to address. Every chapter in this dissertation draws on publications that have self-contained literature reviews of research relevant to the associated chapter. To avoid redundancy, this section provides supporting literature and terminology not contained in the subsequent chapters. This includes a discussion on fire risk assessment models, human reliability analysis, risk assessment approaches, and methods.

1.3.1 Fire Risk Assessment Approaches

The Society for Risk Analysis (SRA) defines fire risk as the potential for realization of unwanted, adverse consequences to human life, health, property, or the environment [17]. The primary goal of fire risk assessments associated with high-rise buildings is to determine the consequences to man and the environment of a specific set of scenarios. These scenarios include details of the room dimensions, contents, construction materials, arrangement of rooms in the building, sources of combustion air, positioning of doors, characteristics of occupants, and any other details which may affect the outcome. To measure fire risk, two parameters are commonly used: The first parameter is the expected risk to life (ERL), defined as the expected number of deaths over the building design life, divided by the building population and the building design life. The second parameter is the fire cost expectation (FCE), defined as the expected total fire cost, divided by the cost of the building and its contents. These parameters are calculated and used by building designers making fire safety design decisions. Estimation of risk (for an event) is usually based on the expected value of the conditional probability of the event occurring times and the consequence of the event, given that it occurred. It follows that risk for a building, a process, or any other entity would be the probability distribution of events and associated consequences relevant to that building, process, or entity.

Deterministic and probabilistic analysis are two common methods to perform risk assessment [18]. Deterministic systems are predictable as they follow a known set of scenarios, system reliability or equation. In a deterministic fire engineering approach, worst-case scenarios are considered, and it is assumed that there will be no failure of fire safety systems such as sprinklers or smoke detectors. This results in a failure to account for the reliability of such systems. In addition, uncertainties are not explicitly considered in deterministic approaches. On the other hand, probabilistic fire safety engineering approaches consider all possible scenarios, as well as their consequences and likelihood of occurrences [19]. Probabilistic systems include some degree of uncertainty in predicting the behaviour of various components in the system and the system's overall behaviour. This is achieved by defining probability of occurrence to describe the system's components and interactions. In Watts and Hall [20], fire risk analysis methods are classified into four categories - narratives, checklists, indexing and probabilistic. While the first three categories are qualitative or semi-quantitative, probabilistic methods are considered more informative and provide detailed quantitative fire risk assessments. Probabilistic methods consider data, mathematical relationships and varied assumptions and their relationship to underlying risk distributions [21]. However, the determination of the probabilities can be viewed as a subjective process, and subjectivity can be reduced by using real-world statistical and historical data, fire brigade data, event trees, fault trees, consistent methodologies, and expert judgement. Deterministic models (field or zone models) may be used to analyse the consequences of multiple boundary conditions.

A main advantage of a deterministic risk analysis approach is the ease and simplicity of the decision-making process. Calculations are relatively easy and straightforward, and the output results a clear answer indicating if a system is safe or unsafe considering that fire safety measures are 100% reliable. Although there are options to conduct uncertainty analysis, deterministic analysis does not provide a full risk appraisal. A deterministic approach does not require expertise in risk analysis and can be carried out by designers with a good engineering background. While deterministic approaches are often sufficient for a rough indication of internal safety management, they are insufficient for risk communication relating to off-site consequences.

One of the main strengths of the probabilistic approach is that it allows for ranking of the issues and results through sensitivity analysis. It considers all types of uncertainties of subsystem reliability (branch probability of an Event tree) and model inputs and can utilize optimization processes. Additional strengths of probabilistic approaches include:

- Probabilistic methods are usually a cost-effective approach to regulation through FCE analysis because they ensure that resources focus on essential safety issues.
- Probabilistic methods can be used to manage operability and enhance safety.
- Decisions and results can be communicated on a clearly defined basis.
- Even if the generated models are not quantified, its use is beneficial due to its structured approach.
- The absolute accuracy of the data is not an issue if probabilistic approaches are used as comparative tools, thus allowing one to decide between different design or operation alternatives. This is also possible when the amount of available adequate probabilistic data is relatively small.
- For applications in some industries, decision-making on design or operation alternatives may relate to equipment with a relatively high rate

of failure occurrences, thus increasing the statistical significance of resulting probabilistic estimates.

1.3.2 Fire Risk Assessment Methods

Definitions of the system and typical fire scenarios require detailed focus to accurately predict fire risks. Many researchers go beyond the deterministic/probabilistic classification of fire risk analysis methods and develop different classifications for fire risk analysis methods. A brief overview of these methods can be found below [20,21]:

- **Narratives:** Narratives include describing and explaining the fire event after it happened. The main role of narratives is to judge and decide if the risk is acceptable or not by comparing the observed risk with published recommendations. The primary limitations of narratives are that they generally do not include the different effects of HOFs, and they lack sufficient supporting data. This lack of data and the exclusion of HOFs can lead to the development of solutions that are less likely to have the desired effect because they may target the wrong cause.
- **Checklists:** Checklists are used to list fire risk factors, but do not distinguish the importance of these factors. Checklists are good for well-defined systems.
- **Indexing:** Indexing includes assigning values based on experience and professional judgement to selected variables. The main goal of indexing is to reach a value comparable to another assessment or standard. This method is a useful, powerful, and cost-effective tool that provides valuable fire risk assessment, especially when an in-depth analysis is not appropriate.
- **Point Scheme Methods:** Point scheme methods are similar to indexing methods in that they correlate fire statistics with parameters such as building size and fire load. The assignment of numerical values to some of the parameters is difficult, hence the correlations are not as accurate. Another disadvantage of this method is that it is not applicable to novel buildings and techniques.
- **State-Transition Models:** State-transition models (STMs) conceptualize a problem in terms of states, or starting conditions, and the

transitions between states. STMs assign probabilities to each event, which can be subjective in nature. Deterministic models are also used to examine the different consequences of starting conditions.

- **Fire Realm Models:** Fire realm models are considered to be a complex version of STMs and can incorporate simulation runs. These models are mainly deterministic; however, the starting conditions and some additional values are obtained from suitable probability distributions. The overall risk is simply given by the average value of certain output parameters over several runs of the simulation. The advantage of this technique is that the structure of the model can be based on experimental measurements and physical theory.
- **Probabilistic methods:** Probabilistic methods are the most comprehensive and informative approaches to fire risk assessment. They generate quantitative values, typically produced by methods that can be traced back through explicit assumptions, data, and mathematical relationships to the underlying risk distribution that all methods are presumably seeking to address.
- **Failure Modes and Effects Analysis (FMEA):** FMEA is an engineering technique used to define, identify and eliminate known or potential failures of systems, projects, processes and/or services. FMEA is systematic and proactive in nature, where a team evaluates a process in order to identify where and how it might fail while assessing the relative impact of failures. The success of FMEA can be shown when its application is carried out in a team, because the best evaluations are drawn from a set of ideas. The advantages and disadvantages of each approach are identified by quantifying the cost and benefits associated with each approach.
- **Hazard and Operability Study (HAZOP):** HAZOP is a structured technique for system examination and risk management. HAZOP is often used as a technique for identifying operability problems likely to lead to nonconforming products and identifying potential hazards in a system. This technique is based on a theory that assumes risk events are caused by deviations from original designs and operation intents. These deviations can be identified by using sets of “guide words” as a systematic list of

deviation perspectives. This approach is a unique feature of the HAZOP methodology.

- **Event Tree Analysis (ETA):** An ETA is considered a reasonable approach to depict fire scenarios by using the knowledge of the mechanisms by which fire occurs, spreads, and is controlled. All events originate from the starting event, which starts the sequence of events. Event trees can be used to analyze systems in which components involve sequential operations or transitions. The goal of an event tree is to determine the scenario probability based on the outcomes of each event in the chronological sequence of events leading up to this scenario.
- **Fault Tree Analysis (FTA):** The FTA is a top-down approach to determine the likelihood of the failure of a system through mapping the relationship between failure, sub-systems and safety design elements using Boolean logic in the form of 'AND' and 'OR' gates. Fault trees provide a visual representation of this combination of events and are usually performed graphically using a logical structure of AND/OR gates. ETA and FTA methods are often used by the frequentists, as their quantification requires statistical data.

1.3.3 Fire Risk Assessment Models using Technical Factors

This section introduces existing fire risk assessment models. Some are well-established and have been applied in real-life situations, while others are still in the development phase. These models primarily focus on incorporating technical factors into the risk modelling process. The following models are described in further detail along with their advantages and disadvantages and a summary is presented at this end of this section and why the weaknesses and gaps in these models justify the development of T-H-O-Risk Model in this thesis:

1. CESARE-Risk (Australia) [22]
2. FiRECAM [23]
3. FIERAsystem (Canada) [24]
4. CRISP (UK) [25]
5. Lund Quantitative Risk Assessment (QRA) [26]
6. CUrisk [27]
7. FRAMEworks [28]

8. FRIM-MAB [29]
9. BuildingQRA [30]
10. Structured Technical Analysis of Risks from Fire (STAR-Fire) [31]
11. Simplified Approach to Fire Risk Assessment (SaFire) [32]

1.3.3.1 CESARE-Risk

The CESARE-Risk model [22] is a cost-effective risk assessment approach to be used by building officials and consultants to help distinguish the building cost saving design solutions. The Centre for Environmental and Risk Engineering at Victoria University in Australia developed CESARE-Risk to quantify the performance of a building fire safety system with the launching of the performance-based Building Code of Australia in 1996 [33].

It was considered that the primary set of performance-based regulations to be adopted by every Australian state. The BCA is based on four levels of hierarchy:

- Objectives
- Functional statements
- Performance requirements
- DTS provisions and verification methods.

The verification methods are implemented to show that an alternative solution conforms to the performance requirements. Alongside the code, a report with fire guidelines created by the Fire Code Reform Centre (FCRC) portrays methodologies and procedures for a performance-based approach to deal with the plan of the structure fire safety system. The guideline document recognizes the quantitative performance parameters that ought to be implemented to show compliance with the objectives.

The CESARE-Risk model depends on recognizing the modelling of the growth of fire and fire spread in a building and that its link to occupant egress may be separated into two segments. The primary model involves setting up an event tree to describe the building conditions. Given the event of every situation, deterministic models are utilized to compute the fire condition, occupant reaction and evacuation, and the expected number of deaths. The ERL for occupants in a given fire situation is the product of the life loss associated with that scenario by the scenario occurrence probability. The overall ERL in a building is the total of the expected life risks of all scenarios over the expected building life. Likewise, the expected fire cost is the total investment in fire safety systems in addition to the expected property loss from fires in the building over the expected building life. Monte Carlo simulations are used to predict the probability of failure of barriers of different materials (timber, concrete or steel). The model has a high computational burden. The methodology does not take into account human and organizational errors or dynamic analysis during the entire lifetime of the building.

1.3.3.2 FiRECAM

FiRECAM (Fire Risk Evaluation and Cost Assessment Model) is a computer program developed by the National Research Council of Canada (NRCC) in collaboration with Public Works and Government Services in Canada [23]. The program identifies cost-effective fire safety designs of apartment and office buildings that meet the safety requirements of the National Building Code of Canada. FiRECAM calculates the expected number of fire losses and deaths for each scenario considered in the model. These values are then combined with the probabilities of occurrence for the fire scenarios to obtain the ERL and FCE. The ASET/RSET method is also applied to calculate the consequences for each scenario. In other areas such as human behaviour, conservative assumptions have been made, hence the model appears to be very conservative in particular when risk is evaluated in absolute terms. Another peculiarity of the model is the separation between risk and costs. The costs of human losses are not addressed here, as only the costs of safety systems and their maintenance are considered. A model for calculating the response time of the Fire department is also present. For human behaviour during evacuation, the Occupant Response Model calculates the response probability for the occupants, based only on the different types of warning. No psychological or social insights are provided and accounted for in the submodel as the model does not consider human and organizational errors or time varying risks.

1.3.3.3 FIERAsystem Model

The National Research Council (NRC) Canada ~~has~~ developed a computer model called FIERAsystem (Fire Evaluation and Risk Assessment system) to evaluate fire protection systems in industrial buildings [24]. FIERAsystem Model is a computer software developed from previous FireCAM model that extends its application to aircraft hangars and warehouses. The outcome of the method is the Expected Number of Deaths, calculated as the product of the residual population of each compartment and the probability of death for occupants in a compartment due to the effects of being exposed to high heat fluxes and hot and/or toxic gases. The model does not support a detailed probabilistic analysis; on the other hand, it takes into account the process of perception and interpretation of the occupants for the calculation of the evacuation time. The model primarily focuses on warehouses and aircraft hangars [21]. FIERAsystem was intended to be implemented as a tool for performance-based fire protection engineering design. There are several calculation options provided by FIERAsystem which allow the user to run individual sub-models, use standard engineering correlations, and conduct a risk or hazard analysis. The standard engineering correlations are a collection of relatively simple equations and models that can be used to quickly perform simple fire protection engineering calculations, including procedures for calculations in the general areas of fire development, plume dynamics, smoke movement, egress, fire severity and ignition of adjacent objects. The assessment is purely qualitative in nature and relies on analytical equations, correlations, and CFD calculations. Neither sensitivity or uncertainty analysis is performed. The model does not consider human and organizational errors, nor risk variations over time.

1.3.3.4 CRISP Model

Fire Research Station developed CRISP (Computation of Risk Indices by Simulation Procedures) to assess fire risk based on simulation models and Monte Carlo methods [25]. CRISP includes mechanisms representing chemical and physical process of fire development as well as occupants' fire escape behaviour. Random parameters are handled by statistical techniques based on Monte Carlo methods. The sub-models representing physical objects include rooms, detectors, items of furniture, doors, windows, smoke layers and people. Stochastic aspects include starting conditions as to whether doors and windows are closed or opened, the number, type and location of people in the building, the location of the fire and the type of the burning item. The submodel is used to represent the behaviour of the occupants during evacuation, and a specific list of rules is elaborated for human behaviour in domestic dwellings. The perception of the fire is modeled simply by assuming specific threshold of the compartment conditions. Flexibility of the system due to the object-oriented approach adopted is a plus of the method. It is deterministic in nature and does not include sensitivity or uncertainty analyses. The model does not consider human and organizational errors outputs risk variations over time.

1.3.3.5 Lund Quantitative Risk Assessment (QRA) Method

Two fire risk assessment approaches using QRA methods were developed by Lund University: Standard Lund QRA and extended QRA [26]. The standard QRA is most frequently used in describing risk in infrastructure applications and process industries. It is also evident in the area of fire safety engineering, but as part of a more comprehensive risk assessment of a system. Standard QRA does not specifically include uncertainty analysis; an extended QRA must be performed to study the influence of uncertainties in branch probabilities or variables. The advantage of using QRA methods is that a large number of events are investigated. The methodology does not consider human and organizational errors or risk variations over time.

1.3.3.6 CUrisk

Another model, CUrisk developed by Carleton University, Canada, also performs fire risk analysis for commercial buildings evaluating their safety levels. The model consists of several sub-models which deal with different aspects of fire, such as fire development and propagation, smoke movement, human evacuation, and economic impacts [27]. The computer model outputs three parameters: Expected Risk to Life, Expected Risk of Injury and Fire Cost expectation. The approach used for the occupant response model is the PIA (Perception, Interpretation and Action): the response is linked to five states: start of fire, time when fire cues are available, local alarm and smoke detector activation, heat detector and sprinkler activation, and flashover. The position of the occupant in relation to the fire is also an input of the sub-model. A rule-based behavioural system is used to model the evacuation movement. The tool is deterministic, and does not include uncertainty or sensitivity analyses. Human and organizational errors are not considered nor risk variations over time.

1.3.3.7 FRAMEworks

FRAMEworks model was developed through a collaborative effort between the National Institute of Standards and Technology (NIST), the NFPA Fire Analysis & Research Division, and the private consulting firm of Benjamin/Clarke Associates [28] and is specifically aimed at estimating the change in expected fire fatalities per year as consequence of changes in materials, in the context of building content and furnishing. The method calculates both number of casualties and probabilities for a large number of fire scenarios. The consequences are calculated using a computer-based hazard assessment method, while probability is taken from statistical data. The occupant evacuation time is calculated on the basis of their initial status (asleep, awake, impaired) and information on ages, sexes and relationships in order to define their speed of movements and behavioural decision rules. The method relies extensively on the expert judgement of the analyst and it is not standardized. Given its focus on the fire ignition and development, it can be used as 'scenario generator' for specific materials in specific contexts (as for example for upholstered furniture in residences), for which the model has been partially validated. The methodology does not consider human and organizational errors or risk variations over time.

1.3.3.8 FRIM-MAB

The model is specifically created for timber buildings and is based on the ASET/RSET approach, aiming at ranking the risk on the basis of the time to hazardous conditions and the escape time [29]. There are various parameters involved, to which a weight is assigned by a Delphi panel and the final result is a single index value for the building. The method focuses on both life safety and property loss objectives. The overall repeatability of the model is very good, with the exception of buildings that have external walkways. The advantage of the method is the usability – no hand calculations needed - the main disadvantage is that it relies heavily on expert judgement. Moreover, human behaviour is not explicitly included in the model or a lifecycle evaluation adopted. The model does not consider human and organizational errors or risk variations over time.

1.3.3.9 BuildingQRA

BuildingQRA a software package that provides quantification of the fire damages in term of both life safety and property loss [30]. Results are presented as FN curves and Paybacks periods. The model uses fault trees to deploy the fire scenarios and probability distributions for input parameters. Human and societal errors are not modeled, nor a dynamic analysis could be performed. Monte Carlo simulation and Uncertainty/Sensitivity analysis are not included. Easy of use and integration in a single software are the main benefits. However, the model does not consider either human and organizational errors or risk variations over time.

1.3.3.10 Structured Technical Analysis of Risks from Fire (STAR-Fire)

Structured Technical Analysis of Risks from Fire (STAR-Fire) is based on nuclear industry's risk assessment methods first developed in the nuclear industry and offshore platforms modified to provide fire risk assessment for the design of buildings [31]. Fault and event trees, and balanced modeling of frequency and consequence, are used. Individual and societal risk to life can be assessed with distributions and results are presented in either tables or FN curves. The outcomes can then be used for absolute risk assessment benchmarking with a code compliant risk design. The advantage is that it has been used in various building types such as retail, public, transport, education, and industrial facilities can address life safety, property protection, and business continuity fire safety objectives. The disadvantages are that the model considers only technical factors and does not consider human and organizational errors or dynamic risk variations over time.

1.3.3.11 Simplified Approach to Fire Risk Assessment (SaFire)

SaFire is quantitative risk assessment methodology similar to STAR-Fire [31] above and was developed by [32]. It uses generic fault and event tree and modelling of frequency and consequences to derive at individual and societal risks. Scenarios are defined by fault and event tree analysis, with Monte Carlo analysis of variable. However, sensitivity and uncertainty analyses are addressed through a qualitative narrative. It has the advantage of being deployed in various building types such as retail, public, transport, education, and industrial facilities. The model can address life safety, property protection, and business continuity fire safety objectives. The disadvantages are that the methodology considers only technical factors and not human and organizational errors or computes risk variations over time.

1.3.4 Summary of Fire Risk Models with Technical Factors

The models described in this section have similar objectives, however, the quality of results differ due to the choice of sub-models and approaches employed to reach the desired outcome. An overview of the fire risk models that focus on technical factors is presented in Table 4.

No	Fire Model	Brief Description	Building type	Main features	Advantages	Disadvantages	Is there a 'risk variation over time' analysis	Are they still in use?	How frequently are they used?	How could their use in engineering projects around the world be described?	Reference
1	CESARE-Risk	Fire risk analysis for quantification of the performance of a building`s fire safety system. Simulation Modelling, risk-cost assessment	Various residential buildings - low to high-rise	1. Models the growth and spread of a building fire and its interactions with the occupant egress. 2. Allows for a cost-benefit analysis using the parameters of the Expected-Risk-to-Life and the Fire-Cost-Expectation. 3. Allows comparison of the safety levels of two or more buildings. 4. Beside common approaches for Fire growth and smoke spread, human behaviour, a fire brigade, and a staff rescue model are also included. 5. Monte Carlo simulations are used to predict the probability of failure of barriers of different materials (timber, concrete or steel) 6. High computational burden. 7. Little focus on human behaviour and dynamic analysis.	1. Use of a combination of deterministic and probabilistic approaches for a large number of scenarios (Zhao &Beck, 1997). 2. Provides two decision-making parameters (i) expected risk to life (ERL) (ii) fire-cost expectation (FCE)	1. Only technical factors are assessed. 2. No Human and organizational factors	No	No	Not in use	Not in use	Centre for Environmental Safety and Risk Engineering (CESARE), Victoria University, Australia [22]

2	FiRECAM	Fire Risk Evaluation and Cost Assessment Model. A set of probable fire scenarios through risk-cost assessment	Residential and office buildings	1. Calculates the expected risk to life and the fire cost expectation in a high-rise building. 2. Assesses the expected risk to life to the occupants in a building, as well as, the costs of fire protection and expected fire losses. 3. Calculates the overall risk as sum of individual risk values estimated for many scenarios. 4. Also applies the AST/RSET method to calculate the consequences for each scenario. 5. Makes conservative assumptions especially when risk is evaluated in absolute terms. 6. Separated risk and costs. 7. Only addresses the costs of safety systems and their maintenance and not human costs. 8. Includes the calculation of the response time of the Fire department. 9. The Occupant Response Model calculates the response probability for the occupants based only on the different types of warning. 10. Does not provide any psychological or social insights.	1. The model can be used for determining cost-effective design solutions for the rehabilitation and refurbishment of residential or office buildings. 2. Offers an integrated software package that contains 15 tools. 3. The user can enter input parameters via a single input file, hence, offering user friendliness.	1. Only technical factors are assessed leaving human and organizational factors.	No	No. The project has been superseded by FIERASystem model	Not in use	Published uses of fire risk assessment have been policy analyses and not evaluations of particular buildings.	National Research Council of Canada (NRCC) [23]
3	FIERAsystem	A set of probable fire scenarios through risk-cost assessment	Light industrial buildings	1. Developed from previous FireCAM model that extends its application to aircraft hangars and warehouses 2. Gives an outcome in the Expected Number of Deaths, calculated as the product of the residual population of each compartment and the probability of death for occupants in a compartment due to the effects of being exposed to high heat fluxes and hot and/or toxic gases. 3. The model does not support a detailed probabilistic analysis. 4. It takes into account the process of perception and interpretation of the occupants for the calculation of the evacuation time. 5. The assessment is purely qualitative in nature and relies on analytical equations, correlations, and CFD calculations.	1. The model provides several calculation options: standard engineering correlations, individual models, hazard analysis or complete risk analysis. 2. The fire development submodel is very accurate and can deal with three fire scenarios: liquid pool fires, storage rack fires, t-squared fires.	1. Only technical factors are assessed. 2. No organizational factors are considered. 3. Does not support detailed probabilistic analysis.	No	Yes	Rare, the software is no longer available at the NRCC site	Light industrial buildings (warehouses and aircraft hangars)	National Research Council of Canada (NRCC) [24]

4	CRISP	Computes risk simulation. Simulation models and Monte Carlo method	Two-storey residential buildings	1. Mechanisms for physical and chemical processes for fire development and propagation, as well as, human behaviour in evacuation. 2. The tool is a two-zone model made up of different sub-models, that are linked through object-oriented programming. 3. The model is deterministic with the final outcome of the average value of casualties out of a Monte Carlo simulation representing the overall risk. 4. The approach does not consider the probability of fire ignition. 5. Uses a sub-model to represent the behaviour of the occupants during evacuation with a specific list of rules for human behaviours in domestic dwellings. 6. Assumes specific threshold of the compartment conditions. 7. Flexible system due to the object-oriented approach. 8. Has no sensitivity or uncertainty analysis included. 9. Offers simple usage not considering dynamic effects on the system. 10. Studied for simple floor plans, not for high-rise buildings	1. Flexibility (object-oriented approach) and usability. 2. The model applies to a variety of residential situations. 3. Uses the Monte Carlo approach to evaluate uncertainty	1. Only considers technical factors. 2. Does not consider organizational factors. 3. Does not include sensitivity analysis. 4. Is suited to simple floor plans. 5. Cannot consider dynamic effect.	No	Yes	Frequent	Proprietary, in-house consulting application. The model is used for in-house consultancy by BRE. It is currently not available "off the shelf"	British Research Establishment, UK [25]
5	Lund Quantitative Risk Assessment (QRA)	Quantitative risk analysis. Used in the process industries and infrastructure applications	Transport infrastructure (road tunnel) and Oil and Gas industry	1. Investigates a relatively large number of events. 2. A quantitative model based on a large number of parameters and values. 3. Risk is expressed as Expected Risk to life and Societal risk. 4. Human behaviour is not considered explicitly, both in the evacuation phase and in the assessment of safety system reliability. 5. In the area of fire safety engineering, safety values are not yet available, and much engineering design is based on subjective judgement and decisions. 6. Is novel in its requirement of describing the principal variables as probability distributions instead of as single point values. 7. The extended QRA method add an uncertainty analysis to the standard QRA.	1. The extended version does not require a lot of data to work, it contains also Uncertainty and Sensitivity analysis	1. Does not consider human and organizational factors	No	No	Not used	Not in use	Lund University, Sweden [26]

6	CUrisk	Sub-models study different aspects of fire, such as fire development and propagation, smoke movement, human evacuation and economic impacts	Predominantly for timber-framed commercial building	1. Performs fire risk analysis for commercial buildings evaluating their safety levels. 2. Outputs three parameters: Expected Risk to Life, Expected Risk of Injury and Fire Cost expectation. 3. Uses the PIA (Perception, Interpretation and Action) approach. 4. The response is linked to five states: start of fire, time when fire cues are available, local alarm and smoke detector activation, heat detector and sprinkler activation, and flashover. 5. Considers the position of the occupant in relation to the fire. 6. Uses a rule-based behavioural system to model the evacuation movement. 7. Is deterministic and includes uncertainty or sensitivity analysis. 8. Does not analyse the dynamics of the system.	1. Provides expected risk to life (ERL) and the expected risk injury (ERI) and the expected annual financial cost of fire	1. Does not consider dynamic assessment. 2. Does not include organizational factors. 3. Only considers occupant position relative to evacuation route in human factors.	No	Yes	Rare, the software is no more available at the Carleton University site	Assessment of fire barriers, risk assessment of timber-frame buildings	Carleton University Canada [27]
7	FRAMEworks	Fire Effect Modelling Statistical method. A method for quantifying the fire risk associated with a specific class of products in a specified occupancy.	Change in material in a building. It can be used as 'scenarios generator' for other methods	1. Can evaluate the impact of new or replacement products with baseline figures. 2. Specifically aimed at estimating the change in expected fire fatalities per year as a consequence of changes in materials in the context of building content and furnishing. 3. Calculates both number of casualties and probabilities for a large number of fire scenarios. 4. Calculates consequences using a computer-based hazard assessment method, while probability is taken from statistical data. 5. Calculates the occupant evacuation time on the basis of their initial status (asleep, awake, impaired) and information on ages, sexes and relationships in order to define their speed of movements and behavioural decision rules. 6. Relies extensively on analysts' judgment (Bukowski et al, Fire risk assessment method: description of methodology', NIST, 1990) and is not standardized. 7. Given its focus on the fire ignition and development, it can be used as 'scenario generator' for specific materials in specific contexts (as for example for upholstered furniture in Residences), for which the model has been partially validated.	1. The model can deal with a large number of different fire scenarios, as it is specifically dedicated to fire ignition and development.	1. Only considers occupant position relative to evacuation route in human factors. 2. Relies only on analysts' judgment. 3. Is not standardized.	No	No	Not available	Not in use	National institute of Standards Technology (NIST), NFPA Fire Analysis and Research Division, Benjamin/Clarke Associates [28]

8	FRIM-MAB	A semi-quantitative approach for fire risk assessment in multi-story timber frame buildings	Multi-storey timber residential buildings	1. Specific fire-related parameters are assessed to give a comparative risk value for a building. 2. Provides repeatable and consistent valuations. 3. Is specifically created for timber buildings and is based on the ASET/RSET approach, aiming at ranking the risk on the basis of the time to hazardous conditions and the escape time. 3. Uses various weighted parameters to assigned by a Delphi panel to give a single index value for the building. 4. Focuses on both life safety and property loss objectives. 5. The overall repeatability of the model is very good, with the exception of buildings that have external walkways. 6. Offers high usability with no hand calculations needed. 7. Relies heavily on expert judgement. 8. Human behaviour is not explicitly included in the model. 9. Does not adopt a lifecycle evaluation.	1. High usability and excellent repeatability due to index method. 2. Provides both expected risk to life and fire cost expectations values	1. Human and organizational factors are not included. 2. Semi-quantitative approach and not probabilistic. 3. Does not offer lifecycle evaluation. 4. Not suited to external walkways. 5. Relies heavily on expert judgement	No	Yes	Yes	Only used and applied to timber-frame buildings in the Nordic countries of Sweden, Norway, Finland and Denmark [34]	Iceland Fire Authority Developed by Karlsson & Tomasson [29]
9	BuildingQRA	A software package to assess safety and fire risk for buildings. Probabilistic analysis, Event Tree analysis, Monte Carlo Algorithm	Assessment of the whole building or of a particular design solution	1. Conducts options assessment and cost benefits prioritization. 2. Provides quantification of the fire damages in terms of life safety and property loss. 3. Presents results as FN curves and Paybacks periods. 4. Uses fault trees to deploy the fire scenarios and probability distributions for input parameters. 5. Human and societal errors are not modelled 6. Cannot perform a dynamic analysis. 7. Monte Carlo simulation and Uncertainty/Sensitivity analysis are not included.	1. Easy to use and integrate in a single software. 2. Software includes options assessment and cost-benefit prioritization	1. Only technical factors are assessed. Human and organizational factors are not included. 2. Cannot perform a dynamic analysis. 3. Monte Carlo simulation and Uncertainty/ Sensitivity analysis are not included	No	Yes. Available free from developer's website upon request http://www.fire-engineering-software.com/buildingqra.html	No data available	No data available	Salisbury Fire Engineering [30]
10	Structured Technical Analysis of Risks from Fire (STAR-Fire)	Quantified fire risk assessment for various building types. Generic fault and Event Trees, Balanced modelling of	Retail, public, transport, education, and industrial facilities	1. Based on nuclear industry's risk assessment methods. 2. First developed in the nuclear industry and offshore platforms modified to provide fire risk assessment for the design of buildings.	1. Broad application to address life safety, property protection, and business continuity fire safety objectives for both new and existing buildings	Only technical factors are assessed. No Human and organizational factors	No	No	No	Not available	Charters and Berry [31]

		frequency and consequence. Monte Carlo Analysis									
11	Simplified Approach to Fire Risk Assessment (SaFire)	Quantified fire risk assessment. Generic fault and Event Trees, Balanced modelling of frequency and consequence. Monte Carlo Analysis	Retail, public, transport, education, and industrial facilities	1. Can assess individual and societal risk to life. 2. Can ascertain absolute risk assessment. 3. Uncertainty, safety factors, sensitivity, precision, and bias are addressed through a qualitative narrative.	1. Broad application to address life safety, property protection, and business continuity to provide fire safety objectives for both new and existing buildings	1. Only technical factors are assessed. 2. Human and organizational factors are not assessed.	No	No	Not frequent	Not available	Charters & Wu [32]

Table 4: Overview of some current Fire Risk Models that focus on technical factors in the Literature

Meacham [35] states that models like CESARE-Risk and FiRECAM which are based on the risk-cost assessment have certain conservative assumptions due to the complexity and insufficient understanding of the fire phenomenon and human behaviour. These models are not appropriate where absolute fire risk and loss assessments are required and can be relied upon for comparative assessments and for the selection of a suitable economic fire safety system [16, 35]. Furthermore, the CRISP model is more comprehensive, has a limited scope and applies only to double storey residential buildings [25]. The model is not suitable for high-rise and complex buildings [35]. Chu and Sun [36] and Bengtsson [37] argue that these models rarely consider the variation of occurrence probability with time and are less dynamic. Based on Table 3 above, it can be seen that most risk models are no longer in use for a number of reasons, such as lack of funding, non-portability, complexity, inflexibility to apply to various building types, or non-suitability to different geographical locations. Only BuildingQRA is made available by the fire consulting firm Salisburyfire Ltd [30] while FRIM-MAB is still in limited used for fire risk assessment in timber framed buildings in the Nordic countries of Sweden, Finland, Norway and Denmark within an organization named Nordic Wood [34]. CRISP is used for in-house consultancy by Building Research Establishment (BRE) of the UK. It is currently not available “off the shelf”. FIERAsystem and CURisk are still in use but rarely as these softwares are no longer available online. It is important to note that none of the risk models reviewed above incorporate human and organizational errors or consider risk variations over time in their methodology, hence, the need for this research to develop a new probabilistic fire risk model that integrates technical, human and organizational risks dynamically.

1.4 Human reliability analysis

Human reliability can be defined as the probability that a person correctly performs an activity required by a system in a required time period (if time is a limiting factor) and performs no error that can degrade the system. It highlights the contributions of humans to systems resilience and possible adverse consequences of human errors or oversights. Human reliability analysis (HRA) is the estimation of human errors [38]. HRA does not view human errors as the result of individual shortcomings but as the outcome of contextual and situational factors that impinge on human performance – these factors are referred to as performing shaping factors (PSFs), which either improve or reduce the quality of human performance relative to a benchmark [39]. For HRA, it is necessary to identify those human actions that can influence system reliability or availability [38]. HRA has always been a serious concern for risk assessment analysts and safety engineers due to the subjectivity of current methods used to evaluate human reliability, the uncertainty of the data regarding human factors and the complexity of the human behaviour [40].

Many methods are developed to quantify human reliability and to estimate the probability of a human erroneous action. The Technique for Human Error Rate Prediction (THERP) is the most widely applied technique and was introduced by Swain and Guttman [38]. It is a hybrid approach according to which not only human errors using both probability trees and models of dependence are modelled, but PSFs affecting the operator actions are also considered. The output parameters are 'Task Reliability', representing the probability of the task being executed correctly and 'Recovery factors' that represent the probability of detecting and correcting incorrect task performance. The fundamental tool in the method is a HRA event tree which links subsequent tasks represented as binary decision node (correct or incorrect action) together with their probability of occurrence (called HEP or Human Error Probability). Those probability are estimated on the basis of interview with workers, inspectors, engineers, psychologists therefore they are prone to subjectivity. The estimates are also influenced by PSFs and performance times. The latter is categorized into: time taken to begin a task, time taken to perform a task correctly, and the available time to perform a task correctly. The former are factors that have effects on the human performance. They can be external (equipment design, written procedures, oral instructions, etc.), internal (skills, motivations, expectations, etc.) and psychological and physiological stresses (dependence, population, stereotypes, etc.).

The main reference for the method is the 'Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications' by Swain and

Guttmann [38]. The document explains in detail the entire methodology and contains tables with HEPs for different types of errors. However, THERP, unlike other first-generation models, lacks a well-defined classification system, an explicit model, and an accurate representation of dynamic system interactions. It characterizes each human action with either a success or failure path. In addition, PSFs influence on human performance is quite poorly represented in the model [40]. Such deficiencies led to the development of the second-generation methods for HRA. One of the most popular from the second-generation is the Cognitive Reliability Error Analysis Method (CREAM) [41]. CREAM offers a consistent error classification system and can be used both as a stand-alone method for failure analysis and as part of a larger design method for interactive systems . Precisely, CREAM can be used by risk analysts to i) identify tasks that require human cognition and depend on cognitive reliability, ii) determine the conditions where cognitive reliability may be reduced and establish a source of risk and iii) provide a judgment of the consequences of human performance on system safety which can be used in risk analyses [41].

The most recent development for HRA is 'A Technique for Human Error Analysis' (ATHEANA) [42]. It is based on a multidisciplinary framework that considers both human factors and conditions of the site that give rise to the need for actions and create the operational causes for human-system interactions [40]. The human factors and the influence of site conditions are dependent on each other and the combined effect of PSFs and site conditions that create a situation in which human error is likely to occur, is an error-forcing context (EFC). For providing error probabilities that are consistent with operational experience, the task of HRA quantification must be based on the likelihood of such error forcing contexts, rather than on prediction of random human error in the face of nominal conditions [40].

1.5 Previous Use of Bayesian Network (BN) and Systems Dynamics (SD) model

This section presents literature related to the use of BN techniques for addressing HOEs and SD techniques for addressing the effects of time-based variables on risk. The Bayesian approach is used to estimate probabilistic relationships among the elements of a model, where there is limited knowledge or lack of historical data. It is used in various fields (bioinformatics, artificial intelligence, financial and marketing informatics) to develop decision-making processes based on parameters affected by large uncertainty. For this reason, it has also been used in risk assessment to represent human and organizational variables affecting the safety of a system. Within this approach, the model is described by means of a direct acyclic graph (DAG) whose nodes are the operational variables (for example, human factors) and edges are the relationships between them. Each variable has two or more states and their associated probabilities. The relationships are expressed in terms of conditional probability tables, which relate the state of the child variable to the state of the parent variable. The Bayesian approach thus provides a method for estimating the human and organizational risks that are important components of this research when applied to fire risk modelling.

System dynamics (SD) is an approach to model the nonlinear behaviour of complex systems over time using stocks, flows, feedback loops and time delays [43]. It fits well to problems that involve interdependence, mutual interaction, and feedbacks. The model can be represented as a series of flow charts over time resulting from variables and linkages between these variables. Different from the BN, the relationships among variables are modeled through non-linear, integral and differential equations. Feedback loops and circular links are also incorporated. One drawback of BN is that it is unable to represent dynamic relationships and interactions among components. This limitation is overcome by incorporating SD with BN as an integrated model allowing for time-varying risk parameters in a fire risk model. Initially developed to describe the impact of management rules and policies in an industrial environment, SD is very useful in representing dynamic human behaviour over time in complex systems with strong interdependence among technical, human and organizational factors.

To better understand human behaviour in fires, Zhao [44] developed a simulation model using an SD approach to study decision-making during pre-movement time. Pre-movement is the duration of time between an alarm activation to movement initiation. Concern rate (state of mind depending on factors such as age and gender), mental stress (psychological pressure due to the event) and social factors (interactions such as instructing others) were the human factors included as intrinsic variables into the model. The author argues that a SD approach is needed to reasonably model the uncertainties and complexities of human decision-making. While this example does not directly model risk, it is relevant to this research because the System dynamics approach was employed to develop a conceptual model of human factors in fire evacuation. Zhao [44] used the causal loop diagram to provide a graphic framework that describes the information feedback of human factors in evacuation. Stock flow diagram performed a quantitative estimation of their influence on information interpretation and decision making. Zhao [44] was able to identify the main causes on the whole system with the feedback loops and conduct quantitative analysis on the state changes in the major variables through the simulation model. This research provides important insights that can be translated into a framework for modelling HOEs during a fire event, however it is limited to the pre-movement period and does not incorporate BN.

Bengtsson [37] assessment of the potential of using BN to improve the current fire risk assessment methods indicates that BN has significant benefits. These include the enhanced ability to model inter-connected occurrences and the possibility to model more detailed variables compared to the methods currently used in fire engineering, including ET/FT. TRANSIT is a road tunnel risk assessment tool-based on BN which considers all three main risk contributors in road tunnels including traffic accidents, fires and accidents involving hazardous materials [37]. The model has several flaws, especially the way it handles uncertainty, yet it was applied by Bengtsson for fire risk assessment of Danish buildings due to the flexibility provided by BN. This justifies the need to develop new dedicated fire risk analytical tools employing BN focusing primarily on buildings. In [45], risk assessment of building structures under fire is based on probabilistic concepts with the inclusion of Bayesian network supplemented by decision nodes which make it possible to estimate the expected total risk for both the buildings and occupants and the actions due to the fire. De Sanctis' model [46] considers several influential factors on fire occurrences and provides a better description of the unique characteristics of a building under investigation. This increases the capability of evaluating the robustness and vulnerability of the building. However, the model does not consider uncertainties and makes some rather coarse assumptions. It is also questionable whether the model adequately covers individual differences in building designs which are difficult to incorporate in a single model. Nevertheless, the model indicates how a combination of dynamic and static BN sub-models can be incorporated into a tool which portrays the entire risk of a given building.

Wang et al. [47] provide a comprehensive fire risk model that includes HOEs for offshore platforms. The authors propose a risk model that includes ET/FT methods as well as BN and SD. The model incorporates HOEs, such as not complying with instructions, deficient training, deficient maintenance and inefficient emergency plans. The study found that the two most important HOE factors in offshore platform fires are (i) not complying with instructions and (ii) not having efficient emergency plans were the two most important factors. Although focused only on fires in offshore platforms, the techniques of BN and SD and the inclusion of HOEs makes the research important to this study.

HOEs alter certain nodes in BN which leads to automatically updating the probabilities in other nodes as prior values are changed when new evidences are introduced. Mohaghegh et al. [48] have integrated probabilistic and deterministic modelling techniques in a hybrid approach to modelling airline maintenance systems while including organizational factors. The authors argue that Bayesian Belief Network (BBN) is a natural framework for probabilistic modelling that can be used when "objective data are lacking and use of expert opinion and soft evidence is inevitable." Using the output from the maintenance unit process model, a step-by-step process is described that incorporates organizational safety practices. Model outputs are inputs to FT/ET networks for technical system risk estimates which are then input into a SD model that generates error probabilities for integration into the BBN model.
There are two main advantages in the application of BN while working with HOEs in this study:

1. BN works well when there is limited data, which is the case with HOE data. BN can provide better results if HOEs are included in PRA.

2. BN can accommodate an unlimited number of states compared to ET/FT's binary states. HOEs are not necessarily binary in nature, which makes BN more suitable for the current study.

SD is recommended by Mohaghegh [49] for complex models where analytical solutions are time consuming. SD can incorporate delays and feedback loops to enhance the BBN framework. The author notes that ET/FT models are the primary modelling technique for probabilistic risk analysis but are insufficient to quantify dynamics and non-linearity in the interactions of causal factors for socio-technical risk analyses. Both [48] and [49] provide an important background for modelling development in fire risk analysis, including BN, SD and organizational safety practices, but the modelling has been developed for the airline maintenance industry and remains as proof of concept.

The existing literature points to the significance of probabilistic methods, the need to incorporate BN and SD methodologies, limitations of using overly conservative assumptions, importance of considering uncertainty and lack of analysis and implementation of HOE in fire risk modelling of high-rise residential buildings. This shortcoming in current fire assessment models, that consider only parts of the risk picture within the overall fire processes, leads to somewhat suboptimal designs of fire safety systems. Regulators, or engineers, require more information for designing effective fire safety systems in high-rise buildings. Presently, there are few performance requirements in building safety codes that are quantified in terms of risk to life safety [50]. With a rapid growth in high-rise residential building construction in Australia, the traditional approach of utilizing empirically developed ‘deemed-to-satisfy’ (DTS) regulatory requirements are insufficient to prevent large fire risks and require more rigorous fire safety codes that can only be developed once more detailed risk models are made available. The current research aims to address this gap of a comprehensive risk approach utilizing probabilistic methods, uncertainties, BN, SD and HOEs.

1.6 Organization of Chapters

The thesis consists of an assembly of related chapters that revolve around **four** intricately linked journal papers written during the PhD candidature. Each paper provides an introduction highlighting the reasoning, existing literature and aims of the paper. Consequently, for the information of the reader, some introductory or basic information might be repeated in the journal publications, which was unavoidable due to the publication requirements for each journal paper. Therefore, opening pages, introduction, background and concluding chapters, together with some supplementary materials have been combined with the publication work to unify the thesis. A concept map is provided in Figure 1, which highlights the chapters that contain the publication work. A brief description of each chapter is shown in Figure 1.

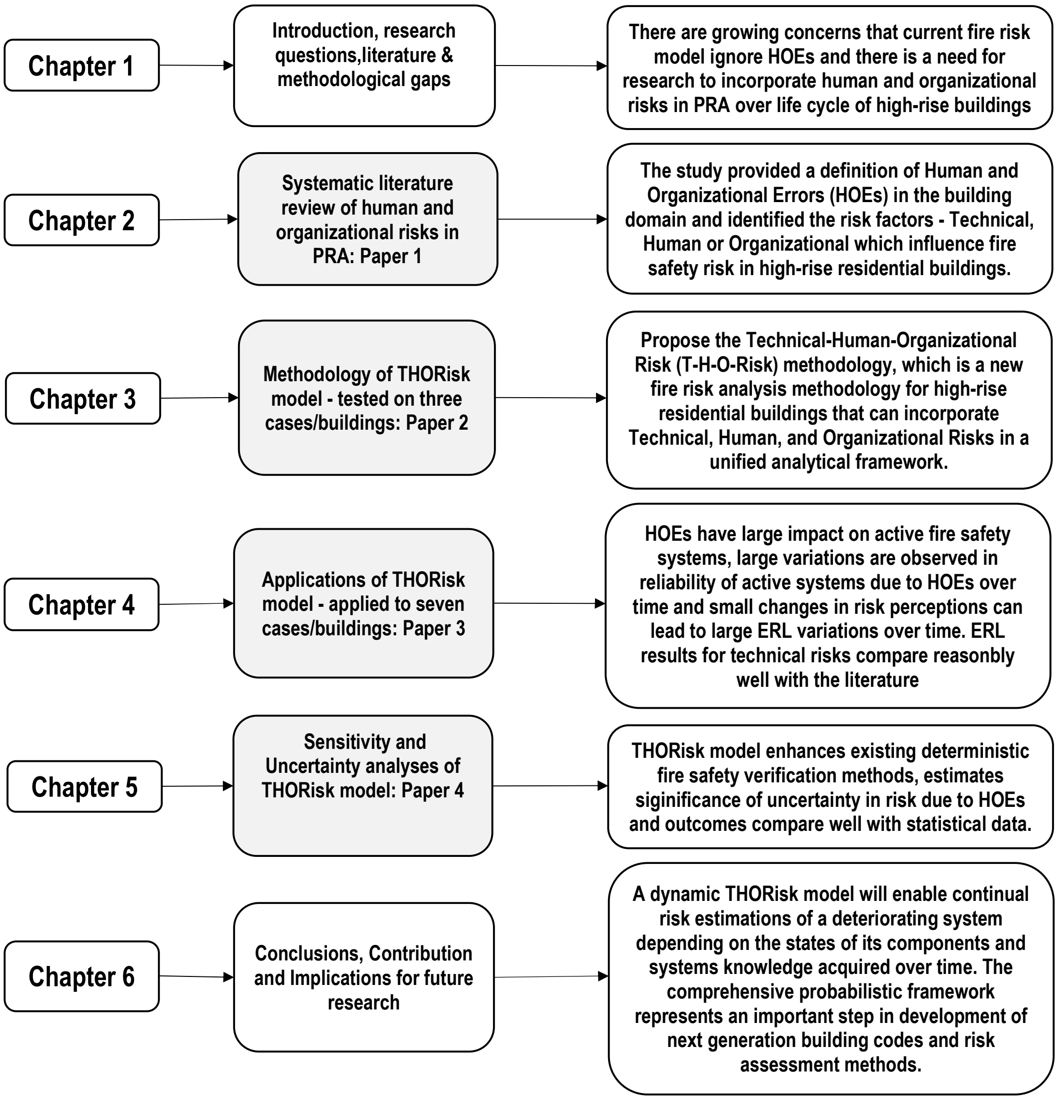

Figure 1: Concept map of the thesis with publication work highlighted in grey.

Chapter 1 provides the introduction, aim, research questions and supporting literature and terminology on fire risk models and approaches. An overview of the methodology framework is also presented. **Chapter 2 (Paper 1)** presents the systematic literature review of human and organizational risks. **Chapter 3 (Paper 2)** articulates the methodological approach and **Chapter 4 (Paper 3)** demonstrates further applications of the model by drilling down to the impact of HOEs on individual active fire safety systems. **Chapter 5 (Paper 4)** addresses sensitivity and uncertainty issues in the risk model and finally, **Chapter 6** closes out the thesis with the main findings, contribution, and recommendations for future work. The chapters are outlined below.

Modelling of fire safety risks in high-rise residential buildings typically includes technical risks and errors, while ignoring the impacts of HOEs may results in significant underestimation of overall risks. This research emphasizes the identification of risks associated with HOEs providing more precise probabilistic risk assessments (PRAs) of high-rise building fire safety designs.

Chapter 2 provides a systematic literature review based on the publication *'Systematic review of human and organizational risks for probabilistic risk analysis in high-rise buildings.'* The paper sets out to define HOEs relevant to the building domain and identifies important HOEs that are prevalent in industries which are critical for fire risk safety in high-rise residential buildings. A five-step process is used in the systematic review that includes framing questions, identifying relevant work, assessing the quality of studies, summarizing the evidence, and lastly discussing methods, results, and findings. A gap in the literature exists when it comes to studies for integrating HOEs in fire risk assessment models for different types of buildings. However, literature related to other industries clearly indicates that existing models that ignore HOEs underestimate risk, possibly by as much as 80%. The pertinent studies in the literature review are ranked according to their relevance to building fire risk resulting in classifications of common HOEs, common staff errors, and common occupant errors. The literature review contains case studies of the Grenfell Tower in London and Lacrosse building in Melbourne fire incidents suggesting that the influential HOEs for high-rise buildings include policy and regulatory factors such as the ineffectiveness of regulatory bodies, competition between public and private sectors, complexity of regulations, and others. The literature review identifies additional factors relevant to fire safety in high-rise buildings regarding deficient training, inefficient emergency plans, personnel not complying with instructions, not checking the rules, deficient maintenance, incorrect risk assessments, not following standards and an improper safety organization or a culture of indifference.

While the literature review makes substantial progress in the identification of HOEs relevant to fire safety in high-rise buildings, it recognizes the absence of empirical quantitative studies, theoretical framework, or guidelines that demonstrate how HOEs risks can be distilled to improve PRAs. To account for limitations in existing fire risk models, two additional methodologies are researched - BNs, a probabilistic graphical method for modelling conditional dependence and SD, a tool for incorporating system behaviour over time. The BN approach has an advantage over conventional ET/FT methods by allowing for interconnections between systems incorporating human and organizational factors. The SD method allows for the inclusion of time-varying parameters that contribute to risk oscillation during the life cycle of a building.

When important consideration of HOEs in the PRA models is established, the next step devises the methodology for their incorporation. Consequently, **Chapter 3** is based on the publication *Incorporation of technical, human and organizational risks in a dynamic probabilistic fire risk model for high-rise residential buildings*. This publication focuses on the comprehensive T-H-O-Risk methodology, developed to enhance the credibility and reliability of PRA models. Analyses of prior research finds hybrid approaches that integrate deterministic and probabilistic modelling perspectives in socio-technical models lead to the development of the T-H-O-Risk methodology. In the model, fire scenarios are simulated in B-Risk[5] to characterise fire initiation, growth. fire and smoke spread. B-RISK is a two-zone fire model preferable to single-zone models due to its Monte-Carlo capabilities that enable uncertainties in fire scenarios to be quantified. Performance thresholds can be indicative of cumulative density functions showing when tenability threshold probabilities are exceeded. It is also determined that field models such as Fire Dynamics Simulator (FDS)[6] are too

[5] B-Risk is a two-zone fire model developed by BRANZ and the University of Canterbury
[6] Fire Dynamics Simulator (FDS) is a computational fluid dynamics fire simulator developed at National Institute of Standards and Technology (NIST)

computationally expensive to implement for probability-based risk modelling. This method quantifies human and organizational risks in a probabilistic model using BN analysis of HOEs and SD modelling for dynamic characterization of the risk variations over time. T-H-O-Risk methodology integrates analyses of building and occupant characteristics, fire safety systems, evacuation, and statistical data. The methodology is flexible and can be applied to a variety of structures, allowing for both relative and absolute risk evaluation. It further addresses the issue of potential underestimation of the risk resulting from the adoption of less demanding maintenance and operational practices along with the life cycle of the system. In addition to providing a tool for quantifying HOEs with multiple levels of analysis and supporting analyses over time, the model accounts for refurbishment activity and interactions with other safety systems that can result in a global loss of safety when these relationships are overlooked. T-H-O-Risk is an incremental risk approach allowing for the quantification of the impact of HOEs on different fire safety systems including the active systems of sprinklers, building occupant warning systems, smoke detectors, and smoke control systems. The methodology enables technical, human and organizational risks to be assessed in multiple fatality number (FN) curves to determine if risk levels meet the tolerability criteria, are situated within the expanded ALARP zone, and whether Cost-Benefit Analysis (CBA) is required.

In **Chapter 3**, three case studies are conducted for the purpose of validation to demonstrate the application of this comprehensive approach to the designs of various high-rise residential buildings ranging from 18 to 24 storeys. These case studies include prescriptive, deemed-to-satisfy (DTS) solutions as per the BCA and performance-based solutions with variations of apartment, retail tenancy and office fire scenarios. It is assumed that retail and office space are present on the first floor, with residents occupying the remaining floors. Smoke detection, sprinkler systems, egress protection systems and fire and smoke spread control systems are the fire safety measures featured in the case analyses. Assumptions are adopted regarding the systems' operability, characteristics of the occupants, and the level of organization. The impact of other parameters including building area and occupancy use on risk levels are incorporated in the ignition frequencies for the case studies and are formulated using the generalized Barrois model [51] in the risk framework. The acceptance criterion proposes that the calculated value of risk be less than the defined expected risk-to-life (ERL) benchmark. Detailed results of the case studies are presented in this chapter.

Chapter 4 draws from the publication *Impact of human and organizational errors on risk and reliability of fire safety systems in high-rise residential buildings - applications of an integrated probabilistic risk assessment model.* The T-H-O-Risk methodology is applied to seven high-rise residential building designs as case studies in **Chapter 4**. The buildings are located in Australia, Hong Kong, Singapore, UK and New Zealand, and the BCA is considered as the reference code for all test cases. The case studies focus on active fire safety systems in high-rise residential buildings by comparing the impact of HOEs on individual fire safety systems and/or combinations of active systems. The active systems considered in the case studies were sprinklers, building occupant warning systems, smoke detectors and smoke control systems. For each of seven buildings (cases), 16 trial designs are considered with various active fire safety systems. Different combinations of active systems lead to a total of (7 x 16=) 112 different trial designs across the seven case studies. The building risk levels are compared to each other and against the absolute benchmark criteria to determine if they exceed the acceptable risk threshold. The quantification of difference in ERL for seven buildings for each of 16 trial designs is a novel aspect of this paper. The ERL for each building design varies in human and organizational scenarios based on either no HOEs or with HOEs - where organizational standards of maintenance, safety culture and emergency planning are determined to be low and human errors occur routinely. Evaluation of the impact of HOEs considers the management strategy on evacuation drills and maintenance activities required for the safety systems to work efficiently.

Chapter 5 is based on the publication *Sensitivity and Uncertainty analyses of human and organizational risks in of fire safety systems of high-rise residential buildings using T-H-O-Risk methodology in high-rise residential buildings.* Chapter 5 addresses sensitivity and uncertainties of the HOEs in the risk model. To determine the impacting factors, sensitivity analysis is present. Uncertainties in the model are analyzed through Monte Carlo simulations. It is noted that the

ERL values are necessarily point estimates, where the probabilities of events occurring do not account for uncertainty. Consideration of the uncertainty inherent in point estimates of HOEs can occur by approximating a range or distribution in which the probabilities lie. T-H-O-Risk is used as a verification method to compare HOEs in a DTS versus performance solution. Furthermore, the T-H-O-Risk model is validated against the risk data derived from statistical and historical data for high-rise building fires.

Finally, **Chapter 6** closes out the thesis by presenting a summary of the research with the main findings of each chapter discussed. Contribution and significance followed by recommendations for future work are also included. Overall, the T-H-O-Risk approach demonstrates how technical, human, and organizational risks are quantified in a comprehensive probabilistic framework representative of an important step in the development of next-generation building codes and risk assessment methods. The results demonstrate that HOEs have a significant impact on overall fire risks in high-rise residential buildings.

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Chapter 2

Systematic review of human and organizational risks for probabilistic risk analysis in high-rise buildings

Overview

Chapter 2 provides a systematic literature review of HOEs in the building domain and sets out to define HOEs and identify important HOEs which are critical for fire risk safety in high-rise residential buildings. The identified HOEs are considered for incorporation in PRAs of high-rise buildings. This chapter uniquely connects HOEs from various industries to likely HOEs associated with risks in high-rise buildings to address an important gap in the literature. A five-step process used in the systematic review includes framing questions, identifying relevant work, assessing the quality of studies, summarizing the evidence, and lastly discussing methods, results, and findings. Literature related to other industries clearly indicate that existing models that ignore HOEs underestimate risk, possibly by as much as 80%. Furthermore, actual case studies of the Grenfell Tower and the Lacrosse building fires identify important HOEs suggesting that influential HOEs for high-rise buildings include policy and regulatory factors such as the ineffectiveness of regulatory bodies, competition between public and private sectors, complexity of regulations, and others.

The lack of understanding about HOEs and how they can be quantified into a holistic PRA for high-rise buildings leads to assessments of studies related to other industry domains. Six relevant studies help build the basis of a HOE risk model for high-rise buildings. This includes fire safety in hotels, metros, offshore oil platforms, oil transportation and air transportation. Furthermore, during the operational phase of a building, the reliability of the fire equipment should not be considered constant and its aging over time must be considered to obtain realistic risk values. Two useful methodologies that have the potential to improve PRAs are identified - BNs, a probabilistic graphical method for modelling conditional dependence and SD, a tool for incorporating system behaviour over time. The BN approach has an advantage over conventional ET/FT methods by allowing for interconnections between systems and the incorporation of human and organizational factors and SD is a method that allows for the inclusion of time-varying parameters that contribute to risk oscillation during the life cycle of a building. BNs are recommended to be employed in the early design phases to model human and organizational risks and to find compensating measures. It is determined that it is viable to integrate technical factors such as aging and maintenance of fire prevention equipment with HOEs in arriving at the risk level. Developing a risk model that includes HOEs and environmental factors, such as building conditions deteriorating over time will enable more realistic estimates of risk in high-rise building fires.

This chapter clearly indicates that incorporating HOEs into a probabilistic fire risk model for high-rise buildings is feasible and is a research area that needs to be explored and understood. An extensive review has suggested that the influence of HOEs on the risk levels in high-rise buildings is important and the policies, procedures (including inspection and maintenance), training, and conditions can impact risk levels during a fire event.

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Review

Systematic review of human and organizational risks for probabilistic risk analysis in high-rise buildings

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ABSTRACT

For fire risk experts, the most parsimonious model is one that identifies errors due to human and organizational factors (HOFs) that can be changed through a series of interventions. This is a difficult task because of the dearth of studies to identify these types of events. However, it is possible to examine and identify human and organizational errors (HOEs) within fire risk situations. Many errors identified in fire risk environments are due to human factors that can be changed through employee training and development. In addition, many organizational factors, such as safety culture, can be changed over time through transformational interventions that shift existing mindsets. This paper presents a systematic review to identify errors due to human and organizational factors that apply to and potentially affect risk estimates in fire safety modelling of high-rise buildings. First, the paper describes the types of errors that occur in fire risk situations and then provides a review that categorizes and links human and organizational factors. The paper is both a qualitative and quantitative review, drawing on research from quantitative studies and case studies, including the Grenfell Fire. The review offers insights and recommendations to incorporate human and organizational risks into probabilistic risk analyses and suggests future directions for research.

1. Introduction

Rule-based safety is implemented in various sectors using procedures, automated mechanisms, protective measures, and training. Managed safety relies on human expertise and quality initiatives where managers can anticipate, recognize and respond to failures. When a planned sequence of actions, or a single action, fails to achieve a predetermined objective, it may be considered that an error existed [1]. Swain and Guttmann classified errors into two classes: errors of omission (errors performing tasks) and errors of commission (cognition-based errors) [2]. For the fire safety context, previous literature has focused on the identification of technical issues yet ignored the human and organizational factors (HOFs) that contribute to fire risk. However, it is critical to consider human errors of omission and commission that increase the likelihood of a fire, the probability of loss, or harm to human life.

Human and organizational errors (HOEs) are a subset of human and organizational factors (HOFs). HOEs are individual and organizational acts which are judged by somebody to deviate from a reference act. They can be subjective and vary with time. On the other hand, human and organizational factors is a common term used within the field of occupational safety. HOFs are factors that affect both individuals and groups and may be external, internal or sociological factors. They include humans and organizations that are involved in the life cycle of an engineered system. HOFs encompass the effects of individual, group and organizational factors on safety. The Health and Safety Executive [3] refers to HOFs as “environmental, organizational and job factors, and human and individual characteristics that influence behaviour at work in a way that can affect health and safety.” The concepts of human factors and human errors are often interchanged in the health and safety field because both refer to the human contribution in the cause of an accident. Allen [4] refers to HOFs as external, internal and sociological factors that influence individuals and teams. These influences can result in HOEs. Teams or individuals can be influenced to make errors by organizations, procedures, and systems. HOEs are therefore outcomes, not causes [5]. Human Errors (HE) that include individual traits, group behaviour, knowledge, experience and management style are departures from acceptable or desirable practice by an individual leading to unacceptable result [5]. Organizational Errors (OE) that include activities such as regulation, compliance, policies and planning are departures from acceptable or desirable practice by a group of individuals leading to unacceptable or undesirable quality. Bea assert that organizational errors have a pervasive influence on human errors [5]. There are four components of HOFs including the organization,

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procedures, structures and equipment and the environment [6]. HOFs can influence the quality and reliability of systems [6]. Stoelsnes et al. [6] argue that understanding HOFs can reduce the prevalence and development of HOEs.

When catastrophic events occur, such as a fatal fire, investigations usually reveal that the cause is not simply due to technical errors. More often, human errors are embedded in organizational and societal processes causing HOEs [7]. In other words, HOEs are multi-level and interdependent with errors and accidents occurring at the individual level while simultaneously contributing to organizational errors. Likewise, organizational culture can contribute to the various types of errors at the individual level. Organizational culture is defined as 'the product of individual and group values, attitudes, perceptions, competencies, and patterns of behavior that determine the commitment to, and the style and proficiency of, an organization's health and safety management [8]. Organizational culture is often described as shared corporate values that influence and affect the attitudes and behaviors of its members. Pate-Cornell [9] defined safety culture as a positive attitude of an organization towards safety measures and an incentive system which encourages operational safety. According to Cooper [10], safety culture is a sub-branch of organizational culture which can affect the attitude of its members in view of an organization's performance with respect to health and safety. Mohaghegh et al. [11] have further elaborated on the term safety culture. They assert that managerial decisions regarding organizational safety practices and structural features are driven by safety culture. However, safety culture can be affected by feedback effects from an organization's safety and financial performances. These effects are part of an organization's learning process. In such a process, the basic assumptions, policies and values resulting in specific performances are first analysed, followed by interrogation with the concerned members and, if necessary, are adapted in the final step [11]. In this study, we focus on HOEs because our emphasis is on individual and organizational problems related to fire risk situations. A focus on HOFs is too broad for this study and the focus on HOEs enables an examination of specific errors made by humans and organizations that contribute to fire risk. In addition, HOEs are outcomes of HOFs rather than causes.

During a fire event, the conditions in the environment, safety measures that are in place, and human behaviour interact to determine the fire response. Response to a fire event is a 'fire response performance', which includes a cue validation period, decision-making period, and movement period [12]. Even though policies and procedures may be in place for a fire event, some policies may not fit an actual fire event. For example, not all mobile people can escape without assistance. There are multiple entities involved in a fire event to consider, including building residents and occupants, building owners, building staff, emergency responders, emergency communications individuals, and support staff for responding agencies. This suggests that the HOEs for fire management in high-rise buildings are different from other buildings and should be identified as so. High-rise buildings are a class of building in which a fire cannot be fought using standard firefighting methods and therefore, require different fire safety measures. The increased number of occupants and height above ground level coupled with limited available stair capacity results in additional length of time needed to evacuate. This mandates a phased evacuation strategy in place of the total evacuation strategy usually adopted for low-rise buildings.

In this regard, this paper aims to identify the commonly accepted HOEs in the existing literature for fire risk assessment with a special focus on applying them to probabilistic risk analysis (PRA). PRA methods allow professionals to estimate risk by computing several scenarios of what can go wrong, the likelihood of the event occurring, and the consequences of the event. Because fire risk is a complex phenomenon, PRA allows the evaluation of multiple factors, so it is a suitable methodological tool. The focus of this literature search will also be on the HOEs related to building residents, occupants and staff, primarily the staff responsible for maintenance, and emergency planning for high-rise buildings. This systematic review will further cover perspectives on the hierarchies of HOEs and their interactions, types of HOEs, and the measures of the impact of HOEs on fire risk. Occupant behavior during a fire event and the methodologies used to categorize occupant behavior are also identified. This paper summarizes HOEs identified in other industries because there is scarce literature on HOEs related to fires in high-rise buildings. However, a focus on HOEs in other industries allows for valid generalizations concerning high-rise buildings.

The novel contributions of this paper include the identification of risks associated with HOEs for consideration in future probabilistic risk analysis of high-rise buildings. While a wide range of HOEs are identified in various industries, not all will be appropriate for high-rise buildings. Important factors are those that emerge consistently from different published sources and are likely to influence risk estimates. Recurring themes and concepts unfold to present HOEs that are likely to be significant for high-rise buildings. Quantifications of the impact of HOEs on risk estimates in other industries justify additional research and inclusion of HOEs for risk estimates in high-rise buildings. This paper uniquely connects HOEs from various industries to likely HOEs associated with risks high-rise buildings to address an important gap in the literature. This paper also includes a review of Bayesian networks and System Dynamics in order to assess effective models for risk analysis of HOEs. It should be noted that this paper primarily utilizes the Australian regulatory framework and codes, possibly limiting the generalizability to other countries yet the paper can still offer useful propositions. The limitations of the findings in this paper revolve around the lack of existing literature specific to quantifiable effects of HOEs on fire risk in high-rise buildings. Prior studies provide estimated effects of HOEs on risk in other industries, and estimated effects of other factors on risks during a fire event in high-rise buildings, but existing literature does not address or quantify the impact of HOEs on risks during fire events in high-rise buildings.

Section 2 provides the methodology and overview of studies on HOEs in fire risk models and evacuation (See Tables 1). In Section 3, a comparison of HOE hierarchies as proposed in the literature are summarized (See Table 2). Details on HOEs and PRA are presented in Sections 3 and 4 respectively. Theoretical frameworks on HOEs and fire risk models are presented in Section 5. Case studies highlighting the role of HOEs in PRA for high-rise buildings are discussed in Section 6, followed by a discussion on factors affecting HOEs with an overview of different studies in Section 7. Sections 8 presents the conclusion and directions for future research.

2. Method

In order to provide an objective and balanced summary for meeting a specific need for information, a systematic review of the literature was adopted in this paper. The systematic review is a way of evaluating and interpreting all existing research relevant to a specific research question, a relevant phenomenon of interest or topic area Brereton et al. [13] define the research papers in a review as the primary studies while the review itself forms the secondary study. Accumulation of evidence through secondary studies can be highly beneficial since it can provide novel insights. For the systematic review, several steps take place since systematic reviews are concerned with the issue of aggregating empirical evidence. Aggregation is of the essence for any evidence-based approach since the aim is to offer objective summaries of existing empirical data. In order to conduct a secondary study as a systematic review, it is paramount to establish a study protocol that minimises bias through defining the way the systematic review is conducted [13]. The systematic review adopted in this paper is based on a step-wise process suggested by Khan et al. [14]. This process comprises five steps of framing questions, identifying relevant work, assessing the quality of studies, summarising the evidence and lastly discussing methods, results and findings.

Step 1. For the first step of framing questions, the main question explored was which HOEs are important for fire safety in high-rise buildings? To provide more details, various sub-headings, keywords, and related areas were also included in the search. We assessed both qualitative and quantitative studies to provide a broad and deep overview to address the research question.

Step 2. For the second step of identifying relevant work, the systematic literature review encompassed researching several databases including ScienceDirect, Elsevier, Taylor and Francis, Sage journals, Wiley, Google Scholar, ASCE Library. The websites of journals included Risk Analysis Journal, Process Safety Progress, IEEE Journal, Building and Environment, Engineering Structures, Fire and Materials, Fire Safety Journal, Fire Technology, Indoor Air, Journal of Hazardous Materials, Journal of Loss Prevention in the Process Industries. The approach adopted was to search for the keywords of Human and Organizational Errors, Fire Safety and High-Rise Buildings. The review was narrowed to the past 15 years, seminal papers that were highly cited and peer-reviewed papers relevant to the objective of this study. Factors discussed in these papers include evacuation and fire-fighting including sprinklers which are important to fire safety in high-rise buildings. Moreover, the reference lists and literature reviews of selected papers were also consulted to identify other studies, that could potentially provide further insights for this paper.

Step 3. To assess the quality of studies, wherever results were identified by reading the paper first through the abstract to reconfirm their applicability, and then through the entire length of the paper. Only peer reviewed journals, conference proceedings, and books from reputable publishers were considered to maintain quality. This process yielded 47 relevant papers and the qualitative and systematic review resulted in pertinent topics as described in the sections that follow.

Step 4. To summarize evidence, the answers to the research questions about HOE factors in fire risk, their impact on controlling the fire risk, and categorization of HOEs were analyzed from the collected data and presented

Step 5. For the last step, the discussion was presented along with the limitations of this review.

Table 1 provides papers that meet the general criteria to be related to fire risk, involve HOEs, HOFs within any environment. Five papers are not directly related to fire risk but involve quantification of HOFs and HOEs with useful implications for fire risk analysis. These are indicated in the last column. The main research methods utilized are literature review, qualitative and quantitative analyses, simulation, fire modelling, expert opinion, and experimental methods. Most papers highlighted human and organizational factors that impacted fire risk, its management, and evacuation behaviours. In Table 1, several studies incorporated a wide range of HOFs while others were more specific. For example, Wang et al. [15] focused on HOFs while Yang et al. [16] modeled specific physical effects in equipment including aging, improper maintenance, and operation. Several studies provide practical implications to deal with fire risks, for example, Hanea and Ale [17] suggest that Bayesian Belief Networks (BBN) can help predict building fire safety levels for more effective fire evacuation.

The reviews are summarized in the following sections and each section addresses a specific aspect of the main research question. Each section concludes with a statement that builds the subsequent section, the summaries add value as this paper develops. The sections will address HOEs and HOFs, PRAs, available theoretical frameworks on HOEs and fire risks, the role of HOEs in PRA for high-rise buildings, factors affecting HOEs, and a section on related studies from various industries. The latter section will address HOEs from diverse domains to strengthen the findings from previous studies and to provide further evidence from the literature review.

For this review, only journal articles were included from selected databases as outlined in Step 2 above. Other articles were obtained through reference list searches. Some articles on HOEs were excluded because their focus was specifically on deep-sea excavations, subways fires, tunnel fires, and simulated contexts for pure quantitative analyses while our focus is on the building industry. There is a lack of substantial empirical studies on HOEs linked to the building industry which affected our final study. The estimation of HOE values and influence is an arduous process as many elements in a building system are impacted by HOFs (e.g. reliability of the fire protection systems depending on maintenance, occupants' behaviour in emergency and in normal conditions, state of the occupants, regulations and policies) and many stakeholders are involved (community, authorities, engineers, contractors, maintenance). It is important to acknowledge that the complex interactions among these variables can have potential limitations on the robustness of probabilistic risk models as these multiple factors of influence do not necessarily have linear relationships due to their feedback loops.

In Table 1, relevance to the main research question is identified in the column marked 'Rel.', signifying the relevance of the paper to the topic of risk analysis for high-rise buildings. A value of '1' denotes papers which were marginally related to the main research question and contained information on buildings and building safety. A value of '2' signifies papers that were moderately related to the main research question, containing information related to accidents or human behaviour during fire events. A value of '3' denotes papers that were significantly related to the research topic containing information on HOEs during a significant fire event. The column labelled HOF affecting risk probability includes the major factors that have been identified by the authors in their respective papers as impacting fire risk analysis.

3. Human and organizational errors (HOE)

3.1. Definition of human and organizational errors (HOE)

In this research, we define HOEs as the collective departures from acceptable or desirable practice by an individual or groups of individuals that may result in unacceptable or undesirable outcomes. We distinguish between human errors committed by staff or occupants. Active failures are those that are directly involved in an accident such as slips, mistakes, and violations whereas latent conditions are failures due to problems in the system [60]. Staff errors are active failures precipitated by a lack of technical knowledge. Occupant errors arise from problems within the system such as ineffective evacuation routes. While HOEs and Performance Shaping Factors (PSF) are interdependent, they are also distinct terms. PSF encompasses all factors related to human performance and these factors can change the likelihood of human error. Consequently, PSF is very broad and encompasses organizational, team, personal, situation, and machine-design and includes both positive and negative effects on human performance [2]. HOEs are considered more specific for this review.

3.2. Hierarchies of HOE

Human and organizational errors are mutually dependent; errors and accidents committed at the individual level contribute to organizational error and organizational culture can contribute to the types and number of errors at the individual level. The Human Factors Analysis and Classification System (HFACS) developed by Weigmann and Shappell [62] provides a four-level analytical framework to analyze HOFs. Tabibzadeh and Meshkati [53] propose a three-level framework for the same purpose of analyzing HOEs. For this three-level framework, a hierarchy of root causes that results in system failure is

Table 1
Overview of studies on human and organizational factors (HOFs) in various risks analyses.

Research by	Rel.	Systems and scenario	Study Population	Transfer to building fires possible?	Qual./ Quan	Measure of Risk Probability	HOFs affecting Risk Probability (RP)	Risk Probability related to fire risk assessment
Kobes et al. [18]	1	Human Behaviour and building safety	Building fires	Yes	Qual.		characteristics of fire, human beings and buildings	Psychonomics has a significant influence on occupants' fire response performances
Wang et al. [19]	2	HOFs in Accidents	All accident investigations	Yes	Both	Fuzzy analytical hierarchy process and decomposition method	HOF	A model to assess the contribution of Human and Organizational Factor (HOF) to accidents
Yan et al. [20]	3	Major subway fire cases	All major subway fire cases in the last 20 years	No	Both	Cause analysis	Equipment, human, environmental, emergency management	a simulation model of subway fire accident rate is constructed
Sun and Luo [21]	2	High-rise buildings	Super high-rise building	Yes	Quan	Risk assessment models	HOF	Risk assessment to guide stakeholders to manage fire
Yang et al. [16]	2	Major urban subways	Subway fire-fighting systems	No	Qual	Content Analysis	Aging of equipment, improper maintenance, divorcement of design, construction and operation, and improper operation of equipment	Suggestions for improving fire-fighting
Baalisampang et al. [22]	2	Maritime transportation industry	Maritime transportation industry	No	Both	Systematic Literature Review	Human error, mechanical failure, reaction, electrical fault and unknown	Alternative fuels like (CrNG), LNG and methanol are more efficient in mitigating fire risk
Sobral and Ferreira [23]	2	Fire sprinkler systems	Fire sprinkler systems	Yes	Both	–	Tests, inspection, maintenance	A methodology to correct maintenance according to dormancy and degradation of sprinklers.
Blum et al. [24]	2	Automatic fire sprinkler systems	Automatic fire sprinkler system failures	Yes	Both	Analysis of occupancies	Mistakes in installation, inspection, and maintenance	Better preparation to investigate and analyze future failures and losses
Moinuddin and Thomas [25]	2	Wet pipe sprinklers	High-rise office buildings in Australia	Yes	Both	Literature review & Survey	Sprinkler zone shut off during tenancy changes and out of specification sprinkler head	Suggestions to improve the reliability of sprinkler systems
Chen et al. [26]	2	Hotel buildings	Hotel buildings	Yes	Quan.	Case studies	Space limitation and high construction costs	A simple fire safety evaluation system for existing multi-purpose hotel buildings
Meacham [27]	2	Fire safety design	All fire safety design	Yes	Qual.	Literature review	Fuel type, loading, configuration, and location, human factors	Improvements in fire safety management plans
Demers and Jones [28]	3	Evacuation Drills	Buildings	Yes	Qual.	Literature review	Assumed role, experience, education, personality, perceived threat, actions of others.	Improvements in planning and execution of fire drills.
Ramachandran [29]	3	Fire risk and safety in buildings	Buildings	Yes	Quan.	Statistical and probabilistic models, regression methods, probability distributions, fault and event trees and stochastic models	All factors affecting fire risk	Applying quant. models to improve fire risk and safety
Li et al. [30]	1	Buildings	6-storey residential building	Yes	Quan.	CUrisk	Smoke Movement, Fire Spread and Fire Growth, Occupant response and evacuation	Application of CUrisk to a residential case study.
Hanea and Ale [17]	1	Buildings	Residential buildings in Netherlands	Yes	Quan.	Risk assessment models	Location, structure, loading of the building, types of fire protection systems inside the building, & characteristics of the fire brigade	Bayesian belief nets can help predict building risk analysis
Gwynne et al. [31]	2	Egress Drills	All buildings	Yes	Qual.	Review of literature	Financial, ethical, methodological, statistical, third-party, pedagogical	Pros and cons of egress drills to improve them.
Lovereglio et al. [32]	2	Pre-evacuation behaviour	All buildings	Yes	Quan & Qual	Evacuation modelling	Environmental and social cues, demographic characteristics of evacuees	An Evacuation Decision Model predicting pre-evacuation behaviour is introduced
Lovereglio et al. [33]	2	Pre-evacuation behaviour	Cinema Theatre	No	Quan & Qual	Evacuation modelling	Time, occupant's position, social influence	Applying random utility theory to a case study to improve pre-evacuation behaviour.
Kuligowski [34]	2	Occupant behaviour during evacuation	Application of model to building fires	Yes	Qual	Engineering hand calculations and computational tools	–	

(*continued on next page*)

Table 1 (*continued*)

Research by	Rel.	Systems and scenario	Study Population	Transfer to building fires possible?	Qual./Quan	Measure of Risk Probability	HOFs affecting Risk Probability (RP)	Risk Probability related to fire risk assessment
								A model of occupant decision-making during emergencies -the protective action decision model (PADM)
Chen et al. [35]	3	Fire safety in ultra-high-rise buildings	Ultra-high-rise buildings	Yes	Quan	Risk assessment	Occupants' and elevators' evacuation efficiency	Reveals the dynamics of elevator assisted evacuation
Ding et al. [36]	3	Elevator evacuation in high-rise buildings	High-rise buildings	Yes	Both	Experiments	Elevator loading and unloading time, time to open, and close elevator doors, number of evacuees, smoke, shapes of queuing	Suggestions, such as the width of doors and the design of elevator lobbies for improving evacuation through elevators
Devlin [37]	2	Risk assessment in high-rise buildings	Nakheel Tower, Dubai	Yes	Both	Case study	–	Risk of death from fire in Nakheel Tower is 15 times less than any other code-compliant building.
Wang et al. [15]	3	Offshore fire and explosion	Jet fire on offshore platform	No	Quan	Hybrid causal logic model with event tree, FT, Bayesian network, and system dynamics	Human factor "not comply with instruction" and Organizational factor "inefficient emergency plan" have the highest influence.	A hybrid logic model to analyse offshore fire risk with HOEs.
DiMattia et al. [38]	3	Offshore oil and gas production platforms	Man overboard, gas release, and fire and explosion	No	Both	Expert opinion of 24 judges	Stress, complexity, training, experience, event factors and atmospheric factors	Probability of success for 18 muster actions for temporary safe refuge
Krueger and Smith [39]	2	Large offshore design projects	Gas Jet Fires in Gulf of Mexico	No	Quan	Scenario-based approach	Credible fire scenarios, platform process equipment, structural members, egress routes, safety systems, and effectiveness of potential options for mitigation	Selection of an optimum safe design for offshore platforms
Norazahar et al. [40]	2	Offshore oil and gas industry	BP Deepwater Horizon accident	No	Qual	Qualitative analysis	Organization, personnel's competence, the evacuation procedures, and the emergency equipment	Insufficient emergency drills, poor communications, impairment of personnel's physical ability due to unsafe conditions, and poor emergency preparedness planning led to failure in evacuation
Ugurlu [42]	2	Tankers transporting hazardous liquid cargoes	Fire & Explosion events between 1999 and 2013	No	Quan.	FTA and FEAHP method	Violation of work permits and a lack of risk analysis	Enhancing training standards and safety awareness and reducing the commercial pressures on ship operations can enhance safety.
Beck and Zhao [43]	2	Building Fire safety Design	3-storey apartment building	Yes	Quan.	Quantitative analysis	Risk to life safety parameter and an economic parameter	Model predictions match statistical data comparatively.
Frantzich [44]	2	All buildings	Hospital Ward	No	Both	ET, sensitivity analysis, uncertainty analysis	Societal risk, individual risk	Use of design values in deterministic equations for fire safety design
Zhang et al. [45]	2	Large steel structures	Gymnasium	No	Quan.	Steel-temperature rise model and evacuation model	Smoke thermal radiation and convection, flame thermal radiation; distance from the farthest point to the safety exit, personnel evacuation speed, width of evacuation exit, and density of personnel	Valuable references to fire simulation, hazard assessment, and fire protection design
Meacham [46]	2	Building regulatory Systems	–	Yes	Qual.	Literature review	Consultation, dependence on expertise, self-regulation, political consideration	A new process for building regulation development is required.
Van Weyenberge et al. [47]	2	PRA	A five storey commercial shopping mall of 25,000 m^2	Yes	Both	Probabilistic risk assessment	Failure probabilities, individual risk, societal risk	Use of an integrated probabilistic risk assessment methodology to quantify the life safety level of occupants in building. Combined deterministic sub-models and probabilistic techniques with failure probabilities, response surface model and providing measures of individual and societal risks. Model allows for comparative risk analysis of various fire safety measures in a large building.

(*continued on next page*)

Table 1 (*continued*)

Research by	Rel.	Systems and scenario	Study Population	Transfer to building fires possible?	Qual./ Quan	Measure of Risk Probability	HOFs affecting Risk Probability (RP)	Risk Probability related to fire risk assessment
Skogdalen and Vinnem [41]	1	Oil and gas industry	Norway and UK Oil and gas industry	No	Quan.	Risk assessment models	HOF	HOF play an important role in the Norwegian and UK legislation. HOFs must be modeled and their role as safety barriers must be revealed to fulfill the legislation requirements.
Ren et al. [48]	1	Offshore Safety Assessment	UK Offshore Safety Assessment/Case study	No	Quan.	Reason's "Swiss cheese" model and Bayesian Network (BN)	HOF	The "Swiss cheese" model developed by Reason is a theoretical framework based on solid behavioural theory and can be used to provide roadmap for BN modelling. The proposed framework is a promising methodology to meet the challenges of modelling HOFs in offshore operations.
Stoelsnes et al. [6]	2	Design, construction and installation of engineered Systems	Different Engineered Systems/2 Case studies	Yes	Both	Traditional quantitative risk analysis/ SMAS (Safety Management Assessment System)	Errors in design, construction and installation phases	Reduction of human error incidence occurrence through study of the HOFs in the different phases of the engineered systems.
Aven et al. [49]	1	Offshore installations	Bora project	No.	Quan.	Barrier block diagrams, event trees, fault trees, and influence diagrams	Loss of containment, ignition,cloud/ emissions, escalation and fatalities	Operational risk analysis reflecting specific factors as technical systems, technical conditions, and organizational factors should be carried out in the offshore industry.
Trucco et al. [50]	2	Maritime industry	Maritime Transport System (MTS)	Yes	Quan.	Bayesian Belief Network, Fault tree analysis	Collision, grounding, contact and striking events.	The approach allows for identification of probabilistic correlations between the basic events and the Bayesian Belief Network model. Not directly related to fire risk but involves HOE in certain environment.
Mohaghegh [51]	2	Socio-technical systems	Aviation safety domain	Yes	Quan	Bayesian Belief Network, Probabilistic Risk Analysis, System Design	Plane crashes and accidents due to manufacturing and maintenance errors.	Combining Bayesian Belief Network and System Design can compensate for the deficiencies of it, which include not capturing the dynamic aspects including feedback loops and delays. Not directly related to fire risk but involves risk assessment of organizational factors and human errors which are applicable to fire systems.
Grabowski et al. [52]	2	Complex, large-scale systems	Marine transportation in Puget Sound	Yes	Qual.	Literature review	Poor quality of data gathered, immaturity of the gathered data, poor training and background of the investigator and reporter	Large organization need to find a method to ensure quality and accuracy of data gathered as it has tremendous effect on event analyses. Not directly related to fire risk but involves HOE in a certain environment
Tabibzadeh and Meshkati [53]	1	Oil and gas	Deepwater Horizon accident	No.	Qual.	Conceptual model which consists of 3 layer: Physical state of the system, decisions/actions in the middle and the organizational factors on top/	Misinterpretation of a critical test, well integrity, oil and gas drilling, high risk operations	Organizational factors are root causes of accumulated errors and questionable decisions made by personnel or management. This paper is not directly related to fire risk but involves HOE in management systems which can be related to fire systems.

(*continued on next page*)

Table 1 (*continued*)

Research by	Rel.	Systems and scenario	Study Population	Transfer to building fires possible?	Qual./ Quan	Measure of Risk Probability	HOFs affecting Risk Probability (RP)	Risk Probability related to fire risk assessment
Kinateder et al. [54]	2	Fire evacuation behaviour	Generic	Yes	Qual.	Literature Review	Fire emergency, evacuation	The HoF that influence perception of risk in fire evacuation are summarized.
Van Coile et al. [55]	2	Fire risk analysis		Yes	Quan.	Maximum Entropy Multiplicative Dimensional Reduction Method (ME-MDRM)	Risk Assessment	Application of ME-MDRM to probabilistic structural fire safety engineering.
Sakurahara et al. [56]	2	PRA for failure mechanisms	Yes	Nuclear Power Plants	Quan.	Integrated PRA	Risk Assessment	An integrated PRA of physical phenomena and human actions help identify system-level risk scenarios.
Wu and Huang [57]	2	Accident causation model	Yes	Tianjin Port	Quan	Accident causing model	Risk Assessment	IF-based Accident causing model (IFAM) can provide a fresh perspective to system safety investigation.
Li et al.[30].	2	Application of Bayesian Network	Yes	Fire incidents	Quan	PRA and simulations	Risk Assessment	A new BN model which looks at initial fire development and occupant response and further fire development.
Hanea et al. [58]	2	BN model	Yes	Schiphol Cell Complex, Amsterdam	Quan	Probabilistic analysis using BN	Risk Assessment	BN model can help design safer buildings by estimating possible fire outcomes.
van Gulijk et al. [59]	3	Chemical Process Plants	High hazard industries	Yes	Quant	Rapid risk analysis tool	HOF	Rapid risk model integrates both technical and human performance for prevention of process leaks. Safety effects of technical failure, human failure and organizational failure are directly modelled through appearance of leaks.

Note:
1 - Rel. is the relevance of the paper for HOEs in fire risk analysis with 1 for least applicable and 3 for the most applicable studies.
2 - Systems and Scenario: The scenario in which the study is based.
3 - Transfer to building fires possible?: The applicability of the findings to building fires.
4 - Qual/Quan: Research approach of the study, qualitative or quantitative.

Table 2
Comparison of HOE hierarchies proposed in the literature.

Tabibzadeh and Meshkati [53]		Dan et al. [61]		Wiegmann and Shappell [62]		Mohaghegh et al. [11]	
Level 1	Basic events level: physical state of the system	Cat 1	Personal characteristics factor: at the individual level and includes the knowledge, skills and personal behaviour of the staff.	Level 1	Identify unsafe acts that directly lead to accidents, errors by operators and directly lead to an accident	Level 1	Individual personal safety factors, human errors from lack of experience, including psychological factor of motivation and personal capabilities
Level 2	Decisions/actions level: associated with failures to follow procedures	Cat 2	Job characteristic factor: involving the quantity of work and the conditions in the work environment including safety equipment, workload management and environmental conditions	Level 2	Preconditions for unsafe acts, identification of influences leading to errors at Level 1	Level 2	Group climate influenced by direct managers attitudes towards safety procedures
Level 3	Organizational level: revolve around procedures and a safety culture			Level 3	Unsafe supervision, management errors in oversight, staffing and communication	Level 3	Organizational climate, the aggregated perceptions of individuals and groups
		Cat 3	Organizational factor: relates to a company-level safety culture and incorporates reporting, training, communication and contracting.	Level 4	Organizational influences, the safety culture including enforcement of safety standards, inspections and safety awareness	Level 4	Organization structure and practices that result from an overall organizational safety culture

developed. Gonzalez Dan et al. [61] have developed three categories of human factors. Yan et al. [20] classified HOEs as groups of environmental, human, emergency and equipment factors, though these factors were not identified as hierarchical. In addition, there are interrelationships between the factors that contribute to an increasing or decreasing probability of an accident.

Although the researchers adopted different categories and numbers of levels, it is noticeable that the categorization of HOEs is somewhat common and consistent. Consequently, it can be concluded that there are interactions between the hierarchy of levels of HOEs as it is presented in Table 2. The reason behind opting for organizational category and two types of individual categories for classifying HOEs is that most studies in the literature did not encompass both staff/operators and occupants which are individual level factors.

3.3. Common HOEs

Regarding organizational factors, safety culture or safety climate of an organization was the most common factor present in most of the studies (see Table 3). Safety culture can be influenced by management yet is not necessarily top-down driven and it appears to impact the procedures, plans, and communication functions. Building staff at a high-rise facility may or may not be present during a fire event, however, they are responsible for activities that can impact risk. The most common errors were related to complying with instructions and obeying standards. Other common staff error factors include waiting to sound the alarm, selecting improper or incorrect equipment, making the wrong risk assessment, a lack of experience, a lack of training, making errors during repairs and a complacent attitude. Occupant error factors include occupant characteristics and their behaviours during a fire event. Common occupant errors include trying to fight the fire or otherwise delaying the evacuation, maintaining higher occupancy levels than reported, tampering with fire detection devices and storing flammable materials on the property. We have highlighted the most common organizational errors, presented in Table 3, and the most common individual errors found in the literature in Tables 4 and 5 for the staff and occupants respectively. Each table has errors grouped into their associated category, containing external, internal and sociological factors, reflecting the usage of the concepts in the literature. These categories of factors resulted in the corresponding errors or outcomes.

4. Probabilistic risk assessment

In order to improve the effectiveness of the analysis and to identify important HOEs that can influence high-risk fire situations, this section considers how PRA can be utilized in a real-world environment. PRA is a comprehensive methodology to evaluate risk in complex engineered systems such as nuclear plants, offshore platforms or high-rise buildings where risk is characterized by the severity and likelihood of an occurrence of a possible adverse consequence. PRA models are used to look at the frequency and consequences of not achieving a safe, stable end-state. The technical bases of the PRA model are multiple sources of information from the traditional engineering disciplines, understanding the initiating event and how the system responds to it. Event trees are normally used to determine frequency and probability of outcomes deriving from an initiating event. While an event tree models the chronological or causal sequence of events from fire ignition to an end state, a fault tree represents the chain of circumstances that lead to the failure of safety systems. Fault trees are useful in predicting the reliability of the mitigating equipment and they provide useful data to compile an Event tree. The outcome from this step is a frequency or a probability, which is the first term in the expression for risk quantification. With the PRA, the risk is defined in terms of frequency and consequences or the failure probability as follows [86]:

Table 3
Common human and organizational errors (HOEs).

Category	Errors	Reference
Training policy	Lack of a safety culture	Guldenmund [63]
	Optimism that nothing will happen	Paté-Cornell [9], Kuliogowski [34]
	Insufficient or deficient training	Reason [60], Paté-Cornell [9], Dhillon and Liu [64].
Maintenance plan/procedures	Lack of operational experience	Aven [65], Paté-Cornell [9],
	Inadequate maintenance procedures	Paté-Cornell [9], Reason [60].
	Deficient maintenance	Paté-Cornell [9], Watts and Hall [66],
Inspections/checks	Infrequent or non-existent inspection of devices	Strauch [67].
	No check rules	Paté-Cornell [9], Mohaghegh-Ahmadabadi [68].
Emergency plan/procedures/drills	Inefficient emergency plans	Meacham [27], Chen et al. [26].
	Lack of emergency drills	Zhang et al. [69],
Economic or financial pressure	Economic pressures that conflict with safety culture	Paté-Cornell [9],
	Errors in design	Frantzich [44], Paté-Cornell [9],
	Errors in installation	Frantzich [44], Meacham [27]
	Errors in maintenance	Paté-Cornell [9], Frantzich [44], Kuligowski [34]
Communication of procedures	Poor communication of procedures in case of fire emergency	Watts and Hall [66], Paté-Cornell [9]
Contracting/sub-contracting	Third party contracts for implementation of fire emergency plans	Meacham [27], Zhang et al. [69]
	Lack of knowledge exchange	Kobes et al. [18]
Equipment replacement	Selection of inappropriate fire-fighting equipment	Chen et al. [26], Paté-Cornell [9],
Aging of buildings	Building deterioration over time	Reason [60], Meacham [46]
	Increased vulnerability to fire	Hanea and Ale [17], Ramachandran [29]

Table 4
Common staff errors.

Category	Errors	References
Sound of the alarm	Ignoring clear indications such as flames and smoke	Bruck [70]
	Waiting for alarm to ring	Moinuddin et al. [71], Meacham [27]
Equipment selection	Selection of improper equipment in case of fire incident	Launder and Perry [72].
Risk assessment/calculations	Using incompetent models	Frantzich [44], Jae et al. [73],
	Choice of wrong parameters	Dallat et al. [74],
	Wrong assumptions	Lindell and Perry [75], Sekizawa [76]
	Wrong risk assessment	Mohaghegh-Ahmadabadi [68], Frantzich, [44],
Experience/training	Lack of awareness/knowledge	Daniellou et al. [1], Kobes et al. [18], Wang et al. [19]
Testing, monitoring and performing maintenance	Negligence towards routine checks, inspections and maintenance	Aven [65], Paté-Cornell [9]
Attitude/motivation	Overconfidence	Cheng et al. [77],
	Optimism that nothing will happen	Paté-Cornell [9], Kuliogowski [34],
Repair	Errors made during maintenance	Paté-Cornell [9], Frantzich [44], Kuliogowski [34]
	Errors in electrical maintenance procedure can lead to electric arc and overheating	Dhillon and Liu [64], Reason [60]
Instructions/standards	Not following instructions or standards set for routine or emergency procedures	Meacham [27], Chen et al. [26]
	Violation of smoking prohibition	Shults [78], Butry and Thomas [79].

Table 5
Common occupant errors.

Category	Errors	References
Occupancy of apartments	Higher occupancy levels than expected	Jennings [80]
	Clusters of family members cohabitating	
Flammability of materials	Presence of highly flammable liquids/ignitable materials	Sun and Luo [21] Ramachandran [29]
Alarm	The fire alarm is for a fire drill	Bruck [70], Proulx [81]
Fire-fighting	Initial attempt to put the fire out using water	Kobes et al. [18]
	Self-help instead of evacuating	Kinateder and Kuligowski [54]
Rescuing/re-entering the building	People may re-enter the building if there is an emotional attachment to items/ inhabitants	Ronchi and Nilsson [82]
Warning others	Failure to alert others	Groner [83]
Gathering belongings	Delaying evacuation due to gathering of belongings	Demers and Jones [28], Proulx [81], Kuligowski [34]
Information seeking	Seeking first response information	Kinateder et al. [54]
Egress Movement	Moving to wrong exits	Gwynne et al. [84], Gwynne [31],
Elevator usage	Overloading elevators	Chen et al. [35], Ding et al. [36]
Tampering of fire safety provisions	Covering smoke and heat detectors to avoid false alarms	Liu and Kim [85]
	Fire extinguishers made unreachable due to objects impeding their access	Kobes et al. [18]

$$Risk\left[\frac{Consequence\ magnitude}{Unit\ of\ time}\right] = Frequency\left[\frac{Events}{Unit\ of\ time}\right] \times Consequences\left[\frac{Magnitude}{Event}\right]$$

The above equation could be adapted for the building domain in the following form:

$$ERL = \sum_{i=1}^{n} P_i x\ C_i$$

where,

ERL is the expected risk in term of probability of death per year

P_i is the frequency of the i-th scenario

C_i is the number of deaths for the i-th scenario

In the context of Australia, each building design must comply with either the Deemed to Satisfy (DtS) provisions or the underlying Performance Requirements of the Building Code of Australia (BCA) [87]. Performance-based building designs step away from prescriptive rules to offer more flexibility to adopt new technologies and innovations in aesthetics, materials, energy efficiency and spatial usage. The PRA approach is an explicit method to comply with the Performance Requirements [66]. Although not used extensively, PRAs have been employed in fire safety engineering in Australia since the early 1990s [88]. The Australian Building Codes Board's (ABCB) recent proposal on verification methods [89] have resulted in a reinvigoration of the PRA method to verify performance requirements. However, while the probabilistic method has been used for evacuation [47,69], structural design [90], cost-benefit analysis [91] and other areas of fire safety engineering, there is a dearth in the literature of comprehensive PRA applications in performance-based building designs [68]. PRAs typically deploy Computational Fluid Dynamics (CFD), zone models and evaluation simulations to quantify consequences coupled with event trees underpinned by statistical data and fault analysis to calculate the likelihood of consequences. These results are then combined in an analysis to determine the Expected Risk to Life (ERL) based on various desired design features in alternative designs to achieve a risk level that meets the acceptance criteria. Further analysis can be achieved with the F-N Curve and Monte Carlo simulations given that reliability and uncertainty are important elements of a PRA.

It is also possible to relate risk probabilities of random system responses under a given external action with cost, hazard and vulnerability, which improves the results and can be easily generalized to any system [92]. One of the challenges associated with PRA is that the quantification of acceptable risk is a very difficult process. This can be improved through continuous research on the refinement of event trees, more analysis of operating data, modelling of external initiating events, atmospheric dispersion and common cause failures. A fully transparent, centralized source of reliable data on past accidents is needed as well in the building domain. This will enable planners, engineers and regulators to better comprehend, and then weigh, all the associated and expected risks Following these measures will enhance the use of PRA and improve its ability to capture the risk associated with any system.

An important topic that is closely related to PRA is Human Reliability Analysis (HRA). Recognizing that major accidents result from human error as well as from technical system failure, a series of HRA methods has been introduced to consider the impact of human error on system risk in PRA. HRA is a structured methodology that applies qualitative and quantitative methods to assess the human contribution to risk [2].

4.1. Development of human and organizational error assessment

Many researchers have assessed the role of human and organizational errors in different complex systems. Rasmussen defines skill-based errors as errors associated with failures to execute well-rehearsed actions, where conscious decision-making is not always needed. The Techniques for Human Reliability Analyses (THERP) was introduced by Swain and Guttman [2]. They identified performance shaping factors such as environmental factors, physiological and psychological states, and organizational factors and related these factors to human errors. Reason advanced the Swiss Cheese model, which suggests that the alignment of active failures and latent pathogens in a complex system leads to accidents [60]. He describes four levels of human failure, each influencing the next. Organizational influences lead to unsafe supervision, unsafe supervision leads to preconditions for unsafe acts and preconditions for unsafe acts lead eventually to unsafe acts. Shappell and Wiegmann [93,94] built on Reason's model of human error to provide a detailed taxonomy of human error at each of the four levels for accident analysis. Grabowski et al. [52] introduced a cognitive framework of human error. This framework classifies unsafe acts into two types of activities: errors, which he defines as unintended actions; and violations, which are intended actions. Macwan and Mosleh [95] introduced another cognitive error framework that provides reference models to categorize human error. The human reliability analyses suggest error identification through task analyses and influence diagrams in the context of specific accident or risk scenarios, utilizing performance shaping factors that influence risk outcomes. Davoudian and colleagues use a set of twenty organizational factors developed for the Nuclear Regulatory Commission [96,97].

Mohaghegh and Mosleh [98] note that while researchers such as Cooke [99] and Leveson [100] have used the System Dynamics method to show how organizational dynamics change over time, their models do not include detailed probabilistic risk analysis of technical systems. Many research studies have tried to incorporate organizational factors into PRA in a formal manner. Examples include MACHINE [101], Omega Factor Model [102] and SAM [103]. Some models use accident data as a basis for their factors, while others use a set of predefined factors. Mohaghegh and Mosleh [98] provide a comprehensive review of relevant theories in various domains to address the inherently multidimensional nature of the problem. These domains include quality management, safety management, organizational culture and climate, safety culture, safety climate, human resource system, human reliability and organizational theory such as socio-technical systems. Based on these approaches, they distilled a set of principles to develop an organizational risk framework called Socio-Technical Risk Analysis (SoTeRiA). This model integrates technical system risk with social (safety culture and safety climate) aspects and forms a useful basis for the development of future HOE risk models for high-rise buildings.

5. Studies on quantification of HOEs in fire risk analyses

Although there are significant impacts by HOEs on fire risk, there is a paucity in the literature when it comes to studies for integrating HOEs in fire risk assessment models for different types of buildings. The literature search in this study managed to find six relevant studies from other domains which provide methodologies or frameworks for quantifying risks based on HOEs in addition to technical factors, that could form the basis of a HOE risk model for high-rise buildings. First, a study by Chen et al. [26] on fire safety in hotel buildings stated that the risk impact from implementing fire prevention and evacuation strategies is estimated at 55%, however, PRA or QRA techniques were not used in their model. Second, a study by Zhao et al. [104] using System Dynamics approach for risk control in automatic metro indicated that implementing safety standards reduced risk by 25%. Third, a study by Wang et al. [15] on the probability analysis of offshore fires indicated that developing and following safety standards impacted risk by 30–50%. Fourth, a study by Mohaghegh [51] on organizational risk analysis indicated that human errors account for approximately 30–90% of all accidents. Fifth, the study by Harrald et al. [105] on oil transportation accidents in maritime systems indicated that HOE risks account for as much as 28% of overall risk. Lastly, a study by Lin et al.

Table 6
Some modelling methods incorporating HOEs applicable to building domain.

Method	Description	Errors / Factors	Outcome
Quantitative risk analysis	Expanded (QRA) method by including uncertainty analysis with the risk analysis. Adding uncertainty to a QRA will increase the amount of work needed to complete the analysis but can account for human error [44].	Can be due to lack of experience, lack of qualifications, lack of education, incompetence and negligence.	Considers human errors in uncertainty analysis which should be included in the risk assessment. Example errors are poor choices during evacuation, poor equipment maintenance and misreading fire cues. However, human errors are not explicitly modelled or quantified.
Bayesian Networks	Wang et al. [15] developed hybrid approach to apply Bayesian Networks to consider HOE in risk analysis for offshore fire and explosion	Considered human and organizational errors such as not checking rules, not complying with instruction, inefficient emergency plan, deficient training, improper safety organization, not obeying standards, deficient maintenance, wrong risk assessment	Study shows that human error of not complying with instruction and organizational error of inefficient emergency plan have the largest contribution to fire risk in offshore accidents.
System dynamics	Zhao et al. [104] focused on the urban metro in China and used system dynamics (SD) to model organizational factors that impact risk.	Human and organizational errors and their influence on and within the system. Consider safety behaviours of system, system improvement, organizational experience, active organization resource and their impact on system risk	Explored the influence mechanism of organizational factors on system risk over time and traced dynamic evolution process of important organizational factors in an auto metro system.
	Bouloiz et al. [106] focused on industrial safety and the human factors (of the operators) that impact risk using SD and fuzzy logic.	Motivation, stress, abilities and confidence, work precision impacted by fatigue and competence	There are interactions between humans, the organization and the safety behaviour that influence the accuracy or appropriateness of activities that are performed.
	Yu and Ahn [73] studied nuclear power plants using SD to incorporate HOFs into safety modelling.	Human investment, time for analyzing problems, regulatory environment, external information, training, and hardware investments.	A low degree of training will result in lower performance. Hiring new staff members did not improve safety and obtaining new skills did not have a large impact on safety. Laying off staff had a significant negative impact on safety
Human reliability analysis	Groth and Swiler [107] focused on the nuclear power industry and using Human Reliability Analysis (HRA) for analyzing the costs of human errors.	Considers Human Errors by using knowledge of Performance Shaping Factors (PSF) to determine of Human Error Probabilities	This study bridges the gap between HRA research and HRA practice by building a Bayesian Network version of the widely used SPAR-H method. To clarify, HRA is closely related to PRA/QRA. It is the aspect of PRA that is concerned with systematically identifying and analysing causes and consequences of human errors. Given that major accidents result from human error as well as from technical system failure, HRA methods have been has been introduced to consider the impact of human error on system risk. Given that HRA is an element in most PRAs and QRAs, there is an overlap with the QRA methods listed above
STPA and FRAM	Dallat et al. [74] studied accident causes and the impact of human error. The System-Theoretic Process Analysis (STPA) and Functional Resonance Analysis Method (FRAM) are identified as methodologies for systems approach to risk assessment. STPA considers the entire sociotechnical system but is complex. FRAM is easier and explores causal relationships	Government, regulators and associations, company, management, staff and the work or action.	Existing risk assessment methods do not maintain consistency with Rasmussen's model developed to explain accident causation, and ignore managerial, supervisory, regulatory and government levels, focusing on staff and/or action levels.
Socio-Technical Risk Analysis (SoTeRiA)	Mohaghegh and Mosleh [98] extended PRA modelling framework to include effects of organizational factors by developing SoTeRiA framework that integrates System Dynamics, Bayesian Network, Event Sequence Diagram and fault tree for complex socio-technical systems in airline safety domain focusing on maintenance systems	Considers industrial & business environment, social and political culture and climate, organizational vision, strategy, organizational culture, safety culture, organizational safety climate, individual PSFs.	SoTeRiA is a holistic, multidisciplinary approach that includes organizational roots of risk. Hybrid approach incorporates Human Reliability, Social and Behavioural Science, Business Process Modelling and Dynamic Modelling. It integrates deterministic and probabilistic modelling perspectives in risk analysis

[106] used a paired comparison approach in air transportation to show that reducing fatigue (a single human factor) lowered the risk of accidents by 16%.

PRA models can be enhanced with the incorporation of HOEs. Gwynne et al. [84] provide guidance on representing human behaviour in egress models, focusing on Required Safe Egress Time (RSET). The authors argue that existing models underestimate the time required to reach safety by using over-simplified assumptions that reduce the levels of safety. In comparison, Kobes et al. [18] note that policies can be developed using inaccurate assumptions, that not only result in inaccurate risk estimates, but can be ineffective when dealing with an actual fire event.

It was found that occupant characteristics and behaviour increase risk especially when the population is vulnerable or when the fire event occurs while the occupants are asleep [27,43]. Zhao et al. [104] point out that approximately 1% of occupants fail to evacuate and that overestimations of walking speeds underestimate risk by a factor of three. In Li et al. [30], evacuation times were found to take 3–8 times longer than the times reported for fire drills, indicating that risks may be underestimated if statistics from fire drill times are used in evacuation modelling.

Table 6 summarizes some of the modeling techniques in other domains that consider HOEs. The main criteria for selection were their focus on quantifying human errors and risk. Researchers have used different methods to consider human errors in the evaluation of risk including QRA, SD, HRA, system-theoretic process analysis (STPA) and

SoTeRiA. Table 6 is not meant to be comprehensive or to include all the available modeling techniques as this is beyond the scope of this paper; its main objective is to showcase examples in the literature of the different methods available, to which cases they are applied, and the outcome in each case. There is a large number or modeling techniques, and some researchers have combined two or more methods together in their studies. For instance, Mohaghegh and Mosleh [98] developed SoTeRiA as a holistic, multidisciplinary modelling approach that extends PRA to include the organizational roots of risk.

6. Role of HOEs in probabilistic risk analysis for high-rise buildings: case studies

When evaluating high-rise fires post-event, various HOEs emerge that may be preventable in hindsight. These HOEs may interact with technical system failures and contribute to culture, policies, organizational decisions, and individual choices. It is prudent not to overgeneralize from one scenario to another because HOFs that lead to a fire incident can be of a different nature depending on different building types. However, it is necessary to identify those factors that are consistent across various scenarios. This section presents two case studies of fire events at the Grenfell Tower in London and Lacrosse Building in Melbourne. The two cases were selected because they have commonalities since both are high-rise residential towers with a similar number of floors, both had the fire spread when occupants were asleep, both had an immediate brigade response, and both had combustible cladding on the exterior.

6.1. The case of the Grenfell Tower fire

The Grenfell Tower fire event that occurred recently in June-2017 in London UK, represents an important case for the adoption of HOE analysis. At the Grenfell Tower, occupants escaped using a single staircase and while more than 65 people were rescued, more than 71 people died, and countless others were injured [108].

Back in 2013, residents had complained about power surges and possible faulty wiring and the property was subsequently renovated in 2016. Rescuers noted that an active gas pipe complicated their job and recent renovations included the use of insulated aluminium cladding which was thought to enhance the fire. The fire started around 1.00 am and the first firemen were on the scene within four to six minutes of receiving notification of a fire, but the fire had spread from the 4th floor to the 18th floor in approximately eight minutes.[1] Firefighters were notified that there was a refrigerator fire on the fourth floor and initially thought the fire was under control, not realizing the outside of the building was in flames.[2] High-ladder and aerial appliances were not initially dispatched and were not on the scene until 1:32 am. This was 32 min after the fire had started. Grenfell Tower had a policy that residents should wait for rescue, called a “stay-put” policy, and some people followed the policy. Others called friends and heeded their advice to leave the building, ignoring the policy. Firefighters directed some people into safer flats during the rescue, but later directed occupants to leave the building using the single exit stair which was smoke-filled. There were casualties in the stairwell.

The Grenfell fire reveals a host of technical and organizational issues including the failure of cladding, failure to control smoke spread making visibility and evacuation difficulty and absence of fire safety measures such as sprinklers and exit staircases. In addition, organizational policy-related HOEs indicate that policy decisions made at the building level can have a significant impact [109]. The “stay-put” policy was in place and this may have contributed to the loss of life. Moreover, complexity and misinterpretation of regulations, culture of indifference within the industry, role ambiguity and lack of clarity, inadequate training and assessment of competencies, ineffective evacuation and employee behaviour, deficient safety routes contributed to the Grenfell fire.

6.2. The case of the Lacrosse Building

The case of the Lacrosse Building is similar but also provides a contrasting fire event. It is a residential tower in Melbourne, Australia and the fire event dates to November 2014 [110]. There were no fatalities in this fire. A mass evacuation was ordered, and the cause was thought to be a discarded cigarette. The fire spread rapidly upward, likely due to the building's external façade. Occupants (400) were evacuated and there were no fatalities. Occupants of the apartment where the fire started initially attempted to put the fire out using water. The sprinkler activated a call to the fire department and the fire department confirmed there was a fire and responded to the scene in about five minutes. By the time the fire brigade arrived, many people had already evacuated, and the fire had spread vertically up the exterior of the building. Fortunately, on that day the winds were blowing in a direction taking the flame away from the building to limit the spread of fire. However, the combustible cladding material exacerbated the fire spread. One surprising finding was that the occupancy levels were higher than expected for many apartments. In other words, there were many apartments with clusters of family members cohabitating. Some apartments had up to eight occupants which were more than reported potentially affecting a safe evacuation. In addition, temporary structures were found in bedrooms to provide privacy that could have hampered the ability to evacuate. Many occupants did not hear the alarm and were awakened by loud noises from neighbours, such as banging. It was found that hot gases, because of the fire, compromised the alarm system, causing it to fail on several levels of the building.

6.3. HOEs as root causes for the fire events

Both cases share very common aspects and Fig. 1 provides a summary of the weaknesses and deficiencies in the UK Building Regulations that led to system failure in the case of the Grenfell Tower [109]. At the human and organizational level, the culture of indifference, ineffectiveness of regulatory bodies, competition between public and private sectors, complexity of regulations, role ambiguity and lack of clarity, lack of assessment to determine competencies, lack of standards and sanctions, misinterpretation of regulations and ineffective reinforcement of regulations, ineffective employee behaviour, ineffective evacuation, and deficient safety routes led to devastating consequences at the Grenfell Tower.

The causal diagram in Fig. 1 has four levels. At the top (Level 1) is the weakness in the UK fire regulation procedures. The second level shows that this weakness in the UK fire regulation procedures is due to the organizational factors identified as being key predictors of system failure. The third level shows that the main organizational factors lead to misinterpretation of regulations and ineffective reinforcement of regulations, as stated in the report. This ineffective reinforcement of regulations leads to ineffective employee behaviour, deficient safety routes and ineffective evacuation. These three outcomes are shown on Level 4. This causal model shows the relationships between the variables and can be tested using a hierarchical mediated model that includes both organizational and human factors. Although the model is correlational and does not suggest causality, it provides some explanation of why people lost their lives during the Grenfell Fire. Future research will need to test the relationship between these factors and fire events to test the validity of the model.

Hackitt [109] found that the combustible cladding system led to an acceleration of the fire at Grenfell Tower. The report recommended a

[1] London Fire Brigade. Actions by Control in Response to Grenfell. 2018; (July):1–203.

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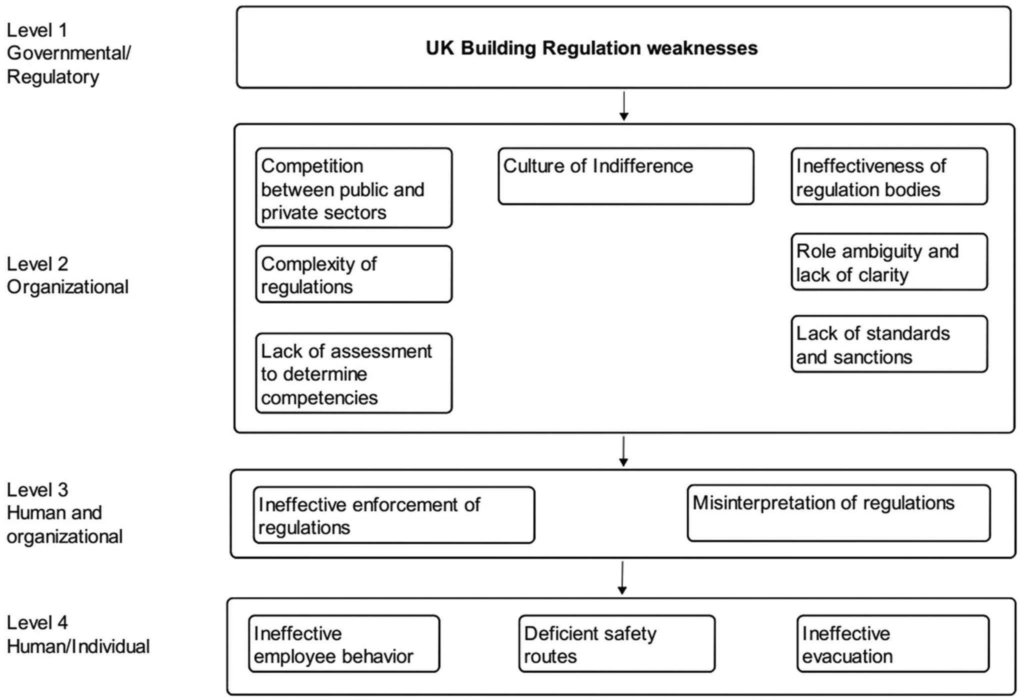

Fig. 1. Weaknesses and deficiencies identified in UK building regulations - human and organizational factors [88].

shift from a government-centric authority towards a greater responsibility placed on duty holders that will ensure building safety to meet government standards [109]. Those duty holders who approve, design and build high-rise buildings are to be fully responsible for ensuring correct safety behaviours. When there is a lack of safety, sanctions must be imposed for poor performance and a more rigorous oversight of duty holders should be created.

Residents of Grenfell Tower had stated that there was a lack of defined roles for the fire and rescue services and demanded a greater role for fire services to ensure safety in existing buildings. The Hackitt report acknowledged these concerns and recommended that residents be given a voice in the system, including providing greater transparency of information on building safety, better involvement in decision-making, and the ability to escalate fire safety concerns through an independent statutory body. Mechanisms should be put in place for residents to understand their role as well as the role of the fire brigade in ensuring building safety. The selection and promotion of individuals must also be aligned with superior human resource management practices. Those engaged in the fire prevention aspects of design, construction and inspection of high-rise residential buildings should possess formal accreditation qualifications to ensure that they are effective in their job performance. Moreover, systematic reviews of the overall integrity of the building should be integrated into the system with a stronger enforcement of policies and procedures, and sanctions for those who disobey the rules and regulations. The most important immediate need is to change the current culture of indifference within the building industry due to the serious shortcomings in the system to address health and safety. It should be noted that Hackitt attributed the Grenfell fire mainly to human and organizational failure due to ignorance, indifference and inadequate regulation, rather than technical factors.

6.4. Integrating case study findings with quantitative solutions

Findings from the case studies highlight the usefulness of specific modeling techniques and quantitative solutions that integrate HOEs into probabilistic risk models such as BBN, HRA and SD. One technique that allows for the incorporation of HOEs into complex system risk modeling is Bayesian Belief Networks. In the Lacrosse and Grenfell fire incidents, BBN could have been employed in the early design phases to model human and organizational risks and to find compensating measures. An enhanced PRA then allows for an absolute quantification of the societal risks which can be used to compare different buildings, supplementing information used for high-level decisions to determine effective policies and regulations. For example, a comparison between the Lacrosse and Grenfell cases will likely ascertain that the level of safety at the Lacrosse solution is much higher than that of the Grenfell Tower. This is supported by the fact that, although the fire ignition, fire origin and fire development were similar in the two cases, the Lacrosse fire ends with no major consequences to the occupants while large damages and consequences occurred at Grenfell. Incorporating HRA analysis to the model can provide objective inputs for human error probabilities, such as the failures during the Grenfell fire. Finally, SD allows for the inclusion of time-varying parameters that cause risk oscillation during the life cycle of a building. These observations could be helpful in defining corrective measures to contain excessive variations in the risk level over the life cycle of the building.

7. Factors affecting HOEs

The literature and case studies indicate that risk factors can be technical, human or organizational. This section will present a review of literature related to each category.

7.1. Technical factors

According to Yang et al. [16], common problems in urban rail-transit fire-fighting facilities are the aging of equipment and insufficient maintenance along with improper operation of equipment. Likewise, for fire and explosion accidents in the maritime transportation industry between 1990–2015, Baalisampang et al. [22] reported the maintenance of equipment to be one of the major causes of accidents. Halim et al. [111] concluded that although equipment failure and human errors are the most common direct causes of fire, job safety analysis, and procedure and maintenance issues are the top contributors.

Dhillon and Liu [64] found that human error in maintenance is a pressing problem and this is underscored in all major studies. The design of fire protection equipment cannot prevent fires unless physical conditions, which exist during fires, and human involvement are considered. Hu [112] presented a detailed reliability analysis and program to maintain equipment in hotel areas following occurrences of many hotel fires. Liu et al.[113]. focused on the importance of risk assessment system and regular maintenance with frequent inspection to prevent fires in large scale commercial buildings. Gregson et al. [114] identified maintenance of equipment as a major source of regulatory and safety problems and argued that equipment maintenance must be disarticulated and outsourcing of maintenance functions should be controlled. Sobral and Ferreira [23] stated that lack of maintenance implies reliability of fire protection equipment goes down, which results in equipment unavailability and increases fire risk. Blum et al. [24] pointed out that maintenance and inspection of automatic sprinkler systems can affect their performance and consequently the fire risk. Moinuddin and Thomas [25] focused on the maintenance of sprinkler systems in high-rise buildings in Australia and they found that the chances of sprinkler systems failing are higher than commonly thought. Human errors identified in this study were failure to observe the alarm, operator's failure to act, overly long repair times and repair errors and planning errors related to part replacements.

The effect of time is critical in its relationship to technical factors because safety levels decrease as buildings age, Aging buildings require regular re-evaluations of building conditions [24]. Chen et al. [26] evaluated fire risks in 16 existing hotel buildings over time around the world. Findings included a lack of fire barriers, lack of fire-fighting equipment, a lack of guest room fire compartments, faulty sprinklers, incomplete fire compartments, a lack of alarm systems, delayed evacuation, blocked escape routes, locked stairways, lack of emergency power supplies, guests guided out incorrectly by staff, open fire escape doors, and improper signage. Three safety strategies for dealing with changes in building conditions over time were developed– fire prevention, fire control, and fire resistance, evacuation and mitigation. Meacham [27] notes that, over time, the condition of buildings may change, including the use and types of materials stored in the facility.

In summary, HOEs can affect the expected performance of equipment and building conditions. Insufficient and improper maintenance of equipment has been found to impact equipment performance, involving both technical and human errors. Aging buildings, along with the associated deterioration of buildings and lack of fire safety equipment decrease building safety while increasing fire risk.

7.2. Human factors

Pre-evacuation behaviour by occupants impact on evacuation time and overall risk. Using three pre-evacuation states of occupants (normal investigation and evacuation), an evacuation model was developed that considers the impact on the evacuees' perceived risk by the environment and social cues [31]. Another pre-evacuation behaviour model based on Random Utility Theory was suggested using the same three pre-evacuation states a year earlier [31]. It was found that the most important factors affecting occupant's movement were the elapsed time since the start of the alarm, occupant's position, and social influence. However, existing literature lacks effective models for predicting occupants' behaviour during evacuation [34]. Thereafter a Protective Action Decision Model (PADM) was suggested [75]. PADM is a multi-stage model that integrates information flow from environmental and social cues with those messages that social sources transmit through communication channels to those at risk.

The Australian Building Codes Board (ABCB) [89] has recognized that use of lifts (elevators) may be appropriate in fire situations, except for special cases such as disabilities and impairments. This has become more acceptable given the World Trade Centre (9/11) event where stairs did not provide a timely egress [35]. However, occupants can experience confusion on this matter because older codes prohibit elevators usage in emergencies. Devlin [37] notes that human intervention may have caused the elevators to be unavailable in the Nakheel Tower in Dubai, an error on the part of the building management and staff. He also states that when using stairs, evacuees experience fatigue after approximately five minutes and move at an average speed of 16 s per floor. Ding et al. [36] found several occupant error factors in their study on the use of elevators. Factors discovered during the experiments were pushing, hesitation, re-entering the elevator, stair preferences, and social bonding. Their research shows that occupant error factors are important to consider in constructing models to explain fire safety risks. However, the research utilizes models rather than testing propositions within empirical research so there is a need to test these models in empirical research. There is a need for more quantitative and qualitative research that determine the importance and magnitude of these factors within fire-risk situations and to analyze rich qualitative information that provides insights into occupant behaviours during fire emergencies.

7.3. Organizational factors

Policies developed and enforced by building management have been found to affect the risk of fatalities and damage during a high-rise fire event. Sun and Luo identified smoking, careless use of naked flames (such as welding) and improper operations by employees to be causes of fires in high-rise buildings during construction in China [21]. Cluttered rooms and unexpected numbers of occupants per apartment, should be monitored by building management Demers and Jones' study [28] determined that fire drills are an educational process for the building occupants that allow occupants to locate and improve familiarity with exits and procedures when there is no real threat and may be required by regulations, codes, and insurance companies. They noted that facilities that have well-prepared employees and well-developed preparedness plans have lower chances of damage to structure or injuries to employees [29].

Wang et al. [19] classified insufficient fire drills as an HOE factor, along with enforcement of safety standards, finding that these two execution deficiencies significantly increased accident risk. Similarly, in [15], execution of drills and safety planning were classified as management factors that contributed to increased accident probabilities. Unfortunately, in buildings where there is mixed-use, or a changing composition of occupants, drills that encompass most or all occupants may not be possible [28]. While building management can create proper safety conditions and engage in regular fire drills, there are occupant HOE factors that need to be considered. Human behaviour during a fire event differs depending on prior experience, education and training with drills, personality traits, the role a person assumes (such as leadership or authority), what others are doing, and the perception of the threat (presence of cues such as smoke or flames). People may not respond to fire alarms that do not use a human voice [27] and can exhibit skepticism as to whether the indicated noise is indeed a fire alarm. Li et al. [30] studied fire drills at a 6-storey residential building and the impact on risk analysis. The authors found that response time and evacuation times of occupants are much longer in an actual fire than in a fire drill (300–800 s versus < 100 s).

According to Hanea and Ale [17], performing evacuation exercises in a building once every three years results in a 91.4% probability of having no victims and annual evacuation exercises increase the probability of having no victims to 91.7%. Gwynne et al. [31] have concluded that the merits of egress drills are not understood properly and their impact on evacuation performance has not been estimated well. In summary, HOE related to drills include factors that can be controlled at the organizational level, such as safety culture, the creation of an emergency preparedness plan, executing the plan, and conducting regular drills that include staff and occupants. Occupant and staff factors include participating in drills, guiding occupants through a proper evacuation (in the case of staff), and becoming familiar with proper

Table 7
Human and organizational risks identified for risk modelling of high-rise buildings.

Study	Human errors	Organizational errors	Main findings
Offshore platform fires Wang et al. [15]	Using unsuitable equipment and not following instructions and standards	Deficient Checks & Controls, Equipment Aging, Deficient Training, inefficient emergency plans, wrong risk assessment	-Probability of occurrence varies 45.4 - 9.17% -HOEs cause 80% of the risk.
BP Deepwater Horizon Accident Tabibzadeh & Meshkati [53]	Failure to follow process & identify critical indicators, multi-tasking, improper calculations, inadequate checking and inadequate staff	Economic pressure -insufficient training & experience, lack of procedures & monitoring, poor communication & management commitment	−80% failures in offshore accidents due to HOEs. −78% causes of incidents in well control are due to HOEs.
Tanker fires and explosions with dangerous cargo Urgulu [42]	Violation of entry permit, violation of work permit, deficiencies like rule or procedure error and timing errors	Lack of risk analysis, Lack of control mechanisms	-Majority of problems due to implementation of safety procedures and rules -More training is needed.
Release of cargo vapours in Chemical tanker industry Wang [19]	Not following proper procedure, not wearing safety equipment, not testing atmosphere, not detecting smells, complacent attitude and lack of awareness	Incorrect risk assessment, defective equipment, deficient training, lack of briefing and instructions, lack of guidance, and insufficient drills, checks, and enforcement	-75–96% of casualties are due to human error. -Lack of enforcing safety standards has the highest impact on risk. -Lack of enforcing a safety standard increased the risk by 6%, -Lack of wearing protective equipment by 8–20% and total risk became 70%.
Monte Carlo simulation in human factors for Chemical processing industry González Dan et al. [61]	Workload, environmental conditions, and skills, knowledge and personal behavior	Deficient training, communication and reporting, workplace design	-Modelling the uncertainty and complexity of HF provides a more realistic and accurate measure of frequency of accidents. –13–34% increase in accident frequency after adding HFs.
Fires in subway systems Yan et al. [20]	Illegal operations, negligence, staff quality, passenger panic, low awareness of prevention, and psychological qualities	Deficient raining, equipment maintenance, supervision & inspections, emergency drills and plans, hindered rescue and guidance	-Equipment failures and individual performance contributed significantly to an increase in the accident probability
PRAs in airline maintenance Mohaghegh [68]	Safety practices, motivation, abilities, and psychological issues	Safety culture, training, maintenance	-Error probabilities increase as management commitment to safety decreases over time with increasing financial stress.

evacuation procedures, signage, and exits. Neglecting to conduct regular drills and participate in drills are HOE factors that increase overall fire safety risk.

7.4. Overview of studies from various industries

The papers identified in Table 7 provide specific risk measurements, important for baselining and validation of risk modelling of HOEs in high-rise buildings. They also give indications of which errors are associated with higher risks, again making them important for future risk modelling of HOEs in high-rise buildings. Human risks are associated errors committed at the individual level, generally during an extreme event such as a fire or explosion. Failing to comply with standards and instructions is a common theme of human risks. Organizational risks describe associated errors committed at the organizational level that are determined through practices and policies of the organization and are generally established prior to an extreme event. Common themes in organizational errors are deficient training, plans, maintenance practices and the overall safety culture. The human and organizational risks identified in Table 7 provide an inventory of HOEs for future consideration in probabilistic risk modelling of high-rise buildings.

8. Conclusion and future research directions

8.1. Conclusion

The main aim of this study was to systematically review available research evidence on HOEs in risk analysis of high-rise buildings, which can be used to improve probabilistic fire risk analysis. This was performed by reviewing studies identified in the literature search. The primary practical contribution of our present research was the identification of knowledge gaps due to the scarcity of literature in the field. The knowledge gaps are specifically in relation to how HOEs are underestimated in risk analysis, the lack of understanding about HOEs and how they can be incorporated into a holistic probabilistic risk analysis for high rise buildings. There is an absence of empirical quantitative studies, theoretical framework, or guidelines demonstrating how HOE risks can be distilled to improve probabilistic risk analysis of fires in high-rise buildings.

An extensive review has suggested that the influence of HOEs on the risk levels in high-rise buildings is important and the policies, procedures (including inspection and maintenance), training, and conditions during a fire event can impact risk levels. Characteristics of occupants and staff, as well as a shift to using elevators in certain circumstances also play a role. The research indicates that fire events that occur during the late evening/night when occupants are asleep can increase risk. There are multiple indications that occupants do not follow building policies even when awake. If a probabilistic risk analysis fails to include these factors or incorporate a proper representation of the vulnerable population in a building, risk will be underestimated.

There are indications that training and maintenance can be deficient such as the adherence to relevant policies and procedures (including emergency procedures). This may be driven by the overall safety culture adopted by the building management and building occupants which has been found to significantly affect risk. Clearly, the inclusion of common HOEs means that more comprehensive risk factors will need to be considered during assessment but by ignoring HOEs, risk estimates may be grossly underestimated, possibly by as much as 80%, as summarized in Table 7 above.

Literature related to other industries clearly indicates that existing models that ignore HOE factors are likely to underestimate risk. This gap in current fire risk models for high-rise buildings could be addressed by incorporating important HOE factors, such as occupant behaviour and characteristics, building staff errors and management safety culture into current models. Developing a risk model that includes these types of HOEs, and considers environmental factors, such as building conditions deteriorating over time will enable more realistic estimates of risk in high-rise building fires. While incorporating HOEs into a fire risk model is likely to be more complex than traditional fire risk models, there are various techniques, such as System Dynamics, HRA and BBN that have been used successfully in other industries, e.g. Mohaghegh [51]. These successful implementations indicate that incorporating HOEs into a probabilistic fire risk model for high-rise buildings is feasible and is a research area that needs to be explored and understood.

8.2. Future research directions

The findings from this systematic review provide useful directions for future research. First, more research is needed on HOEs and how they interact in prediction of fire events, especially in high-rise buildings. Currently, there are scarce sources in the literature specific to high-rise buildings where HOE scenarios and their impact on risk, estimated and presented, either individually or collectively. Some attempts have been made but involving only part of the risk picture, for example, probability/reliability assessment [23] or evacuation effectiveness [31]. In other cases, general frameworks have been presented with limited quantitative considerations of HOEs [73].

Research is needed to identify the controllable characteristics of individuals and organizations to include in probabilistic risk models for better estimation of risks levels of fire incidents and is a promising area of research as well. This requires a systematic and comprehensive methodology for causal modeling with a view to relating the risk scenarios to their human and organizational performance roots, and to the regulatory and oversight functions. In the realm of fire safety science, meaningful and reliable correlations between behavioral and technical systems are sparse, and thus pose as a serious drawback.

The findings also show the need for more computational modeling studies that are specific to risk in high-rise buildings. New mathematical models will need to be developed that include occupant behavior, building staff errors and safety culture in the risk analysis. The process of validating these models includes comparisons with statistical data in high-rise residential buildings where there is more available data and existing models relevant to fire hazards in high-rise buildings. Much of the recent research in building fire risk is heavily focused on reducing risk and developing risk-informed oversight by improving technical systems in fire risk assessments. Current methods in the building domain do not include the possible impact of explicit human and organizational errors on safety performance of equipment and personnel.

The advent of modern modeling techniques and computational power allows for rapid simulation techniques that can facilitate HOE analysis in PRA. A toolkit of techniques to assess risk across technical, human and organizational systems would be an appropriate approach to the scarcity of a systems approach found in this review. Various techniques, such as System Dynamics, HRA, BBN and socio-technical systems approach have been used successfully in other industries that can be deployed to study HOE risks in high-rise buildings.

Future research should consider the development of dynamic probabilistic risk models that address risk variations over time. Such models can account for changing risk profiles during the life cycle of a complex system as safety components age and/or fail over time, and are required to be repaired or replaced. Updates of risk profiles can be performed dynamically to reflect the safety state of the overall system. These changes may be physical such as equipment modifications, operational such as procedural enhancements or human and organizational such as knowledge-driven, operational experience and data. A dynamic PRA will enable continual risk estimations of a deteriorating system depending on the states of its components and systems knowledge acquired over time.

New methods such as the development of a form of machine-assisted interpretation can be used to bridge the gap between data sources and the theoretical and practical mechanisms. This has been used to deliver safety in railways and can be applied to high-rise buildings. One main advantage of this approach is that existing data can be mined for relevant safety and risk information that can be used to develop new safety solutions, where the data becomes the driver for safety [115]. Another potential tool is the use of ontology, which is a systematic way to capture and classify domain knowledge into a system that supports the use of different databases in risk analysis situations [116]. Ontologies can tap into the core of big data analytics for safety and support risk analysts to discover new knowledge and insights.

The high-rise building construction in Australia is experiencing rapid growth and enhanced Probabilistic Technical-Human-Organizational Risk models will support the development of more rigorous fire safety codes. Currently, no such comprehensive model exists for fire risk analysis in high-rise buildings, but fortunately, groundwork exists where probabilistic and dynamic features have been included successfully in risk modeling in related applications, such as offshore platform fires. Developing methodologies to incorporate human and organizational risks into an existing technical risk model will enable a broader understanding of fire risks in high-rise buildings.

Declaration of interest

None.

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2.10 Synopsis of Chapter 2

This chapter has set out to define HOEs relevant to the building domain and identifies important HOEs that are prevalent in industries which are critical for fire risk safety in high-rise residential buildings. Gaps in the literature were identified – namely, the significance of incorporating HOEs in PRA which has hitherto been absent in the building domain. As the importance of considering HOEs in the PRA models is established, the next step is to devise a methodology for their incorporation which is presented in Chapter 3.

Chapter 3

Incorporation of technical, human and organizational risks in a dynamic probabilistic fire risk model for high-rise residential buildings.

Overview

Chapter 3 focuses on the development of a comprehensive T-H-O-Risk methodology. An analysis of prior research finds hybrid approaches that integrate deterministic and probabilistic modelling perspectives in socio-technical models can lead to the development of the T-H-O-Risk methodology. The method quantifies human and organizational errors (HOEs) in a probabilistic model using BN analysis of HOEs and SD modelling for dynamic characterization of the risk variations over time. The T-H-O-Risk methodology integrates analyses of building and occupant characteristics, fire safety systems, evacuation, and statistical data. The methodology is flexible and can be applied to a variety of structures, allowing for both relative and absolute risk evaluation. It further addresses the issue of potential underestimation of the risk resulting from the adoption of less demanding maintenance and operational practices along with the lifecycle of the system. In addition to providing a tool for quantifying HOEs with multiple levels of analysis and supporting analyses over time, the model accounts for refurbishment activity and interactions with other safety systems that can result in a global loss of safety when these relationships are overlooked. The method is an incremental risk approach allowing for the quantification of the impact of HOEs on different fire safety systems including the active systems of sprinklers, building occupant warning systems, smoke detectors, and smoke control systems.

Three case studies are conducted to demonstrate the application of this comprehensive approach to the designs of various high-rise residential buildings ranging from 18 to 24 stories. Case studies include prescriptive, DTS solutions and performance-based solutions with variations of apartment, retail tenancy and office fire scenarios. Societal risks are represented in F-N curves and the model utilizes the ALARP principle in comparing risk acceptance for the case studies. F-N curve method incorporates ERL (expected risk to life) calculation within it and ERL calculation involves ETA (event tree analysis).

The shortened version of the T-H-O-Risk methodology is described in Paper 2 publication: *Incorporation of technical, human and organizational risks in a dynamic probabilistic fire risk model for high-rise residential buildings*. The following sections provide an outline of the research and methodological steps as a primer to the approach.

3.1 T-H-O-Risk Methodology

Rather than utilizing pre-existing Human Reliability Analysis (HRA) methods to assess the risk of human factors separately, the current study aims to incorporate human and organizational errors into current risk approaches in an enhanced T-H-O-Risk framework. Instead of performing HRA for human errors by subjective methods and fire risk assessment by conventional models separately, it is essential to consider all the technical, human, and organizational risk factors simultaneously for a detailed and enhanced risk analysis for high-rise residential buildings. Fire scenarios and modelling parameters will be based on existing published research, wherever possible, thus necessitating a qualitative component that incorporates engineering judgement. The execution of the model and evaluation of the outputs requires a quantitative approach incorporating analytic calculations.

Collating necessary factors and fire scenarios from prior research is based on a grounded theory approach, where a systematic review of existing data for factor and scenario development is performed. The quantitative aspect uses simulation modelling that is based on an exploratory and descriptive research design. This design was chosen due to the existence of a large body of literature related to fire research in general, but very little research in assimilating technical, human and organizational risks into a fire risk model. It should be noted that incorporating HOEs will increase the model complexity due to the increased number of interactions between different parameters needed to assess a building's overall fire risk [1]. However, this is mitigated by integration if the HOE framework into existing risk models, rather than building a new risk model from ground up. This ensures the feasibility of the project within the given timeframe and available resources. While realistic and detailed analyses are possible with BN and SD methodologies, their wide-scale applications in fire risk models are scarce as only a few models exist, including TRANSIT [1] or the ones by De Sanctis et al. [2] and Holický [3] developed more recently for other industries.

This project incorporates both a literature review and simulation modelling. The methodology for performing the research includes collecting and analysing HOE data for building the HOE framework, evaluating probabilistic scenarios, and constructing the probabilistic framework. Then simulations of scenarios are performed to evaluate fire risks. Initial research, information and data can be found at the National Institute of Standards and Technology (NIST), as well as peer-reviewed sources in libraries and journals.

3.2 Modelling Approach

Event tree/fault tree (ET/FT) methodologies are often considered appropriate for assessing technical risks in fire engineering, while BNs are more suitable for modelling human and organizational risks. By assimilating the advantages of these methodologies, the resulting model based on the combination of ET/FT and BN will provide a more detailed and holistic risk model. However, while the model can express the static relationships between logical variables, it is unable to deal with the dynamic characteristics of human and organizational variables.

In order to quantify the dynamic influence of HOEs on overall risks, SD methodology will be incorporated in an overall T-H-O-Risk framework that can quantify risk variations over the life cycle of buildings. This conceptual framework is presented in Figure 1, which indicates the linkages between the various methodologies. The first interface in the T-H-O-Risk framework arises between ET/FT analysis and BNs. The SD model describes dynamic deterministic relationships and integrates with the ET/FT and BN models. In the framework, different models have varying inputs and outputs to the SD model which allows the T-H-O-Risk framework to capture detailed feedback, flows and delays

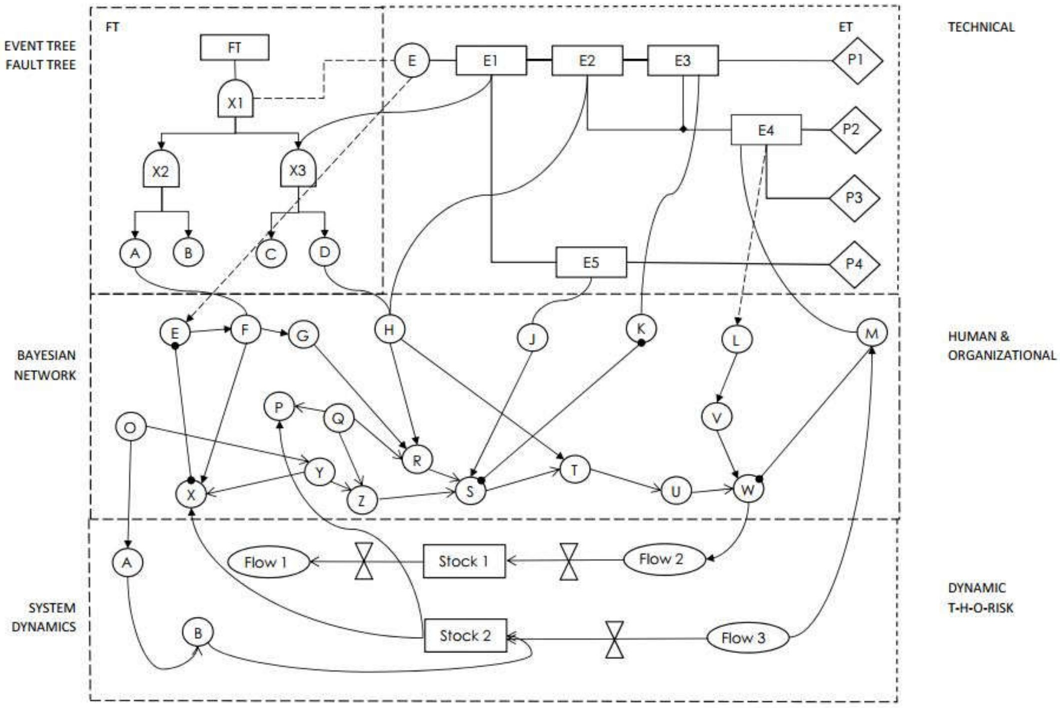

Figure 1 – Integrated Technical-Human-Organizational model framework

3.3 Detailed Model Development Framework and Research Steps

The probabilistic framework combines analyses of technical, human, and organizational errors in an enhanced model that builds upon the approach developed by Wang et al. [4] for offshore platforms. The approach in [4] is limited to offshore jet fires with a fixed number of probabilistic scenarios. The ET/FT methodology of the existing CESARE-Risk [5] model is used as the baseline to develop the enhanced risk model. The ET/FT model is modified by the inclusion of human and technical risks through the incorporation of BN and SD methodologies in the model. The resultant model integrates technical, human, and organizational risks.

BN modelling is used for HOE inclusion and SD modelling is incorporated to deal with dynamic characteristics of process variables and organizational factors. BN and SD tools incorporate an infinite number of states and consider the response of a system to the effects of other systems. Hence, more realistic and detailed analyses are possible by using these tools, however, their applications in fire risk models for high-rise residential buildings are scarce. BN and SD modelling are generally utilized for large, complex systems and can be extremely time-consuming. To keep the current research scope manageable, only specific aspects of BN and SD methodologies relating to risk mapping and propagation are incorporated into the fire risk model, with attention given to risk measurement and characterization, quantification of consequences and the resulting risk levels for limited types of high-rise residential buildings only.

In the model, fire scenarios are simulated in B-Risk[1] to characterise fire initiation, growth and fire and smoke spread. B-RISK is a two-zone fire model that is preferred over single-zone models due to its Monte-Carlo capabilities that enable uncertainties in fire scenarios to be quantified [6]. Performance thresholds can be indicated as cumulative density functions showing when tenability threshold probabilities are exceeded [7]. It was also determined that field models such as Fire Dynamics Simulator (FDS)[2] would be too computationally expensive to implement for probability-based risk modelling. The model developed in this research will provide improved probabilistic measures for uncertainty modelling and is expected to perform better than existing models. Additionally, the results are expected to compare favourably with actual statistical data. A comparison of model results to statistical data was performed with CESARE-Risk in [6] and a similar comparison will be completed to ensure model accuracy. A comparative analysis of the BCA with other international codes and trends for verifying fire safety designs are also carried out during model development.

The BSI PD7974-7 [8] Fire Engineering Guide provides a general approach to probabilistic fire risk assessment as shown in Figure 2. Specific enhancements to the approach carried out in this research are indicated in red dotted lines in Figure 3.

[1] B-Risk is developed by BRANZ and the University of Canterbury

[2] Fire Dynamics Simulator (FDS) is a computation fluid dynamics fire simulator developed at National Institute of Standards and Technology (NIST)

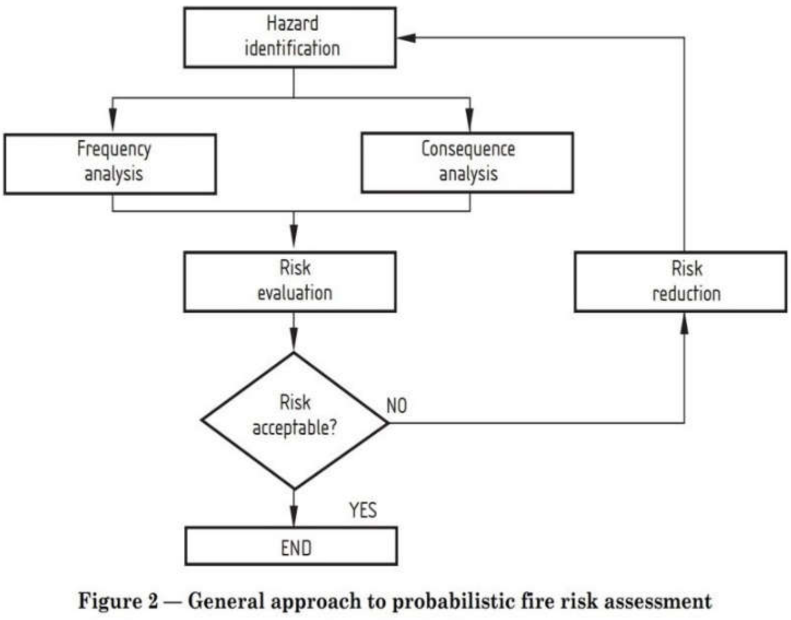

Figure 2: From BSI PD 7974-7- General approach to probabilistic fire risk assessment [8]

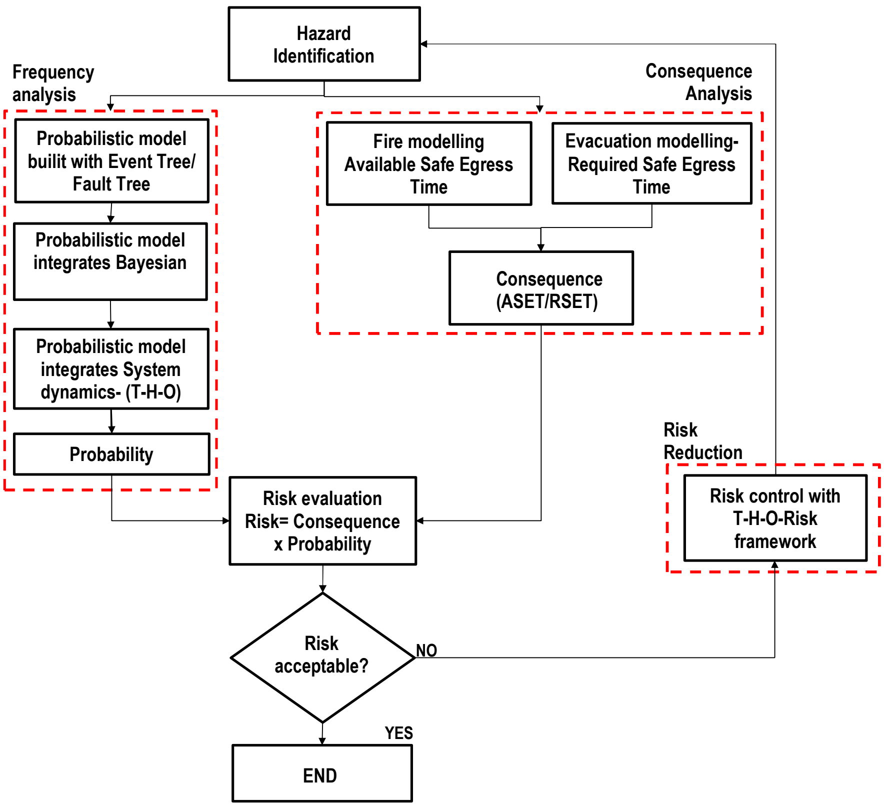

Figure 3: Specific enhancements to the general approach to probabilistic fire risk assessment provided in BSI PD 7974-7

Based on the enhanced probabilistic risk framework above, the research steps are depicted in Figure 4. The details of each component/sub-model of the proposed research outline are further described in the next sections.

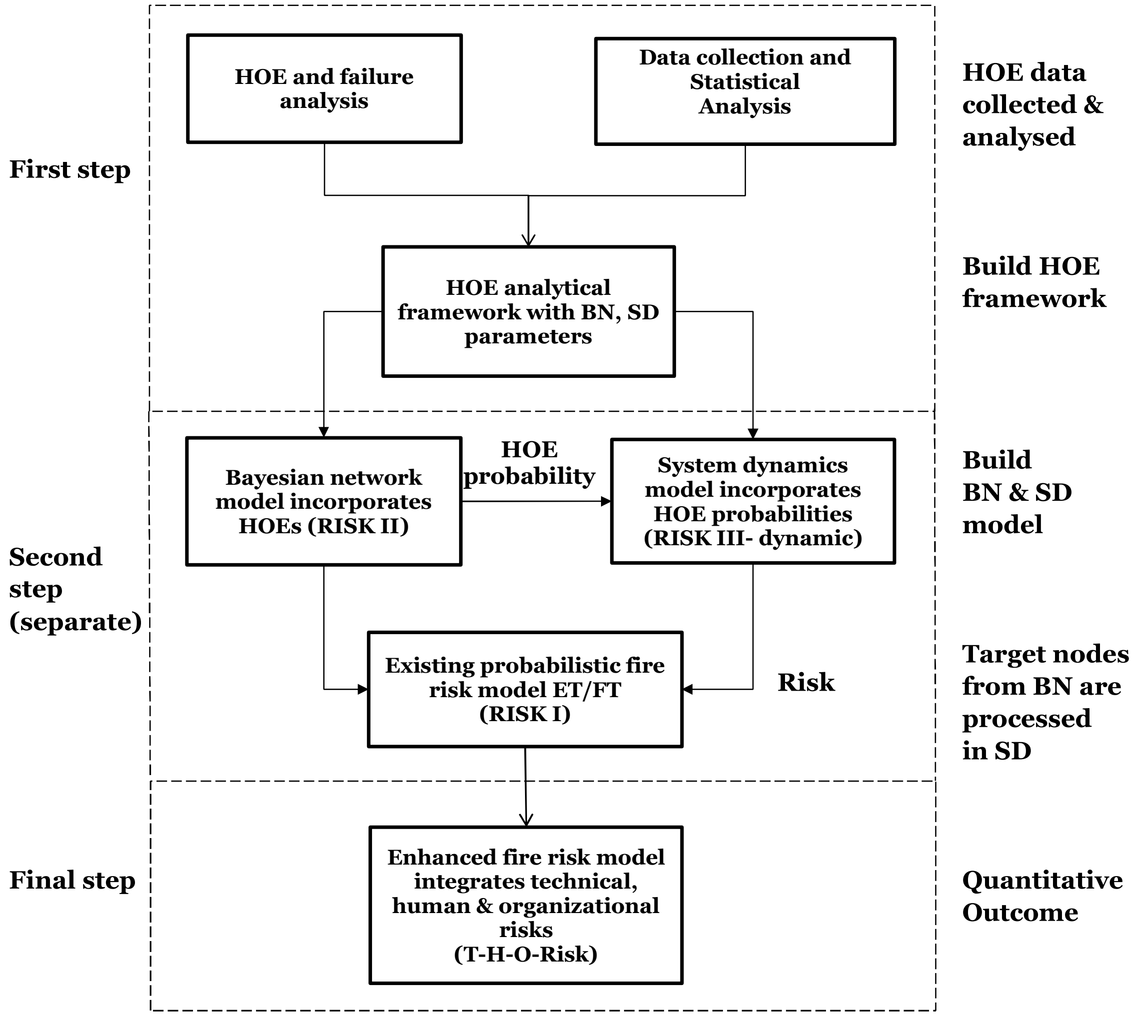

Figure 4 – Research Steps for T-H-O-Risk framework

3.4 Estimation of Human and Organizational Errors

There are several potential HOEs that could be included in the modelling however to limit the scope the important and relevant HOEs must be determined. Examples of HOEs related to high-rise buildings include:

1. Planned and regularly executed fire drills.
2. Annual maintenance, bi-annual maintenance, or no maintenance.
3. Regularly executed staff training.

4. Policies of stay-put or total evacuation.

For example, the impact of executing regular fire drills is expected to produce a more orderly and timely fire response, and probabilistic estimates of the impact of performing/not performing drills will need to be identified [9].

Probabilistic risk factors relate to scenarios that can go wrong, such as lack of regular drills, or evaluating levels of an event, such as the severity of a fire event. For risk assessment, a commonly used measure is ALARP and it means that an undesirable event has an acceptably low probability of occurrence. In this phase of the research, a list of probabilistic risk factors for HOEs will be developed in a comprehensive literature search. The estimation of the factors will be performed by identifying those factors found in the literature that relate to the HOEs associated with high-rise residential buildings in Australia. From the literature, necessary HOE probabilities can be identified and/or calculated through fault analysis. Once the relevant probabilistic risk scenarios are identified, the framework can be developed for eventual inclusion in the risk model.

3.5 Bayesian Networks

The Bayesian approach provides a method for estimating human and organizational risks, an important component of the T-H-O-Risk method when applied to fire risk modelling. In this approach, the probability required for risk estimation is initially computed as the "prior" estimate of the probability. BNs provide a blend of the prior probability and the new building data to obtain a "posterior" estimate of the probability value as discussed in Hanea [10] and can combine subjective and objective information from two or more data sources.

The BN approach is based on Bayes theorem which is fundamental to conditional probability. Let $P(B)$ be the prior probability of an event B. The conditional probability of event A occurring given B has occurred is denoted by $P(A/B)$. The posterior probability $P(B/A)$ which denotes occurrence of B given A has occurred is:

$$P(B/A) = \frac{P(A/B).P(B)}{P(A)} \qquad (1)$$

3.6 System Dynamics

System Dynamics modelling is another important element in the analysis. SD modelling is used to obtain time-varying probabilities that allow for the representation of feedback loops and delays. Because BN is used where is there is limited knowledge and lack of historical data, it can be appropriate for use in fire risk assessments. The approach has an advantage over conventional ETA and FTA methods by allowing for interconnections between systems and the incorporation of human and organizational factors. SD can be modelled in graphical form or written in mathematical form and works in two phases: qualitative and quantitative. In the qualitative phase, feedback loop diagrams are developed which provide cause-and-effect relationships between systems. In the quantitative phase, mathematical insights are provided to the qualitative model. Although the change in the technical systems does not change significantly over time, monitoring of human and organizational factors in the models is an important element in SD Models.

3.7 Methodology to Quantify Technical-Human-Organizational Risks for High-Rise Residential Buildings

In this section, a methodology is presented that incorporates technical, human, and organizational risks, called the T-H-O-Risk methodology. It is divided into four modules as follows:

- Building and Occupant Characteristics, Fire Safety Systems
- Fire and Evacuation Modelling
- Statistical Data Analysis
- T-H-O-Risk Analysis and Output

The model compares and analyzes building solutions using the following methodology:

1. Each building solution, either DTS or Alternative, is inserted into the risk model by specifying the number of apartments, floor level, travel distances to the nearest exit stair, occupancy load within each sole occupancy unit (SOU) and fire safety systems provided in the building (both passive and

active systems). Variables in fire safety measures that impact technical risks within the model are shown in Table 1.

Item	Fire safety measures/variables
A	Number of exit stairways
B	Travel distance to exit
C	Number of residential units
D	Heat detection
E	Smoke detection
F	Sprinkler system
G	Smoke management system at corridors
H	Building notification system
I	Fire rating between apartment and corridor
J	Self-closers at apartment door
K	Smoke seals at apartment doors

Table 1 - Fire safety systems/variables

2. Both DTS and Alternative solutions are evaluated in the event tree where the number of scenarios is dependent upon the fire safety measures provided. The model performs an Available Safe Egress Time (ASET)/Required Safe Egress Time (RSET) analysis for each SOU for all scenarios in the event tree. The ASET/RSET methodology is discussed in detail in Section 3.9 below. ASET will be determined using fire modelling in B-Risk[3] and will be calculated by summarizing the detection time (t_d), response time (t_r), and travel time (t_t) for each apartment. Travel time is determined by hand calculations based on the Society of Fire Protection Engineers (SFPE) hydraulic model equation [11]. Detection times are determined and specially programmed in an Excel spreadsheet and premovement times are based on criteria for residential occupancy provided in BSI PD7974-7 (Application of fire safety engineering principles to the design of buildings. Probabilistic risk assessment) [8].

[3] B-Risk is a two-zone fire modelling software developed by Branz and University of Canterbury, New Zealand

3. Technical risks are computed by multiplying the probability for each scenario with its summarized consequences and the expected frequency of fires at the floor level (as described in Equations 2 and 3). The resultant technical, RISK I is presented as individual risk, average risk at the floor (expected number of fatalities per year) and an F/N curve.

   In fire engineering, the measurement of ERL is described in Equation 2 by David Yung [12] below:

$$ERL = P \times C \tag{2}$$

   where P is probability of a fire scenario and C is consequence, which is the expected number of deaths resulting from the scenario.

   Given that scenario methodology is commonly used in fire engineering, risk to occupants is calculated based on all probable fire scenarios, so the ERL is expanded into a comprehensive ERL as described by Equation 3 below:

$$comprehensive\ ERL = \sum_{i=1}^{N} p_i \times c_i \tag{3}$$

   where i represents an individual scenario.

4. Technical RISK I for both DTS and Alternative solutions are then compared with the absolute risk criteria given in BSI PD7974-7 [8] to determine acceptance levels.

5. To perform an analysis for human and organizational risks (RISK II), the event tree for each building solution (either DTS or Alternative) is mapped into a BN model in Module 4: T-H-O-Risk Analysis and Output. A representation of the BN-technical risks is illustrated in Step 2 of Figure 5.

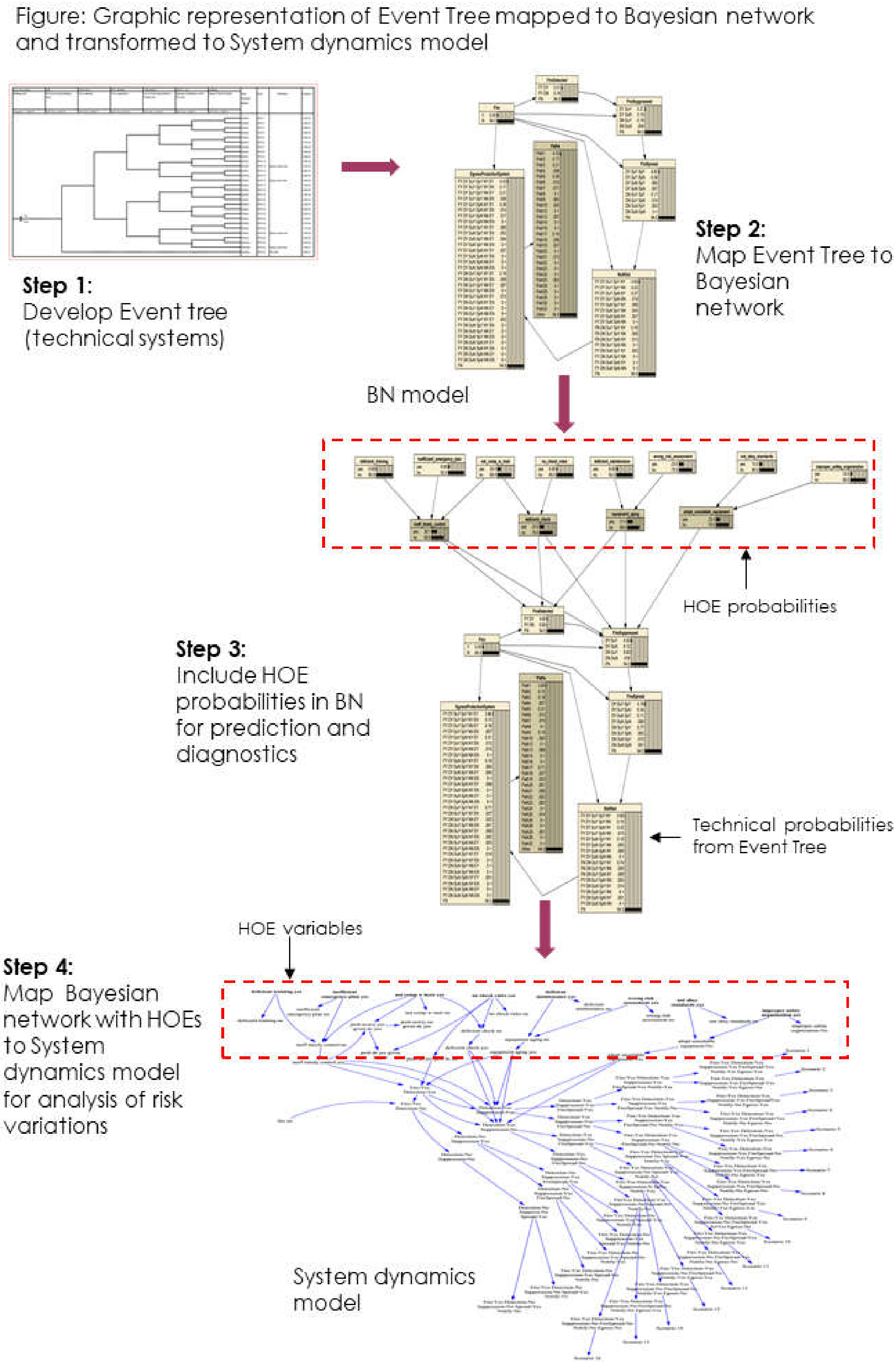

Figure 5 - Mapping the Event Tree to the BN and SD Model

When unknown elements are given, Bayesian networks are generally used as the decision-making criteria [13] because they help incorporate the following:

• Multi-state variables

• Dependent failures

• Expert opinions that cannot be performed using standard FTA.

BNs allow for the combination of previous probability assignments with the newly available statistical data. In this study, Bayes' theorem is applied to derive a scenario probability that depends on uncertain factors. The key features of the method are:

• For the incorporation of HOEs, ET is mapped into a BN.

• In the first instance, the BN inserts observations in the nodes that are observable and then utilizes the rules of probabilistic calculations forward and backward from the nodes that are observable to the target node via an intermediate node, if exists.

• The extended BN model incorporating HOEs, determines a more precise estimate for the probability of occurrence of the top event if a specific configuration of critical HOEs is given.

• The critical parameters are revised based on prior probability, posterior probability, and mutual information (i.e., entropy reduction) computed for each given HOEs.

• The BN scheme is essential when the system state depends on more than one event. Since ETs are only capable of representing single input in a node, multiple inputs are ensured by adopting a Bayesian approach [10]. This is the case when human errors are considered.

By writing a conditional probability table, an ET can transform into a BN that provides the probability of an outcome given the probability of its causative events using the method suggested by Unnikrishnan et al. [14]. Netica[4] which is a BN tool from Norsys is used for the BN modeling due to its ability to:

• To incorporate case files;

• To provide sensitivity analysis;

[4] Netica is a Bayesian Network software developed by Norsys Software Corp. Canada and available free from https://www.norsys.com/netica.html

• To operate in batch mode.

Netica computes standard belief updating which solves the network by finding the marginal posterior probability for each node. The exact calculation of those values is computed by Netica and exported to an Excel spreadsheet.

6. From the HOE analytical framework, probabilities for relevant human and organizational risks are inserted into the BN model (see Step 3 of Figure 5). These human and organizational variables will influence the probability of each scenario depending on their locations within the BN model. The new risk of each scenario is re-computed by multiplying the new probability for each scenario with its summarized consequences and expected frequency of fires at the floor level. The resultant RISK II is presented as an individual risk, representing the average T-H-O-Risk at the floor and an F/N curve (See Figure 6). The difference in risk values between RISK I (technical) and RISK II (human and organizational) will provide indications of relative risk levels attributed to HOEs.

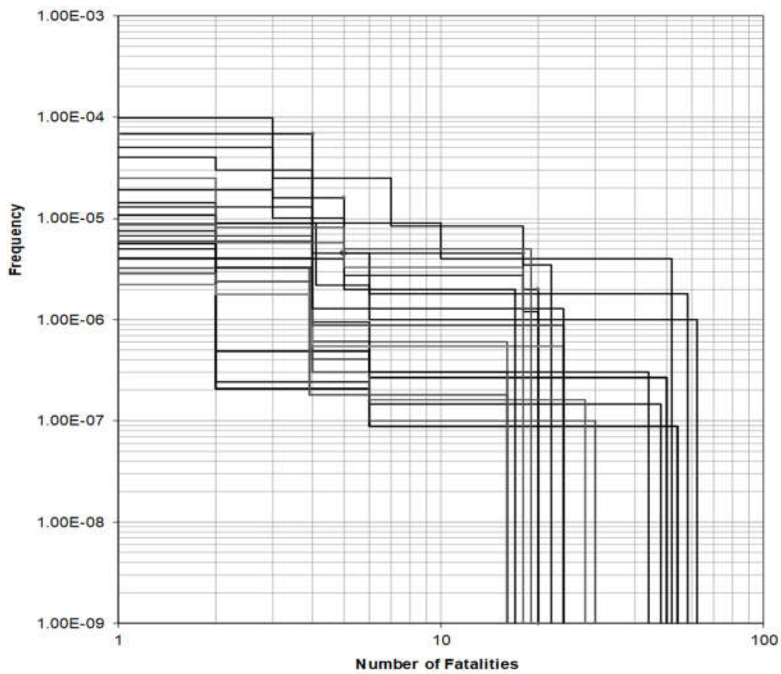

Figure 6: Example of multiple F/N curves on log-log scale

7. The final step to determine risk variations over time (RISK III) is performed by mapping the BN (T-H-O-Risk) into a SD model using

Vensim software from Ventana Systems[5]. An example representation of the SD model is indicated in Step 4 of Figure 5. Causal loop diagrams that describe the information feedback which may simulate human and organizational risks are then added. A stock flow diagram provides a quantitative estimation of their influence on human and organizational variables. A quantitative analysis of the state changes in the major HOE variables is conducted using the simulation model. The output provides a characterization of the risk variations in the form of a probabilistic risk-time curves over a selected period in the life cycle of the building solution, such as 10, 20, or 30 years.

8. The model will be able to perform several parameter variations for comparative risk analysis as indicated in Table 2.

Item	Parameter variation	Type of Risk
A	1 stair vs 2 stairs	Technical
B	Smoke management vs no smoke management	Technical
C	Planned and regularly executed fire drill vs no fire drill	HOE
D	Annual maintenance vs bi-annual maintenance vs no maintenance	HOE
E	Trained staff vs untrained staff	HOE
F	Stay put vs total evacuation	HOE

Table 2 - Parameter variations for probabilistic risk analysis

To limit the scope of the risk analysis, the four HOEs were included in Table 2 as they have been identified in the literature as important and likely relevant to risk in high-rise residential buildings. The above approach will provide a practical way to estimate the risk levels of different fire safety measures as well as

[5] Vensim is a freely available system dynamics modelling tool developed by Ventana Systems Inc URL: https://www.vensim.com

performance levels of different building management policies and strategies at the building planning stage.

3.8 Consequence analysis

To calculate the consequences for scenarios in the event trees an ASET/RSET Timeline analysis is conducted for each scenario where the ASET is determined by the time when fire evacuation by occupants is no longer possible due to untenable conditions. The RSETs are calculated by summarizing the detection time, response time and evacuation time for the occupants to reach an exit. To determine the ASET, tenability criteria are selected. The effect of fire environments on occupants is an onerous subject to quantify because harm can be both psychological, physiological or physical and accurate data on humans are rarely available from actual fire incidents [15]. Various options include evaluating the height of the hot layer to determine the visibility - if the hot layer below 2 metres has visibility below 10 metres, occupants would be exposed to toxic conditions and are unable to evacuate or when occupants are exposed to more than 60 °C or 2.5 kW/m2 radiative heat. The current model uses the Fractional Effective Dose (FED) of 0.3 as tenability criterion where occupants are deemed to be fatalities at the time they receive 30 % of an incapacitating dose of toxic concentrations of gases since fire ignition. The FED criterion is normally exceeded much later than visibility or smoke layer height and so it is expected to generate more accurate outcomes.

3.9 The ASET/RSET Timeline Analysis

This section provides a brief overview of the ASET/RSET Timeline Analysis for fire safety engineering in the literature.

Performance Based Design (PBD) has been proposed as the building design future for fire safety offering a cost-effective and innovative solutions to different fire safety challenges for nearly two decades. The core of PBD for life safety is the principle that there is sufficient time for occupants to exit the building before being overcome by fire. In engineering terms, this mean that the ASET should be significantly larger than the RSET in order to have a safe design, typically referred to as the Timeline Analysis Method [16]. ASET is defined as the time from ignition to loss of tenability while RSET is defined as the time from ignition to escape. The ASET/RSET principle is fundamental to the required performance of buildings and other structures including transport vehicles. Since its establishment over 30 years ago, the concept of ASET/RSET Timeline analysis for fire safety assessment has been extensively used in performance-based fire safety engineering design by fire safety engineering professionals. Although it is widely used, some researchers such as Babrauskas et al. [17] and Chow [18-21] have criticized the method.

The main issue in ASET/RSET Timeline Analysis is that it ignores the randomness of human behaviour in fire events. The researchers argue that humans act in different ways from robots, and it is common to find that individuals engage in actions that are counterproductive, unsafe, or seemingly unreasonable. Babrauskas et al [17] present a historical review of the adoption of the ASET/RSET method, starting from 1975 through the research at NIST which is based exclusively on fire drills with the exclusion of single-family houses. At that time research studies began by interviewing single-family house occupants focusing on occupants who had evacuated successfully. If the goal is to improve fire safety, failures must also be studied by interviewing fire fighters, neighbors, and family members. An interesting observation the researchers highlighted was that the escape behaviour humans in an institutional, commercial or high-rise building is very different from that in a private house, where the majority of fires initiate.

The ASET/RSET concept ignores the effect of different fire scenarios on the same building which results in different ASET and RSET values, further indicating that these variables may not have a true or unique value [17]. If the occupants are asleep or awake affect the values of RSET, while the type of fire and the intimacy of the occupant with it can affect the ASET. Babrauskas et al. [17] argue that providing ‘as much escape time as physically and economically viable’ implies a safer approach than the ASET/RSET. In some cases, the difference between the ASET and RSET is significantly larger, but this cannot be distinguished because if the ASET>RSET condition is satisfied. both cases are considered safe. Thus, two designs that are exceedingly different in practice are treated as identical. From this perspective, Fleming [22] suggested an improved approach that describes a margin of safety given by ASET-RSET. The greater the margin, the safer the design. Another issue is the choice of the tenability criteria for the ASET assessment. Babrauskas et al. [17] point out that both psychological and physical elements are involved in the tenability, hence, there is a lack of scientific support for the selection.

Poon [23] states that the ASET-RSET method has been devised for a simple two-zone model for a single compartment, hence it may not be ideal for more complex geometries. The author also doubted the definition of adequate safety margin and argue that a variation analysis is challenging to pursue because of the high number of parameters involved. For advanced simulation models Poon [23] proposed a new dynamic approach to assess the level of safety. Albrecht [24] proposed a method that involves the estimation of the failure probabilities of different safety systems and a cost-benefit analysis. The comparison between the systems is made using the ASET concept. Albrecht acknowledges that there is no precise quantification of the uncertainties related to the input elements of the method which implies that the safety margin cannot be quantified. Hence, he recommends the adoption of partial safety factors for each contribution. Minegishi and Takeichi [25] propose that the ASET/RSET concept could be replaced with more sophisticated methodologies such as crowd management and crowd flow control. Fleischmann [26] indicates the variability in the input elements has an influence on the ASET/RSET analysis and highlights the complexity in the choice of input parameters.

Chow [19,20] analyzed the application of the ASET/RSET timeline approach in the Far East and noticed that in the design of large spaces such as subway stations, malls, halls and long tunnels, the timeline analysis has been mishandled frequently. Firstly, the approach has not been supported by large-scale field tests related to the Far East population characteristics. For example, since no data is available on the evacuees' behaviour within a highly populated area like Hong-Kong, data and parameters are typically taken from foreign countries with lower population density. This uncertainty also impacts the choice of safety margin. Secondly, the fire scenarios are often underestimated, with very low values of the heat release rate (HRR). Moreover, tenability limits only included thermal and smoke effects, while any other parameter linked to the toxic effect of gases is excluded from the analysis. Chow [19] summarized the following six points of concern with PBD projects in the Far East:

1. Scenarios with small design fires were utilized to obtain elongated ASET
2. Only thermal and smoke effects were included in Tenability limits.
3. Human behaviour under local conditions was not investigated in detail while estimating RSET.
4. Low occupant loading factor was used to obtain short RSET
5. Safety margin (SM) was assumed as a percentage of RSET.
6. Safety Index (SI) was used through dividing SM by the RSET [15] and human behaviour had a large contribution to RSET.

Chow [19] suggests that more realistic fire scenarios with higher HRR must be applied to achieve more reasonable ASET values, while higher safety margins would account for uncertainty. Also, fire safety management practices will need to be enhanced. Finally, Purser [27] believes that the ASET/RSET principle as fundamental to the required performance of buildings and other structures and states further that there has been little progress in the calculation of parameters that affect escape performance and hazard evaluation. In summary, most criticisms in the literature concern the application of the analytical method more than the method itself. Also, a lack of scientific support is obvious in important areas such as human behaviour or fire scenarios development. Moreover, the stochastic nature of most of the input parameters cannot be represented using a single number.

Despite all the criticisms above, the ASET-RSET Timeline Analysis can be considered an intuitive method and has been successfully utilized in various validation experiments, such as in Purser [27]. More research could be done at a larger scale to make available more data for better setup while further work is needed on the data collection of key ASET and RSET parameters, ranges of variability, measurement of recognition and response pre-movement behaviours. An important issue in the building safety evaluation is the implementation of a safety margin which allows the comparison between different safety systems.

Kurniawan [28] has listed several parameters that influence the efficiency of a performance-based evacuation. These include the following:

- Building physical characteristics such as corridors, stair width, landing areas.
- Occupants' behavioural characteristics that affect the evacuation time during both pre-movement time and movement time.
- Occupants' physiological characteristics such as sex, age, height and weight in addition to gas and heat tolerance.
- Environmental fire characteristics since the speed of the evacuation process is hampered by exposure to smoke.

The inclusion of these parameters in the evaluation of the ASET and RSET Timeline analysis could offer more accurate results to validate the methodology. Several software packages have enabled ASET/RSET calculations, for example, CFAST[6], CURisk[7] and CFD-FDS[8] for ASET. Typical parameters considered in these studies are ventilation, passive and active protection, type of smoke and fire, wind condition, room type and environmental condition. EXODUS[9] and FDS+Evac[10] have been used to evaluate RSET where parameters considered in these studies were physical attributes, behaviour attributes, number of occupants, type of time travel and person mode. The building performance assessment against fire hazards is also done using computer simulations by considering some parameters related to ASET and RSET. Another approach proposed by Schröder et. al [29] is the map representation of ASET and RSET where a difference map is introduced to represent the safety margin throughout the domain instead of cherry-picking these numbers. Their method seeks to reduce the extensive information contained in the difference maps to one scalar

[6] CFAST or Consolidated Model of Fire Growth and Smoke Transport is a two-zone fire model developed by NIST

[7] CURIsk is a quantitative fire risk analysis computer model CUrisk developed at Carleton University, Canada

[8] CFD-FDS or Fire Dynamics Simulator is a computational fluid dynamics fire simulation modelling software developed at NIST

[9] EXODUS is an evacuation simulation tool developed by Fire Safety Engineering Group at the University of Greenwich.

[10] FDS+Evac is an evacuation simulation module of FDS developed at VTT Technical Research Centre of Finland

measure of consequences. This facilitates multivariate approaches or risk-based analysis to reduce the uncertainties in PBD.

There is a consensus amongst stakeholders and practitioners around the adoption of the ASET/RSET approach as the basis for PBD. As discussed earlier, the ASET/RSET Timeline approach is intuitive and capable of representing complex phenomena in a concise and understandable way. Moreover, the approach facilitates new research paths involving the work of specialists from different disciplines. In this study, the following definition of RSET is adopted, i.e., RSET is the time taken by the occupants to reach safety and is subdivided into several intervals:

$$RSET = T_d + T_p + T_m \qquad (4)$$

where:
T_d = detection time
T_p = pre-movement time, or the time from notification until evacuation commences
T_m = movement time

Detection time can be determined or estimated using two-zone models such as CFAST or B-Risk. Notification time is typically assumed equal to 0, unless particular procedures are in place, like for example a pre-alarm sent to a control room for assessment of false alarm cases. Pre-movement time is generally taken from literature, with large uncertainty. An estimation for its distribution is proposed by Hasofer and Odigie [30] and Zhao et al. [31]:

$$f(t) = 0.232e^{\frac{(t-t_{mean})^2}{17.6}} \qquad (5)$$

Travel time can be estimated by the ratio of the length of the exit way and the speed of evacuees. The latter is computed using the SFPE hydraulic approach [11], given by the following equation:

$$S = k - akD \quad (6)$$

where:
S = speed along the line of travel in m/s
D = density in persons/m2
k = 1.40 constant for corridor
a = 0.266 constant for speed in m/s

ASET is the time from fire ignition until untenable conditions arise in the compartment. Hence, it is necessary to select those parameters that affect tenability which are typically as follows:

- Upper layer temperature < 200 °C
- Lower layer temperature < 60°C
- FED asphyxiant = 0.3
- FED thermal = 0.3
- Visibility > 10 m

They are commonly estimated through CFD such as FDS or two-zone fire models, such as B-Risk. The safety margin is the difference between ASET and RSET; if the ASET is found to be greater than RSET, then the system is safe, otherwise, the system does not ensure safe evacuation of occupants. To compare the level of safety of different components, the safety margin (SM) is described in [19]:

$$SM = ASET - RSET \quad (7)$$

The greater the Safety Margin, the greater the component safety.

3.10 Occupant Behaviour

As discussed earlier, the ASET should be much larger than the RSET to have a safe design. In this study, occupant behaviour is not considered explicitly in the RSET calculation because of the structure of the ASET/RSET method and the available information in literature related to our study as discussed below. Studies have shown that when first introduced, the ASET/RSET method utilized data obtained from interviewing the survivors of single-family occupants [32].

These studies focused on the occupants who were evacuated successfully. However, this was misleading as their analyses took the success stories as a reference, while failures better contribute to the fire safety improvement. Furthermore, the available studies have mainly focused on single-family residences although their escape behaviour is very different from institutional, commercial or high-rise building, where the majority of fires initiate. The ASET/RSET concept ignores the effect of different fire scenarios on the same building which results in different RSET and ASET values. This indicates that these variables have no unique values [17]. Whether the occupants are asleep or awake when the fire starts, affects the RSET values, while the type of fire and the intimacy of the occupants with it can affect the ASET values.

Another aspect of ASET/RSET Timeline analysis is the pre-evacuation time. The pre-evacuation time for an occupant, often referred to as pre-movement time or pre-response time, is the time beginning when the occupant is alerted that something may be wrong and ending when the occupant begins purposive movement within the exit stair or exit. The occupant needs to perform some actions when a fire occurs. These actions include investigating the incident, searching for others, getting personal items, warning others and preparing to leave. These actions take time to complete, however, there is very little or no data available on the time necessary to complete each type of pre-evacuation action. Hence, most of the RSET calculations still rely on overall time distribution data to describe the entire pre-evacuation period.

Kuligowski and Hoskins [33] discovered that the main influential factors of pre-evacuation times were actions taken during the pre-evacuation period and initial floor location (likely due to the information that occupants received on these floors). For some actions, specifically seeking information and helping, occupant factors (before or during the fire event) combined with performing these actions revealed significant differences in pre-evacuation times. Several studies have linked the pre-evacuation actions and pre-evacuation delays in the fire field. Research has established that actions performed during this period increase an occupants' delay time [34]. Moreover, it is discovered that each action type performed by occupants increases their overall pre-evacuation time. These factors can result from the environment, the actions of the occupants perform during this period, and occupant characteristics. It was demonstrated that during the pre-evacuation period, occupants who take certain actions have increased the overall pre-evacuation time. Also, certain actions, i.e., searching for information and confirming information about an incident, have been identified to increase pre-evacuation delays [35].

Environmental factors can influence the occupant's pre-evacuation time, specifically the information that people receive about the incident [36,37]. Occupants who were instructed through the emergency voice/alarm communication system rather than simply hearing an audible notification were shown to be more proactive to theses instructions [38]. Based on this outcome, it was hypothesized that occupants in high-rise buildings were more likely to report a longer overall pre-evacuation time when instructions were given via the emergency voice/alarm communication system to wait on their floor [39]. It should be noted that cultural factors can also impact occupant behaviour during evacuation. Ding et al. [40] found several factors in their study on the use of elevators for evacuation – pushing, hesitation, re-entering the elevator, preferences, and social bonding. Participants were all well-educated students, and the researchers note that both the type of participants and the Chinese culture may influence the results of the experiments. Culture is a universal phenomenon that influences human performance from country to country. Culture influences not only how we perceive the actions of others, but also our response to fire events. In general, it is expected that human errors during evacuation will vary by culture as culture influences the probability of a person following a specific course of action which may affect the probability of actions [41]. Culturally heterogeneous groups, in which individuals differ in sufficient degree in critical social and/ or cognitive dimensions, will be more likely to commit human errors than would culturally homogeneous groups. Also these human errors are more likely to be committed during high-stress environments such as during emergency evacuation than during routine ones [42-44].

Based on the discussion above, the pre-movement time was selected for values that are relatable to the available information in the literature and implicitly assumes that all people in the building behave rationally. The occupants of the case buildings that have been investigated are considered identical, in the sense that the characteristics and behaviour of the occupants have been considered constant throughout all the cases analyzed. In addition, the HOEs in the study are related exclusively to maintenance activities and their impact on the reliability of fire protection systems (detection and suppression). These activities have been linked to parameters that can be controlled through organizational practices and training. This fact enables the management to react to failures and flaws.

3.11 Risk perception

Given that the focus on this study is on HOEs in risk analysis, an important input variable in our risk model is the 'risk perception' of occupants, evacuees, building managers, etc. Risk perception is expected to have a significant an impact on the overall risk to life variations over the life cycle of a high-rise residential building. Since perceptions of risk and risk-related behaviours may increase the social, economic, and political impacts of disasters well beyond the direct consequences, risk perception is a key variable that needs more attention than is currently given in the literature and real-life applications [45]. Risk perception can be defined as the perception of a looming threat to a person's health and life. Risk is independent of one's perceptions and perceives risk as an outcome [46]. For example, getting lung cancer is a risk to a person who smokes, however, and how this person judges the risk of getting the cancer is risk perception. For a person, the risk of lung cancer could be extremely undesirable given the serious consequences, however, looking at the likelihood of the risk, he/she may find that the likelihood is low, leading him/her to accept the risk and continue to smoke [47]. In the context of fire evacuation, risk perception is a psychological process that assesses the probability of the occurrence of an unwanted incident subjectively in a specific situation, and the evaluation of a person's perceived susceptibility and available resources. Risk perception is influenced by emotions and susceptible to cognitive biases [46].

Risk perception has two major approaches i.e., expectancy-value approach and the risk-as-feelings approach. According to the former, the two components of risk perception are: i) a person's evaluation of a natural hazard and ii) his/her perceived vulnerability. Be it rational or irrational, the approach is comprised of an individual, group, and/or society's beliefs about the likelihood, scale, and timing of a hazard. In other words, the approach refers to the subjective evaluation of probabilities of a specific hazard and how the consequences impact that person. In the case of a building fire, the definition reflects on a person's self-posed question if he/she is at risk after receiving fire cues such as a fire alarm or smoke [48]. The risk-as-feelings approach, however, decries the assumption that risk perception is a deliberate cognitive process in its entirety. The approach emphasizes the role emotions play in the instant a decision is made. It further assumes that information needs to convey emotions to become significant for an individual. In other words, how much threat the individual feels if a fire event occurs, is what refers to as risk perception in the latter approach. In the case of building fires, the approach reflects on a person's gut feeling after receiving the aforementioned fire cues. Both the approaches are theoretically sound, relevant, and can be linked to fire evacuation, however, refer to different aspects of how a building fire is experienced. Therefore, a holistic approach to risk perception in fire evacuation must take both approaches into account [46].

Furthermore, the major difference between the two approaches rests in the psychological processes. While the expectancy-value approach focuses on rational cognitive processes, risk-as-feeling concentrates more on emotional and associative processes. This distinction is crucial for fire evacuation since the outcomes of the risk estimates as a result of the application of these processes can be distinct and the human behaviour may vary depending on the prevalent approach [46]. The actions an individual could take during the cognitive process such as gathering information and responding accordingly are largely based on the perceptions of the situation and the risk which is created over years of experiences in both emergency and non-emergency scenarios [49]. Multiple factors may decrease the threshold criteria of detection or increase the sensitivity to fire cues. Hence the amount of sense-based noise increases with the increase in complexity of an environment and makes it challenging for an individual to distinguish between the fire cues [48]. Finally, once the individuals who are exposed to fire situations feel the risk, they may communicate with each other and even evolve into violent resistance. Therefore, to reduce unnecessary disputes among laypeople, the difficulties caused by risk communication must be investigated thoroughly and the mechanisms of barrier formation must be studied in detail. Based on the assessments and their outcomes, effective solutions must be established among all stakeholders including the general public, experts, and the decision-makers [46]. In Tan and Moinuddin's [50] systemic review of human and organizational risks in high-rise buildings, the researchers list behaviours that directly affect human behaviour which are relevant for fire risk assessment and planning. There are also human perceptions such as biases or heuristics (mental shortcuts) that may impact fire risk assessment. However, as perceptions act through behaviours [51], they have not been included in [50] or this study. For instance, when people possess normalcy bias, they underestimate risk which manifests in the lag taken in gathering their belongings, raising the alarm, warning others, and initiation of egress movements [52]. Similarly, in the case of optimism bias, people are likely to delay emergency measures because they feel optimistic that no harm will befall them [53]. As in all cases of perceptual biases, the impact is seen in human behaviours, it is the latter that have been indicated in [50]. Hence, one of the aims of this study is to quantify the extent in which variation in the input variable 'risk perception' generates corresponding variations in the output ERL value for fire risk in high-rise residential buildings.

3.12 Model Validation and Case Studies

Once the model is developed, it is evaluated against statistical data and then case studies of high-rise residential buildings are used for parametric studies. Measuring the sensitivity of the model results to parameters is critical, while dependent on the availability of data, as well as the assumptions and constraints that evolve during the modelling phase. Sensitivity analysis is necessary to determine the impact of various inputs on overall risks. An uncertainty analysis of the effects of various fire safety measures on risk levels are also be carried out through Monte Carlo simulations using Excel and Modelrisk modelling [54] software.

3.13 References

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In the case of the above publication, the following authors contributed to the work as follows:

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1. They meet criteria for authorship in that they have participated in the conception, execution or interpretation of at least that part of the publication in their field of expertise;
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4. Potential conflicts of interest have been disclosed to a) granting bodies, b) the editor or publisher of journals or other publications, and c) the head of the responsible academic unit; and

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Name(s) of Co-Author(s)	Contribution (%)	Nature of Contribution	Signature	Date
Samson Boon Hua Tan	75	Conceptualization, methodology, software modelling, validation, formal analysis, investigation original writing, review editing	[redacted]	04-Mar-2021
Khalid Moinuddin	15	Conceptiualization, methodology, validation, resources, writing, review &editing, project adminstration, supervision		08/03/21
Paul Joseph	5	Validation, writing- review & editing, resources, supervision		08-03-21
Darryl Weinert	5	Validation, review & editing, supervision		

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3.14 Synopsis of Chapter 3

This chapter outlines the comprehensive T-H-O-Risk methodology, developed in this research to incorporate HOEs in PRA to enhance the credibility and reliability of PRA models. Results show that in general, fire safety designs that do not consider HOEs underestimate overall risks generally by ~20% and can reach up to 42% in an extreme case. Furthermore, risks over time due to HOEs vary by as much as 30% over a 10-year period. An initial sensitivity analysis of HOE variables in the three case studies indicates that deficient training, poor safety culture and ineffective emergency plans have significant impact on overall risk. More comprehensive sensitivity and uncertainty analyses of HOEs, expected risk to life, societal risk and time varying reliability are provided in Chapter 4 and will be discussed later.

The T-H-O-Risk approach demonstrates how technical, human, and organizational risks can be quantified in a comprehensive probabilistic framework and represents an important step in the development of the next generation risk assessment methods and incorporation building codes. In addition, the results demonstrate that HOEs can have a significant impact on overall fire risks in high-rise residential buildings. Next, Chapter 4 presents further applications of T-H-O-Risk methodology on seven buildings in different geo-political locations and the impact of HOEs on the reliability of active fire safety systems are investigated.

Chapter 4

Impact of Technical, Human, and Organizational Risks on Reliability of Fire Safety Systems in High-Rise Residential Buildings—Applications of an Integrated Probabilistic Risk Assessment Model

Overview

In the previous chapter, three case studies are conducted to demonstrate the application of the T-H-O-Risk approach to the designs of various high-rise residential buildings ranging from 18 to 24 storeys. The risk evaluation is based on a comparison between both prescriptive and alternative solutions. To compensate for the risk increment in the alternative solutions, a number of fire protection measures are analyzed and implemented in the building designs. This chapter, on the other hand, focusses on the application of the T-H-O-Risk methodology to seven case studies in various geographical locations with different climatic conditions to assess and compare HOE risks due to fires in high-rise residential buildings. These buildings are located in Australia, Hong Kong, Singapore, UK and New Zealand, and the Building Code of Australia (BCA) is considered as the reference code for all test cases. The case studies focus on active fire safety systems in high-rise residential buildings by comparing the impact of HOEs on individual fire safety systems and/or combinations of active systems. The active systems considered in the case studies were sprinklers, building occupant warning systems, smoke detectors and smoke control systems. Different combinations of active systems led to a total of 112 different trial designs across the seven case studies. The building risk levels are compared to each other and against the absolute benchmark criteria to determine if they exceed the acceptable risk threshold. The ERL for each building design has different human and organizational scenarios based on either no HOEs or with HOEs - where organizational standards such as maintenance, safety culture and emergency planning are determined to be low and human errors occur routinely. The impact of HOEs was evaluated considering the management strategy on evacuation drills and maintenance activities needed for the safety systems to work efficiently.

The chapter presents detailed results from the T-H-O-Risk model for HOEs and risk variations over time for all the trial designs in all the case studies. The methodology enables technical, human and organizational risks to be assessed in multiple F-N curves to determine if they meet the tolerability criteria, if risks are situated within the expanded ALARP zone, and whether Cost Benefit Analysis (CBA) will need to be carried out.

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Samson Boon Hua Tan	75	Conceptualization, methodology, software modelling, validation, formal analysis, investigation, data curation, original writing, review & editing	[redacted]	04-Mar-2021
Khalid Moinuddin	15	Conceptualization, methodology, validation, resources, writing- review&editing, supervision	[redacted]	08/03/21
Paul Joseph	5	Validation, writing- review & editing, project administration, supervision	[redacted]	08-03-21
Darryl Weinert	5	Validation, writing- review & editing, supervision	[redacted]	

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Impact of Technical, Human, and Organizational Risks on Reliability of Fire Safety Systems in High-Rise Residential Buildings—Applications of an Integrated Probabilistic Risk Assessment Model

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Abstract: The current paper presents an application of an alternative probabilistic risk assessment methodology that incorporates technical, human, and organizational risks (T-H-O-Risk) using Bayesian network (BN) and system dynamics (SD) modelling. Seven case studies demonstrate the application of this holistic approach to the designs of high-rise residential buildings. An incremental risk approach allows for quantification of the impact of human and organizational errors (HOEs) on different fire safety systems. The active systems considered are sprinklers, building occupant warning systems, smoke detectors, and smoke control systems. The paper presents detailed results from T-H-O-Risk modelling for HOEs and risk variations over time utilizing the SD modelling to compare risk acceptance in the seven case studies located in Australia, New Zealand, Hong Kong, Singapore, and UK. Results indicate that HOEs impact risks in active systems up to ~33%. Large variations are observed in the reliability of active systems due to HOEs over time. SD results indicate that a small behavioral change in 'risk perception' of a building management team can lead to a very large risk to life variations over time through the self-reinforcing feedback loops. The quantification of difference in expected risk to life due to technical, human, and organizational risks for seven buildings for each of 16 trial designs is a novel aspect of this study. The research is an important contribution to the development of the next generation building codes and risk assessment methods.

Keywords: technical; human; organizational risks; probabilistic risk assessment; fire risk; high-rise residential buildings; human and organizational errors; ALARP

1. Introduction

The recent Grenfell fire and Hackitt's [1] report on the use of safety cases in fire safety engineering have generated renewed interest in probabilistic methods for fire risk assessment [2–4]. Recent work in probabilistic risk assessment (PRA) includes Van Coile et al. [2] which provides an explicit definition of the acceptable level of safety and the relationship between various risk acceptance concepts in PRAs. The Australian Building Codes Board (ABCB) has proposed some benchmarks for individual and societal risk levels [5]. The recent publication of BS7974-7:2019 [6] focuses on the 'as low as reasonably practicable' (ALARP) principle, an explicit framework for PRA, and cost-benefit analysis (CBA) in fire safety engineering [2,3]. The ALARP principle recognizes that beyond a certain point, risk reduction may be too costly to implement. The monetary valuation of human life is assessed by adopting a parameter called 'societal willingness to pay' (SWTP) for one statistical life, based on the life quality index (LQI) approach [7]. In this approach, the risk to death is reduced in exchange for the increased monetary amount that society is willing to pay. In other words, until the SWTP is achieved there is an additional capacity for society to invest to reduce unnecessary loss of life. Gross domestic product (GDP) and life expectancy are typical variables used to indicate the health of a society where resources allotted for safety purposes get translated into an increasingly healthier life. Straalen and Meacham [8] propose a framework for the fire safety goal life safety, which links a quantified risk criterion for life safety with a series of well-defined fire safety criteria for the operative requirements for ignition of fire, fire development, evacuation, and strength of structures. These fire safety criteria can be related to generally applied fire safety solutions.

To implement PRA in buildings, Sabapathy et al. [9] provide a systematic approach through a case study of a six-storey commercial building based on comparative expected risk-to-life (ERL) methodology. Weyenberge et al. [10] developed an integrated quantitative risk assessment framework based on response surface modelling. There have been various other comprehensive risk models which were listed in [11,12]. All are focused on the quantification of technical risk factors without considering human factors. Oldham et al. [13] proposed a framework for prioritization of safety risk where rankings of risks are based on societal risk and weightings. They suggest the introduction of human factors into the analysis, with systematic follow-up.

Human and organizational factors (HOFs) are important variables in assessing fire risk and the literature suggests that human and organizational errors (HOEs) should be considered in PRA and are likely relevant to high-rise residential buildings [14]. Tan and Moinuddin [14] define HOEs as "the collective departures from acceptable or desirable practice by an individual or groups of individuals that may result in unacceptable or undesirable outcomes." In other high-risk sectors, personnel conditions in terms of training, and safety culture are usually implemented in PRA to ensure an adequate level of safety. HOEs related to fire safety in high-rise buildings include risk factors such as lack of regular drills or not following safety procedures, and poor safety culture. Gwynne et al. [15] assert that given the impact of executing regular fire drills on timely fire response, it becomes important to accurately estimate the value of probability towards performing or not performing fire drills. As much as 80% of accidents are caused by human and organizational errors [14,16] and our recent study of high-rise buildings found that in general, fire safety designs that do not consider HOEs underestimate overall risk by approximately 20% [17].

Fire safety protection in high-rise buildings consists of both active and passive systems that can be affected by HOEs. Automatic fire suppression and detection systems such as sprinklers, alarms, detectors, and smoke control systems are considered active systems while passive systems are designed to slow the spread or contain fires [18]. Reliability of passive systems is generally considered to be higher than active systems while active systems, such as sprinklers are considered highly efficient [19]. This perception of a difference in reliability may be related to a requirement that active systems require either automatic or manual intervention to initiate activation in a fire event [20]. In [19] the highest percentage of incidents of failure of sprinklers to activate was that the water supply was disabled or inadequate. Other causes were insufficient maintenance, damaged components, and antiquated systems or components. Indeed, there is evidence that both active and passive systems in a variety of fire systems may be affected by HOEs, including safety culture and maintenance activities, as well as the passage of time [14].

Meacham and Straalen [21] developed a Socio-Technical System (STS) framework of risk assessment based on both technical and human errors was developed. To show the importance of the link between safety practices and safety culture on risk assessments, Pence et al. [22] developed the socio-technical risk analysis (SoTeRiA) framework and used it to identify critical human factors in a nuclear power plant. Mohaghegh et al. [23] developed a framework using multiple levels of analysis to bridge the gap between safety culture and safety climate and comprehensively included human errors. The scope of this study was extended by Mohaghegh et al. [24] to operationalize multi-dimensional measurements using a Bayesian approach. Mohaghegh et al. [24] used the Bayesian Belief Network (BBN) technique to deal with human and organizational factors to develop a socio-technical predictive model. Further, SD was included in the model to predict risk as a function of time [25]. The approach by Lin [26] focuses on paired comparison quantification to differentiate and prioritize a set of management influences to reduce human or technical failure, and to quantify the size of different management influences on risk by combining it with BBN. The difference between BBN and paired comparison is that management interventions are independent of each other in the paired comparison. A third-generation hybrid algorithm that enhances both the qualitative and the quantitative basis of HRA, adding significant scientific depth and technical traceability to the highly complicated problem of modelling human–machine team failures in complex engineering systems is proposed by Groth et al. [27]. The main elements of the hybrid algorithm include a comprehensive set of causal factors, human–machine team tasks and events, Bayesian Network causal models, and Bayesian parameter updating methods.

Another methodology for the incorporation of risks related to human factors include human risk assessment (HRA) methods. In the first generation HRA methods, a human operator was considered a component of the system, but decision-making processes and motivation were not considered. In the next generation, HRA methods considered cognitive effects into the reliability analysis. It identified technical, human, and organizational factors for risk analysis but lacked transparency and traceability. A systematic study of HRA was made by Lyons et al. [28] wherein the methodology involved data collection, task description and simulation, human error identification, and finally quantification of human errors. The mismatch between humans and their tasks were identified through performance shaping factors (PSFs). Using this mismatch, human error probability is calculated which then becomes part of risk assessment. Such HRA techniques are generally time-independent models and do not consider human factors in an integrated way. Groth et al. [29] proposed the use of Bayesian methods to formally incorporate simulator data into the estimation of human error probabilities (HEPs) in existing HRA methods. The approach enables even limited amounts of simulator data to be used to enhance the technical basis of existing and future HRA methods. An automated approach to risk estimation is made in [30] where the semantic and spatiotemporal representation of knowledge of the urban area relies on a software system including a knowledge base; two components for quantitative and qualitative risk assessments, respectively; and a WebGIS interface. The knowledge base consists of the TERMINUS domain ontology, to represent urban knowledge, and of a geo-referenced database, including geographical, environmental, and urban data as well as temporal data related to the levels of operation of city services.

The literature review suggests that it is necessary to adopt both technical and human- organizational errors for realistic risk assessment of building design from a practical viewpoint. Furthermore, during the operational phase of the building, it is not reasonable to assume that the reliability of the fire equipment remains constant and its aging over time will need to be considered to derive a more realistic risk assessment value. To address the literature gaps and follow the suggestions made by researchers in their studies, we employ a technical-human-organizational risk (T-H-O-Risk) methodology in this article to assess and compare HOE risks due to fires in high-rise residential buildings. The T-H-O-Risk methodology is a novel, inclusive approach that overcomes the aforementioned difficulties and therefore provides a more realistic estimate of risk that covers multiple dimensions. Hollnagel's [31] Cognitive Reliability and Error Analysis Method (CREAM) deals with human errors, attempting to quantify human reliability and their impact on technical variables. The approach provides a good integration of human reliability into a probabilistic risk assessment through a cognitive reliability model. The CREAM approach is a bi-directional method, applicable both for predictions and for retrospective analysis (looking for the causes of an accident). This recursive method takes into consideration the context in which human actions take place and considers performance as the result of two different aspects: competence and control.

This paper focuses on active fire safety systems in high-rise residential buildings by comparing the impact of HOEs on individual fire safety systems and/or combinations of active systems. This study breaks down the impact of HOEs on sprinklers, building occupant warning systems (BOWS), smoke detectors, and smoke control systems. The building risk levels are compared to each other and against the absolute benchmark criteria to determine if they exceed the acceptable risk threshold. The ERL for each building design has different human and organizational scenarios based on either no HOEs or with HOEs-where organizational standards such as maintenance, safety culture, and emergency planning are determined to be low and human errors occur routinely.

2. Methodology

In our proposed T-H-O-Risk methodology [17], the ERL of an alternative solution can be compared to a deemed to satisfy (DtS) solution within the framework of F-N curve to determine the acceptability of the design. When designing a building, both performance solutions and DtS solutions can be used to achieve compliance with performance requirements. This approach allows for testing of the interrelationship between different sub-systems and removal of unnecessary subsystems. The risk approach enables the quantification of different fire safety systems in an F-N curve assessment. The methodology of T-H-O-Risk described in [12,17] is further improved in this paper with the inclusion of ALARP principle [2–4] in comparing the calculated risk values. The major steps in T-H-O-Risk methodology are depicted in Figure 1.

The first step in this methodology is to collect and analyze both technical and HOE data. Likely fire scenarios are created and then using this data, a preliminary risk analysis is carried out. An event tree (ET) is generated with all possible outcomes by considering each fire safety subsystem. The probabilities are computed for relevant events and then the ET is mapped to a Bayesian Network (BN). Probabilities for relevant HOEs are inserted into the BN model and the HOEs will influence the probability of each scenario depending on their location within the BN model. The variation in risk with time is computed by integrating the BN with an SD model that captures feedback loops and delays. A quantitative analysis of the state changes in the major HOE variables is conducted through simulation providing a characterization of the risk variations in the form of a probabilistic risk-time curve over a selected period in the life cycle of the building.

The model requires building inputs such as the number of apartments, floor level, travel distances to the nearest exit stair, occupancy load, and fire safety systems provided in the building. Both DtS and alternative solutions are evaluated in the ET where the number of scenarios is dependent upon fire safety measures provided. The event tree leads to the computation of overall fire risk to life if a fire occurs based on all the fire scenarios for each trial design using the simple Equation (1) involving probability and consequences.

$$Risk = \sum_{i=1}^{n} P_i \times C_i \tag{1}$$

Here P_i is probability of a fire scenario i, and C_i is consequence or expected number of deaths resulting from scenario i, while n is the total number of scenarios. It must here be noted that this is only one of the various definitions of risk, which only implicitly invokes the concept of uncertainty. In fact, according to Aven et al. [32] there are two main categories of risk definitions, one involving probability and expected outcomes, and a second one explicitly expressing risk as uncertainty. The definition adopted here is based on the first group and care should be considered to the fact that, even if not clearly stated, uncertainty is a fundamental aspect when dealing with risk; for this reason, risk-based methods require an uncertainty analysis.

The overall risk to occupants is calculated based on all probable fire scenarios leading to the computation of ERL in Equation (2).

$$ERL = F\frac{\sum_{i=1}^{n} P_i \times N_i}{POP} \tag{2}$$

where, F is the annual fire ignition frequency for the building, N is the number of fatalities in scenario i and POP is the number of occupants in the building.

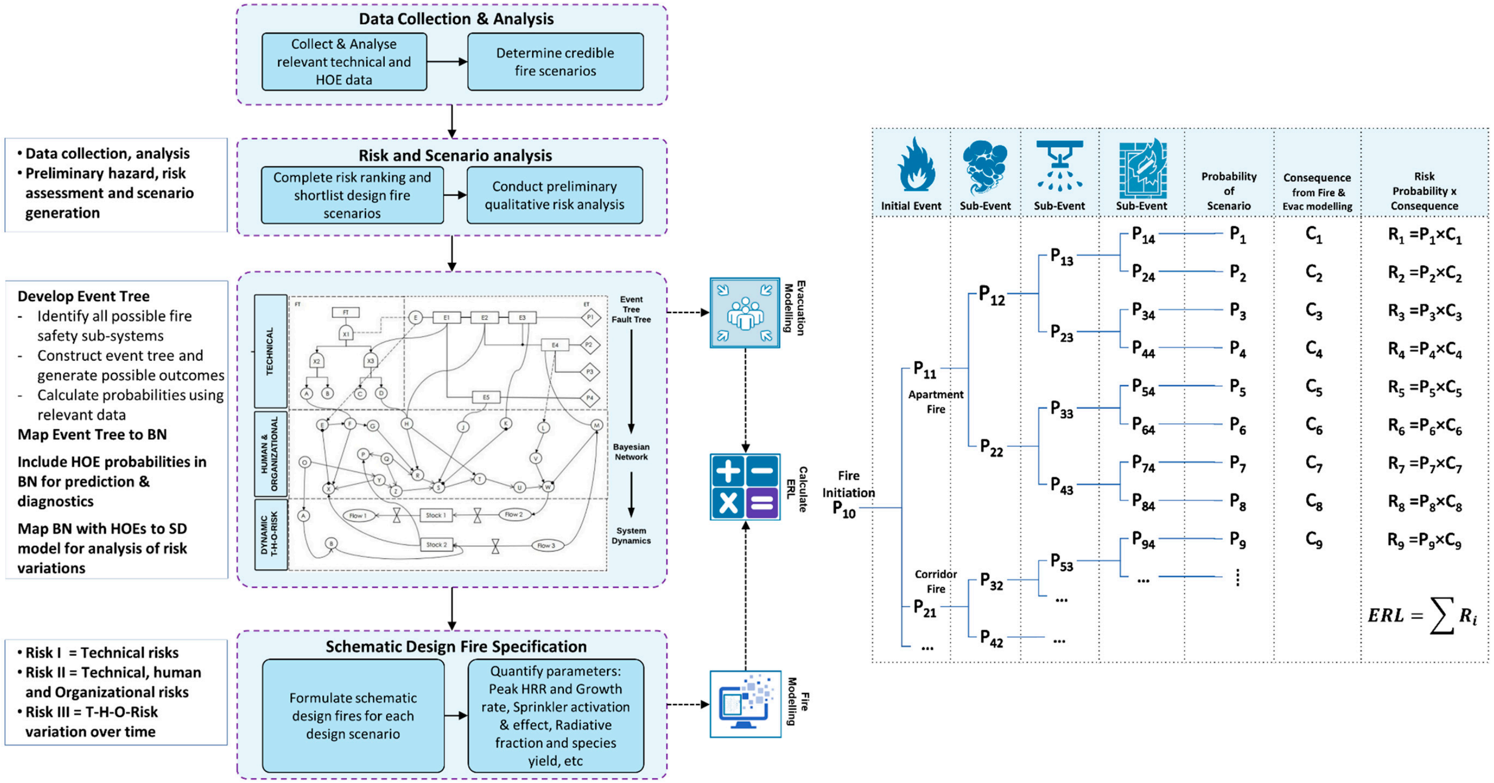


Figure 1. Technical-Human-Organizational-Risk (T-H-O-Risk) methodology. Note: ERL: Expected risk to life; BN: Bayesian Network; HOE: Human and Organization Error; SD: System dynamics; R: Risk; P: Probability; C: Consequences.

Both DtS and alternative solutions are then compared with the absolute risk criteria given in BSI PD7974-7 to determine acceptance levels.

2.1. Collection and Probability Analysis of HOEs

In this study, the important HOEs result from the Fussel–Vesely method which measures the importance of the basic events [33]. This method can be described as the ratio of the occurrence probability of the union of the minimum cut sets containing event X to the occurrence probability of the top event. To understand, consider a basic event *e* defined by the following equation:

$$p(e\ S) = \frac{p\ (eS)}{p\ (S)} \tag{3}$$

In the above equation, *e* is defined as the event where a model element of the hybrid approach is set to a specific probability of a risk state *S* (e.g., failure of a hardware component appears as a basic event in an event/fault tree analysis, or as a specific state of a BN variable such as procedural quality of maintenance set to low as opposed to a higher level). Hence the notion of the risk importance is now expanded for the inclusion of soft causal models and/or multi-state model elements. Once the notion of an event is generalized in the prescribed manner, the computation of important measures can be carried out in the usual manner.

A review and analysis of the literature is performed to obtain industry average probabilities/frequencies of HOEs, which are assigned to initiating events and basic events in the model to carry out a quantitative analysis of the frequency of occurrence. The results of this analysis may to some degree reflect specific building conditions since specific data should be applied whenever possible. Data may be found in incident databases, log data, and maintenance databases. In practice, extensive use of industry average data is necessary to carry out the quantitative analysis. The accuracy of results obtained from the model depends upon the assigned probability values of the HOE variables and equipment reliability data obtained from [34–39]. The applicability of the data from these sources to the building sector should be carefully considered. In fact, given that the analysis is largely based on probability, it is of the utmost importance that the provided data reflect the state of similar situations from the past. Therefore, before starting the application of the method, a survey of the existing databases is required. In some cases, where neither specific data nor generic data are found, it is necessary to use expert judgment to assign probabilities.

2.2. Event Tree

For each scenario, an ET will consider a fire event as the initiator and represents each subsystem and all possible outcomes. The event tree has the following events: (1) initiating event, (2) fire detected, (3) fire suppressed, (4) fire spread, (5) fire notified, and (6) egress protection system. For each of the scenarios in the ET, a probability of occurrence is calculated. For example, a scenario may be represented by the following chain of events (with the symbol of the associated probabilities):

- fire yes-*P(f)*
- detection yes-*P(d)*
- suppression yes-*P(Su)*
- smoke control yes-*P(SC)*
- building occupant warning system yes-*P(BOWS)*, and
- fire department response-*P(Fdr).*

The probability of each scenario is given by the product of the probabilities of the single events:

$$P(Sc) = P(f)P(d)P(Su)P(SC)P(BOWS)P(Fdr) \tag{4}$$

2.3. Bayesian Network

A BN is a probabilistic graphical model that represents a set of random variables and their conditional dependencies [40]. A BN consists of directed acyclic graph (DAG) where each node denotes a random variable, each edge denotes direct influence of one variable over another, and each variable is independent of its non-descendants given its parents. Further, each node has a conditional probability distribution represented in Equation (5).

$$P(X_1, \cdots, X_n) = \prod_{i=1}^{n} P(X_i \,\middle|\, Parents(X_i)) \tag{5}$$

A BN provides a compact representation of a joint probability distribution, capturing independence and conditional independence if they exist (see also Appendix A for details on BN equations). Further, it encodes the relevant portion of the full joint probability among variables where dependencies exist. The values in the CPT and their corresponding influence on the subsequent nodes are calculated based on expert judgment; higher values of the probability of a HOE are assumed to reduce the reliability of the technical systems. Furthermore, each combination of the states of a HOE variable is associated with a value for conditional probability. Through Bayes' theorem, the model allows calculations of the reliability of a technical system as a function of HOEs. HOE variables such as emergency plans, training, compliance with instructions and standards, maintenance, risk assessment, safety organization, and checking of rules are all analyzed for their impact on the reliability of a given technical system (e.g., sprinkler or detection system). The major outcome is the risk level for building design while alternative solutions are further investigated based on HOE risk-based parameters. The T-H-O-Risk methodology compensates for the weaknesses in HOE-related risks overlooked in a typical PRA. An example of BN for a building design can be found in our earlier study [17]. The BN structure has been developed by calculating the importance measures of basic events in the event/fault tree approach and multi-state BBN variables. The HOE basic events that contribute significantly to the occurrence of fire accidents have been identified from statistical data and presented in Table 1 below.

Table 1. Probability of relevant HOE basic events obtained from the literature [34–39].

Basic Events	Probability (10^6 h)
Poor safety supervision	4.60×10^{-4}
Deficient training	1.89×10^{-3}
Not following procedures	1.70×10^{-4}
Deficient risk assessment	1.80×10^{-4}
Deficient knowledge	1.89×10^{-3}
Inexperience	1.10×10^{-3}
Insufficient technical handover	6.30×10^{-3}
Insufficient safety check	2.50×10^{-2}
Inadequate periodic inspection	2.50×10^{-2}
Invalid daily record	5.60×10^{-3}
Inadequate emergency plan	5.00×10^{-4}
Failure to read monitoring data correctly	2.50×10^{-3}
Design error of operator	2.20×10^{-3}
Failure to follow technical requirements	1.92×10^{-4}
Not following technical requirements	1.92×10^{-4}

2.4. System Dynamics

While the BN model incorporates HOEs, it does not consider their risk variation over time; the BN helps in the computation of risk value at a given time. Since the condition of building and equipment varies over its lifetime, it is natural to ask whether risk can be computed that varies with time. Fire events are complex dynamic processes, yet HOEs can be analyzed utilizing SD modelling [41,42]. This requires interaction of the BN with the SD model for the HOE variables. The SD model incorporated for this analysis extends the model in [17] to encompass HOEs based on the reliability associated with maintenance practices and perceived safety. From a more general view, the maintenance regime is a subsystem linked with other subsystems, such as building management strategy and organizational safety culture.

The SD model is a two-step approach, the first being the causal loop diagram. A causal loop diagram is used to visualize the causal relationships in a system. It consists of all the elements representing the system and their interactions with each other including feedback loops and time delays, which are an integral part of the system. It helps conduct a qualitative analysis of the system's structure and behavior. The second step is the stock and flow diagram which is a quantitative analysis technique with the use of stocks and flows. Stocks are accumulations in the system and stocks are used to represent variables that change with time. Flows are entities that control these stocks. Flow entering a stock (*Entry flow*) increases the value of a stock and a flow exiting a stock (*Exit flow*) decreases its value. Mathematically, the relationship between stocks and flows is shown in (7):

$$Stock = \int_0^t (Entry\_flow - Exit\_flow)dt \tag{6}$$

In this approach, each node of BN is made equivalent to a node in SD model. For example, if one of the nodes of the BN is represented by state yes or no, it is assigned with a probability and represented as a single state variable in the SD model. To bring time-varying values into this variable, it is perturbed by a known value. For example, a variable *fire*:*yes* is associated with a normal probability value of 0.03. From experience, it is known that there is a variation of 25% on the probability values. This can be implemented as:

$$P(fire : yes) = 0.03 \pm (25\%\ of\ 0.03) \tag{7}$$

For the child nodes, the conditional probabilities are calculated using the chain rule application of Bayes' theorem. The CPT shown in Table 2 is translated into an equation using the Boolean logic.

Table 2. CPT for the BN node 'inefficient timely control'.

Deficient Training	Inefficient Emergency Plan	Not Comply with Instruction	Inefficient Timely Control
yes	yes	yes	yes
yes	yes	no	yes
yes	no	yes	yes
yes	no	no	yes
no	yes	yes	yes
no	yes	no	yes
no	no	yes	yes
no	no	no	no

Consider a child node 'inefficient timely control', which has three parent nodes—'deficient training', 'inefficient emergency plan', and 'not comply with instruction'. In the SD model, it is represented by the variables—'inefficient timely control yes' and 'inefficient timely control no' and can be translated into the following equations:

$$P(ineff\ timely\ control\ yes) = (P(deficient\_\ training\ yes))(P(not\ comply\ w\ instr\ yes))\\(P(ineff\_\ emerg\ plan\ yes)) \tag{8}$$

$$P(ineff\ timely\ control\ no) = (1 - P(deficient\ training\ yes))$$
$$(1 - P(not\ comply\ w\ instr\ yes))$$
$$(1 - P(ineff\_\ emerg\ plan\ yes)) \quad (9)$$

The same reasoning is applied to all other nodes in the BN. The final ERL variable contains the risk value for the specific design solution given by the sum of the ERLs of each single outcome.

The mapped SD model is shown in Appendix B and explained there.

2.5. Available Safe Egress Time (ASET)-Required Safe Egress Time (RSET) Analysis

Available safe egress time (ASET) is defined as the time between fire detection and the onset of conditions which is hazardous to continued human occupancy. This time is a function of visibility, temperature, and fractional effective doses. The time can be estimated using a fire modelling simulation tool B-Risk. Required safe egress time (RSET) is the amount of time required after a fire ignition for occupants to evacuate a building or space and reach the building exterior or a protected exit enclosure. RSET is the sum of the detection time, the evacuation delay time (sometimes called the pre-movement time), and the movement time. Detection time is the time at which occupants first become aware of a fire through a building's fire alarm system. The pre-movement time is the time that elapses between activation of the occupant notification system and the time at which occupants make the decision to begin evacuating. Pre-movement time includes the search for family and friends and to check whether the fire is real or not. The movement time is calculated by applying empirical relations for walking speed through egress elements such as doors, stairs, and corridors or using B-risk simulations. Evacuation time calculations were performed using the hydraulics methods outlined in Society of Fire Protection Engineering (SFPE) Handbook [43] and Pathfinder evacuation modelling software from Thunderhead Engineering.

In building safety design, it is considered acceptable if the ASET is greater than the RSET, after applying an appropriate safety factor. The ASET can be increased by limiting combustibles, providing large separation distances between fuel drums (if any), providing fire suppression systems to suppress developing fires, or provide active or passive smoke detection systems. Live voice messages help in reducing the pre-movement time. Proper location of exit signs helps in reducing the movement time.

2.6. Risk Estimation

The model is tested on different building solutions in different regions. First, a frequency of ignition is calculated as a function of the building use and area; this frequency is then inputted into the first node of the ET and the probabilities for each of the outcomes are calculated. The corresponding consequences (in terms of casualties) are determined using software simulations and RSET/ASET analysis. Finally, the total ERL is calculated for each case, adding up the contributions of all outcomes.

The introduction of HOEs is then considered by applying to the BN the same ignition frequency calculated previously. The BN contains HOEs and their impact on the global ERL is analyzed. In order to include the dynamic effects of time-varying parameters, the SD graph is applied to the cases. Here, the initial ignition frequency is input, and the simulation is performed in Vensim from Ventana Systems. Vensim is a simulation software capable of representing and modelling the dynamic behaviour of a complex system. Besides direct causal relationships among variables, it performs calculations of the temporal evolution of feedbacks and loops.

The risk estimation is generated using the basic equation involving probability and consequences. The overall risk to occupants is calculated based on all probable fire scenarios leading to the computation of ERL. The resultant ERL for each building solution without HOEs (from ET) is compared with the solution with HOEs (from BN) to determine the impact of HOEs on overall risk. The ERL is compared with the acceptable industry standards and a go-ahead is given to design if it meets the same.

3. Analysis

Section 3 describes the application of the framework's methodology to case studies of real buildings. As a starting point, in Section 3.1 the design parameters for input into the model are illustrated for each case study. After that, starting from the base case, different building solutions are systematically deployed by adding one safety measure at a time. Sprinkler, detection, building occupant warning, and smoke control systems have been combined to form 16 different trial designs. The main assumptions for the adoption of the model are stated in Section 3.3. Following that, the ASET/RSET calculations are presented, which form the basis for the estimation of the consequences.

3.1. Case Studies and Building Characteristics

We selected seven different high-rise residential building designs from Australia, Hong Kong, Singapore, UK, and New Zealand as shown in Figure 2 to apply the T-H-O-Risk methodology. General descriptions of the case studies are provided in Table 3.

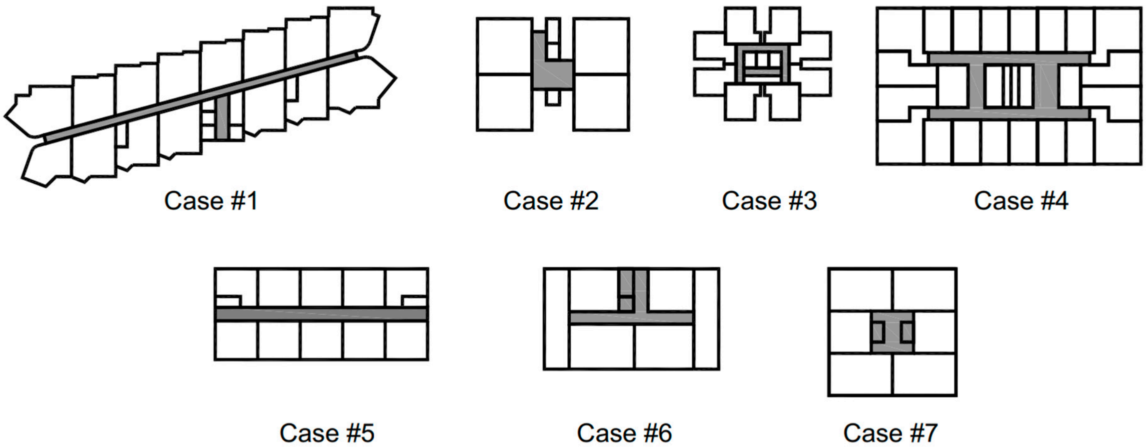


Figure 2. Floor plans of case studies.

Cases #1, #4, and #5 are alternative solutions with extended travel distance, Cases #2, #6, and #7 are alternative designs with single stair, while Case #3 is a DtS solution under the Building Code of Australia (BCA). Although the buildings are located across different countries, BCA is adopted as the reference building code for this study.

3.2. Trial Designs

The analysis incorporates trial designs for the seven case studies to understand the impact of HOEs on active fire safety systems. The active systems are sprinklers (Sprk), building occupant warning systems (BOWS), smoke detectors (Detect), and smoke control systems (SC). For each case, 16 different technical solutions have been analysed, applied to both apartment and corridor fire scenarios as shown in Table 4. Trial Design 1 has all active systems while Trial Design 16 has none.

3.3. Assumptions

The key assumptions in this study are discussed below.

Table 3. General description of case study buildings.

Parameter	Case #1	Case #2	Case #3	Case #4	Case #5	Case #6	Case #7
Building height (m)	58.7 m	60.0 m	107.0 m	63.0 m	51.0 m	57.0 m	67.0 m
Number of storeys above ground	21	20	38	21	18	20	24
Occupancy	Residential	Residential	Residential	Residential	Mixed	Mixed	Mixed
Location	Australia	Singapore	Hong Kong	Australia	Generic	NZ	UK
Climate	Temperate	Tropical	Subtropical	Temperate	Temperate	Temperate	Temperate
Development type	New build	New build	New build	Conversion	New build	New build	Renovation
Structural framing	Reinforced. concrete	Reinforced concrete	Reinforced concrete	Reinforced concrete	Reinforced concrete	Reinforced concrete	Reinforced concrete
Floor to floor height	3.0 m	3.1 m	3.6 m	2.9 m	3 m	2.4 m	2.4 m
Floor area per storey (m^2)	1099 m^2	505 m^2	324 m^2	1343 m^2	618 m^2	556 m^2	476 m^2
Number of apartments per floor	15	4	8	20	8	6	6
Number of occupants per floor	54	24	32	58	22	18	24
Stair and corridor ventilation type	Partial	Natural	Mechanical	Mechanical	Natural	Mechanical	Mechanical
Number of exit stairs	2	1	2	2	2	1	1
Stair width [m]	1.2 m	1.0 m	1.0 m	1.5 m	1.5 m	1.5 m	1 m
Stairwell door [FRL] min	60	60	60	60	60	60	60
Firefighting elevator	Yes	Yes	Yes	Yes	No	No	No
Structural fire resistance level [FRL] min	60	60	60	60	60	60	60

Table 4. Fire safety systems considered for case studies.

Trial Design	Sprk	Detect	BOWS	SC
TD01: Sprk Detect BOWS SC	On	On	On	On
TD02: Sprk Detect BOWS	On	On	On	Off
TD03: Sprk Detect SC	On	On	Off	On
TD04: Sprk Detect	On	On	Off	Off
TD05: Sprk BOWS	On	Off	On	On
TD06: Sprk BOWS	On	Off	On	Off
TD07: Sprk SC	On	Off	Off	On
TD08: Sprk	On	Off	Off	Off
TD09: Detect BOWS SC	Off	On	On	On
TD10: Detect BOWS	Off	On	On	Off
TD11: Detect SC	Off	On	Off	On
TD12: Detect	Off	On	Off	Off
TD13: BOWS SC	Off	Off	On	On
TD14: BOWS	Off	Off	On	Off
TD15: SC	Off	Off	Off	On
TD16: No Active Systems	Off	Off	Off	Off

Note: Sprk—sprinkler system; Detect—local smoke detector; BOWS—Building occupant warning system; SC—smoke control.

3.3.1. Fire Spread

The two main fire scenarios considered are an apartment fire and a corridor fire; the first one is a 5 MW t-squared fire (α = 0.0117 kW/s^2), the second one is a 300 kW t-squared fire (α = 0.0117 kW/s^2). The heat release rate (HRR) of the fire [44] is most important in fire risk analysis as it impacts primarily on smoke and heat production. The peak heat release rate for the apartment fire was based on 100 Monte Carlo simulation runs using B-Risk Design Fire Generator (DFG) fire modelling software. The peak heat release rate for the corridor fire has been assumed to yield from the complete burning of three waste baskets and corresponds to the above value [43]. As soon as the peak heat release rate is reached, the fire burns at the maximum rate until the simulation ends. When the smoke management system is in operation, it offers tenability conditions for the entire simulation duration, hence no fatalities outside the apartment of fire origin are expected for similar scenarios. Similarly, when the sprinkler system is in operation, it offers tenability conditions for the entire simulation duration, hence no fatalities are expected for similar scenarios.

Design fires are listed in Table 5 and are based on building use and the effects of the sprinkler system. For apartments, the design fire was developed for a typical dining/living compartment of 5.5 m width by 9 m length by 2.6 m height with a single window opening of 1.2 m height by 2 m wide. Flashover criterion was set at 500 °C for upper layer temperature. Fire load density range of 0–1000 MJ/m^2 and 80-percentile design value of 800 MJ/m^2 with triangular distribution and a mode of 400 MJ/m^2 were selected.

Table 5. Schematic design fires.

Design Fire	Type	Sprinkler Control Fire	Fire Growth Rate α (kW/s^2)	Peak HRR (kW)	Fuel Load Density (MJ/m^2)
1	Apartment	Yes	0.0117	197	800
2	Apartment	No	0.0117	5000	800
3	Corridor	Yes	0.0117	197	75
4	Corridor	No	0.0117	300	75

3.3.2. Occupants

Occupants are assumed to be awake and responsive to audio-visual warnings from the fire alarm system and can move normally. An emergency management plan is assumed to be part of the building fire safety system and building owners and managers have been trained on the necessary actions upon activation of the building occupant warning system. The assumptions in Table 6 have been applied to the four case studies.

Table 6. Assumptions applied to the four case studies.

Parameter	Assumption
Egress protection system working	No fatalities (SFPE [43])
Sprinkler system working	No fatalities (SFPE [43])
RSET greater than ASET	All people in the area of analysis (apartment/retail/floor) are considered as fatalities
Mobility impaired people	Travel speed for evacuation considered to allow for varying types of occupants
Tenability in the stairwell	Infinite
Scenarios with fire in the stairwell, when organizational rules governing the allocation of combustible materials are fully observed	Not considered
Fire effects outside the floor of fire origin	Not considered
Time for the Fire brigade to secure the building	1200 s
High level of organization	No human and organizational error
Middle level of organization	Human and organizational errors are associated with a probability of occurrence
Low level of organization	All human and organizational errors occur at the same time
Interactions between safety systems	Fire detection and sprinkler activation systems are considered as independent one from another
Soot yield	0.1 g/g
CO yield	0.026 g/g
Upper layer temperature	<200 °C
Lower layer temperature	<60 °C
Visibility	>10 m
FED_{CO}	<0.3
FEDth	<0.3

3.3.3. Tenability Limits

Tenability criteria are as follows: (1) upper smoke layer temperature above 2 m to be less than 200 °C, (2) lower smoke layer temperature below 2 m to be less than 60 °C, (3) visibility through the smoke layer to be greater than 10 m, at 2 m of height, (4) a fractional effective dose (FED) of carbon monoxide (CO) is to be less than 0.3, and (5) a FED from thermal effects is to be less than 0.3.

3.4. Determination of ASET/RSET

The activation time of the smoke/heat detector in the apartment of fire (AOF) origin is shown in Tables 7 and 8. Other times have been estimated or calculated analytically. ASET results are shown in Table 9. The results correspond to Trial Design 1 (all active systems are turned ON).

Table 7. Inputs for the ASET/RSET analysis.

Smoke Detector	Optical Density (m^{-1})	0.097	Sprinkler	RTI ($m^{1/2}\ s^{1/2}$)	135
	radial distance (m)	7		activation temperature (°C)	68
	distance below ceiling (m)	0.025		c-factor	0.85
	characteristic length (m)	15		water spray density(mm/s)	4.2
	Location	centre		radial distance (m)	3.25
				distance below ceiling (m)	0.025

Table 8. RSET analysis [different cases] based on Trial Design #1.

Case	Case #1	Case #2		Case #3		Case #4		Case #5		Case #6		Case #7	
Scenario fire	Apt	Corridor	Apt	Corridor	Apt	Corridor	Apt	Corridor	Apt	Retail	Apt	Office	Apt	Office
Detection (s)	36	209	35	138	37	34	36	37	211	156	125	125	25	25
Pre-movement time (s)	100	100	100	100	100	100	100	100	100	100	100	100	100	100
time to exit AOF (s)	12	12	19	19	5	5	12	12	58	55	18	18	64	29
time to exit floor (s)	57	57	29	29	22	22	52	55	1110	15	50	50	120	268
RSET AOF (s)	148	321	154	257	142	139	148	149	369	311	243	243	189	154
RSET floor (s)	193	366	164	267	164	156	200	189	421	408	275	275	245	393

Table 9. B-Risk ASET results based on Trial Design #1.

Case		Apartment				Corridor			
Design	**Scenario**	**Lower Temp.**	**Visibility**	**FED Thermal**	**FED CO**	**Lower Temp.**	**Visibility**	**FED Thermal**	**FED CO**
#1	Apt	420	51	216	648	Inf	200	644	871
	Corridor	Inf	140	1198	Inf	950	80	452	1152
#2	Apt	330	92	255	540	Inf	150	513	718
	Corridor	Inf	150	Inf	Inf	Inf	40	208	Inf
#3	Apt	280	50	185	500	580	280	341	626
	Corridor	Inf	Inf	Inf	Inf	210	40	151	Inf
#4	Apt	300	80	220	573	Inf	190	617	968
	Corridor	Inf	190	Inf	Inf	840	80	267	Inf
#5	Apt	350	110	220	322	1200	200	652	435
	Retail	210	75	135	200	630	130	299	273
#6	Apt	1200	70	244	797	1200	1200	1200	1200
	Office	510	34	130	402	1200	80	1200	1200
#7	Apt	310	130	226	488	1200	1200	1200	1200
	Office	180	50	137	312	1200	100	311	423

4. Results

The results of the impact of HOEs on the risk and reliability of fire safety systems in the case studies are presented as follows: individual risk (Section 4.1), societal risk in the form of F-N curves (Section 4.4), and System Dynamics (Section 4.5). Sections 4.2 and 4.3 focus on how human and organizational errors impact the individual risk of the buildings.

4.1. Expected Risk to Life (ERL) and HOE Quantification

The ASET-RSET analysis together with the risk assessment yields an overall ERL for technical risks for each building solution. A description of the ERL acceptance criteria, tenability, and ASET/RSET can be found in [19]. The results from T-H-O-Risk modelling for the trial designs for each case study are summarized in Table 10. These results are expressed in terms of ERL without HOE (noHOE) in the first column and ERL that includes HOE in the second column for each case.

Figure 3 shows the ERL results for all 16 trial designs for Case #1. It is interesting to note that the influence of HOEs increases with the complexity of the system; a design with the full set of safety provisions (Trial Design 1) shows a +33% increase in ERL when considering HOEs, while the simpler design with only the sprinkler system (Trial Design 8) has a +20% increase in the ERL. However, even with HOE, Trial Design 1 has lower ERL without HOE in any other design.

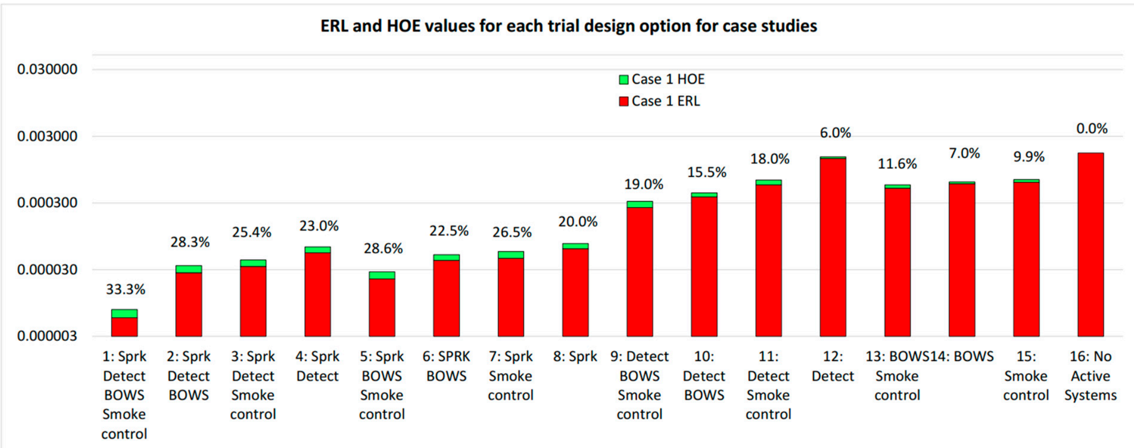


Figure 3. ERL and HOE impact on trial designs for Case #1 [log y-axis].

The HOE/ERL ratio (in %) as a function of number of active systems is depicted in Figure 3. The HOE/ERL ratio increases with an increase in the number of active systems. With one active system, the HOE values range from 8–13% and increased to 25–38% when all four active systems are present in the trial design.

In Figure 4, a linear relationship exists between the variable HOE/ERL% and the number of active systems. A correlation analysis indicates that HOE/ERL% and the number of active systems are strongly correlated in positive direction with respect to all cases #1 to #7-HOE/ERL% increases when active systems increase from 1 to 4. It can be concluded that a strong correlation exists between those variables for each case and for all data when considered together. The magnitude of correlation for each case is summarized in Table 11. While Case #1 and Case #7 have the highest correlation, Case #5 has the lowest correlation.

Table 10. ERL HOE results for case #1 to #7.

Trial	Case #1		Case #2		Case #3		Case #4		Case #5		Case #6		Case #7	
Design (TD)	**no_HOE**	**HOE**	**no_HOE**	**HOE**	**no_HOE**	**HOE**	**no_HOE**	**HOE**	**no_HOE**	**HOE**	**no_HOE**	**HOE**	**no_HOE**	**HOE**
1	5.68×10^{-6}	7.56×10^{-6}	3.23×10^{-6}	4.04×10^{-6}	6.72×10^{-6}	8.85×10^{-6}	1.42×10^{-5}	1.92×10^{-5}	2.23×10^{-6}	2.88×10^{-6}	6.45×10^{-6}	8.68×10^{-6}	5.01×10^{-5}	6.86×10^{-5}
2	2.69×10^{-5}	3.45×10^{-5}	1.54×10^{-5}	1.88×10^{-5}	3.50×10^{-5}	4.50×10^{-5}	4.39×10^{-5}	5.78×10^{-5}	3.22×10^{-6}	3.96×10^{-6}	3.34×10^{-5}	4.14×10^{-5}	8.06×10^{-5}	1.06×10^{-4}
3	3.34×10^{-5}	4.19×10^{-5}	1.89×10^{-5}	2.27×10^{-5}	4.54×10^{-5}	5.56×10^{-5}	5.94×10^{-5}	7.27×10^{-5}	6.44×10^{-6}	7.85×10^{-6}	4.33×10^{-5}	5.41×10^{-5}	8.42×10^{-5}	1.07×10^{-4}
4	5.38×10^{-5}	6.61×10^{-5}	4.12×10^{-5}	4.88×10^{-5}	7.56×10^{-5}	9.18×10^{-5}	8.32×10^{-5}	1.01×10^{-4}	8.84×10^{-6}	1.06×10^{-5}	7.36×10^{-5}	8.84×10^{-5}	2.79×10^{-4}	3.49×10^{-4}
5	2.18×10^{-5}	2.80×10^{-5}	1.35×10^{-5}	1.66×10^{-5}	2.86×10^{-5}	3.70×10^{-5}	3.93×10^{-5}	5.21×10^{-5}	3.02×10^{-6}	3.87×10^{-6}	2.67×10^{-5}	3.48×10^{-5}	7.82×10^{-5}	1.02×10^{-4}
6	4.12×10^{-5}	5.04×10^{-5}	2.46×10^{-5}	3.03×10^{-5}	5.29×10^{-5}	6.45×10^{-5}	6.06×10^{-5}	7.55×10^{-5}	8.13×10^{-6}	1.02×10^{-5}	4.65×10^{-5}	5.65×10^{-5}	8.87×10^{-5}	1.11×10^{-4}
7	4.44×10^{-5}	5.61×10^{-5}	3.08×10^{-5}	3.71×10^{-5}	7.40×10^{-5}	9.08×10^{-5}	7.73×10^{-5}	9.63×10^{-5}	8.26×10^{-6}	1.13×10^{-5}	7.11×10^{-5}	8.67×10^{-5}	1.06×10^{-4}	1.36×10^{-4}
8	6.56×10^{-5}	7.77×10^{-5}	6.03×10^{-5}	7.23×10^{-5}	7.92×10^{-5}	9.62×10^{-5}	9.41×10^{-5}	1.13×10^{-4}	9.58×10^{-6}	1.15×10^{-5}	7.77×10^{-5}	9.32×10^{-5}	3.31×10^{-4}	4.02×10^{-4}
9	1.56×10^{-4}	1.85×10^{-4}	1.18×10^{-4}	1.41×10^{-4}	2.86×10^{-4}	3.08×10^{-4}	3.91×10^{-4}	4.71×10^{-4}	8.57×10^{-5}	1.03×10^{-4}	2.33×10^{-4}	2.77×10^{-4}	7.52×10^{-4}	9.09×10^{-4}
10	3.69×10^{-4}	4.26×10^{-4}	1.59×10^{-4}	1.77×10^{-4}	4.87×10^{-4}	5.38×10^{-4}	6.27×10^{-4}	7.34×10^{-4}	9.55×10^{-5}	1.06×10^{-4}	4.56×10^{-4}	5.09×10^{-4}	1.40×10^{-3}	1.64×10^{-3}
11	5.63×10^{-4}	6.64×10^{-4}	3.94×10^{-4}	4.43×10^{-4}	6.68×10^{-4}	7.48×10^{-4}	7.62×10^{-4}	8.70×10^{-4}	3.88×10^{-4}	4.28×10^{-4}	5.98×10^{-4}	6.61×10^{-4}	2.12×10^{-3}	2.52×10^{-3}
12	1.37×10^{-3}	1.46×10^{-3}	1.01×10^{-3}	1.08×10^{-3}	1.52×10^{-3}	1.61×10^{-3}	1.86×10^{-3}	1.99×10^{-3}	5.43×10^{-4}	5.75×10^{-4}	1.33×10^{-3}	1.41×10^{-3}	6.66×10^{-3}	7.25×10^{-3}
13	5.01×10^{-4}	5.59×10^{-4}	3.81×10^{-4}	4.21×10^{-4}	6.59×10^{-4}	7.45×10^{-4}	7.42×10^{-4}	8.57×10^{-4}	3.55×10^{-4}	3.94×10^{-4}	5.73×10^{-4}	6.41×10^{-4}	1.62×10^{-3}	1.83×10^{-3}
14	5.80×10^{-4}	6.20×10^{-4}	4.18×10^{-4}	4.47×10^{-4}	6.86×10^{-4}	7.67×10^{-4}	7.83×10^{-4}	9.10×10^{-4}	3.98×10^{-4}	4.32×10^{-4}	6.16×10^{-4}	6.89×10^{-4}	3.44×10^{-3}	3.71×10^{-3}
15	6.12×10^{-4}	6.72×10^{-4}	6.15×10^{-4}	6.61×10^{-4}	8.11×10^{-4}	9.04×10^{-4}	8.85×10^{-4}	1.00×10^{-3}	4.56×10^{-4}	4.92×10^{-4}	7.58×10^{-4}	8.55×10^{-4}	4.12×10^{-3}	4.66×10^{-3}
16	1.68×10^{-3}	1.68×10^{-3}	1.23×10^{-3}	1.23×10^{-3}	1.82×10^{-3}	1.82×10^{-3}	2.27×10^{-3}	2.27×10^{-3}	1.04×10^{-3}	1.04×10^{-3}	1.77×10^{-3}	1.77×10^{-3}	8.38×10^{-3}	8.38×10^{-3}

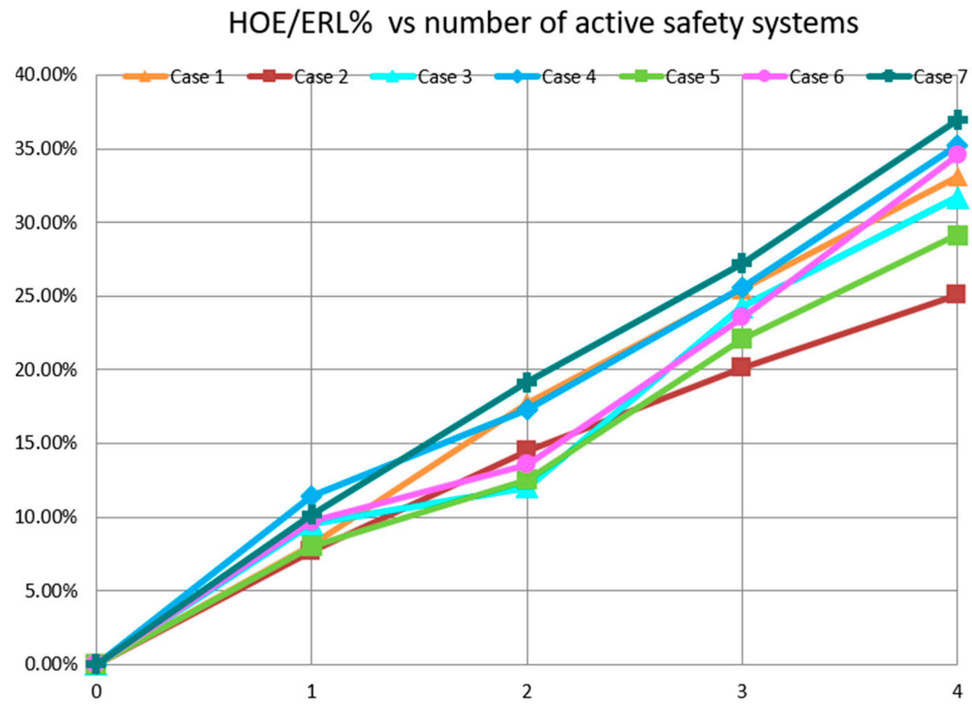


Figure 4. HOE/ERL% ratio vs. active systems.

Table 11. Correlation between HOE/ERL% and the number of active systems.

Cases	Pearson Correlation Coefficient
All	0.867
#1	0.945
#2	0.878
#3	0.863
#4	0.889
#5	0.760
#6	0.905
#7	0.944

4.2. Impact of HOEs on Active Systems

The fire fatalities in residential buildings vary across different countries and statistical data extrapolated from the literature indicate a range between 7.3×10^{-6} to 1.3×10^{-5} death/year in Australia, Canada, New Zealand, and the UK [45]. In this study, the calculated ERL with active systems indicate a range between 2.23×10^{-6} to 5.01×10^{-5} which compares reasonably well with the literature. With no active safety systems, the ERL range from 1.68×10^{-3} to 8.38×10^{-3} (Trial Design 16). As expected ERL values are higher in the absence of active safety systems.

Trial Design 1 provides the most comprehensive fire safety systems as it includes sprinklers, BOWS, smoke detectors, and egress protection but is also most influenced by HOEs. Indeed, Trial Designs 1–9 consist of more complicated systems for fire safety, while Trial Designs 10–15 fire safety systems are less complicated. In general, these more complicated systems result in the lowest ERL.

HOEs have significant risk impact ranging from an average of 19.7–33% (average values of cases) with combinations of sprinklers, BOWS, smoke control systems, and smoke detectors for Trial Designs 1–9. For design options 10–15, HOEs had a lower impact on risk, ranging from 6.5% to 16.3% (average value of cases). HOEs have limited or no impact when active systems are absent.

4.3. Summary of HOE Results

Results of the T-H-O-Risk analysis compare reasonably with fire risk reported in the literature where available [45–48]. The influence of HOEs is significant for Case #4 and Case #7 at 32% and 33% respectively with active systems of sprinklers, BOWS, and smoke detectors as these require regular maintenance. Case #4 is a building that has been converted from office to residential use while Case #7 is an old residential building that has been remodelled—both have inherent inflexibilities and legacy compliance issues which likely heightened their risk levels. As the number of active systems increases, the influence of HOEs becomes more significant since human interventions are required for maintenance and operations of these systems. Results indicate that overall, Cases #1, #2, #5, and #6 have comparably lower risk levels compared to Cases #3, #4, and #7. Case #1 is a double-loaded straight corridor block with full-height window openings at either end, which results in longer tenability conditions. Case #2 is a four-unit high-rise point-block with a single naturally ventilated stairwell and short cross-ventilated corridors. It is to be noted that this configuration can only be built in a tropical climate. Case #5 has naturally ventilated corridors and stairwells while Case #6 has low occupant load, short corridors, and travel distance to stair. Fire modelling results indicate that tenability conditions remain infinite at these corridors for Cases #2, #5, and #6 on account of the natural ventilation. The absence of a second exit stair in both Case #2 and Case #6 does not seem to compromise their risk levels likely due to the low occupant loads and corridor tenability. Case #7 has the highest overall risk on account of the sole stairwell and low tenability due the corridors filling up with smoke rapidly. Further, there is a strong positive correlation between the ratio HOE/ERL with the number of active systems–for each case, the correlation among its variables is high.

4.4. F-N Curve Assessment of Case Studies

Societal risks for the case studies are presented as F-N curves and constructed using the following equation:

$$F = k \times N^{-a} \quad (10)$$

where F is the cumulative frequency of N or more fatalities, N is the number of fatalities, a is the aversion factor and k is a constant (please refer to Appendix B for inputs).

The individual tolerability limit based on PD 7974-7:2019 is given as 1×10^{-4}/year while the de minimis limit is set at 1×10^{-6} [6]. From the draft ABCB Tolerable Risk Handbook, the Upper and Lower Individual Tolerance Limits are set as 5×10^{-4}/year and 5×10^{-6}/year respectively for residential classes.

Kaneko et al. [49] suggest a method for building the tolerability limit curve mathematically from raw data of previous events. An F function is minimized to obtain some parameters that define the tolerability limit curve. The method also aims at extrapolating the curve values for low probabilities/high consequences events when data for such events are not available. To create an approximating function that fits with the curve, a minimizing function F is introduced. The equations for generating the tolerability limit curve are provided in Appendix C. Figure 5 shows the F-N curves for Case #1 to Case #7: Trial Design TD01 to Trial Design TD04: [noHOE, HOE, fullHOE]. The F-N curves for the other Trial Designs TD05-TD16 are provided in Supplementary Material—Figures S1–S3. F-N curves for each individual Trial Designs for each Case #1 to #7 (total 112 individual F-N graphs) are provided in Supplementary Material—Figures S4–S10.

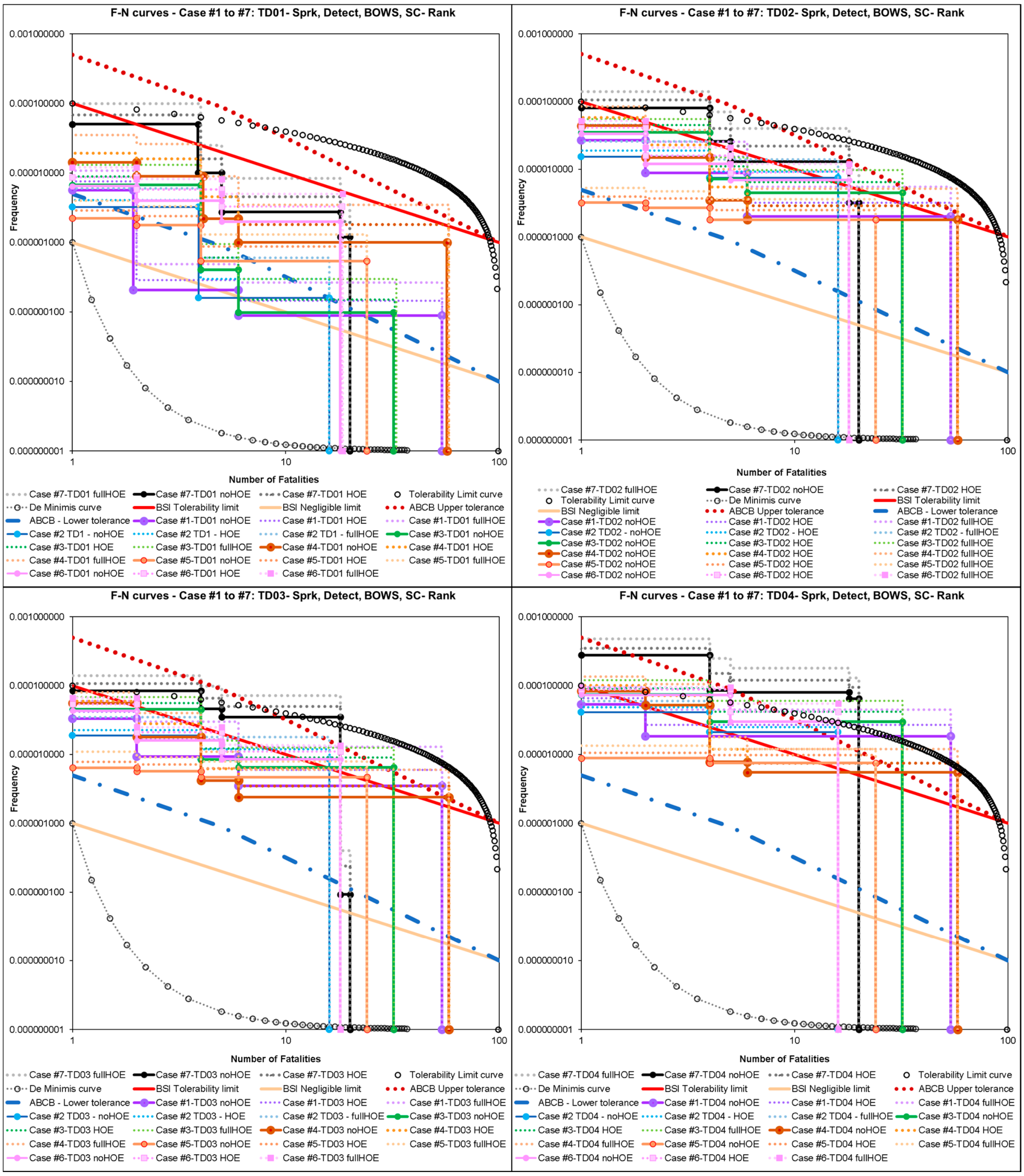


Figure 5. F-N curves for Case #1 to Case #7: TD01 to TD04: noHOE, HOE, fullHOE.

The tolerability and de minimis limit curves are indicated in Figure 5 as follows:

- The de minimis limit (denoted by dotted lines with black circle as markers) is the lower threshold below which designs are denoted as 'broadly acceptable' indicating no further requirement to investigate further risk reduction measures below this threshold [2].
- The gradient of tolerability limit curve (denoted by circle markers) is shallow for low consequences and steep for high consequences to explicitly acknowledge risk aversion.
- The shape of the tolerability and de-minimis limits results in a wider ALARP region, increasing the range of design solutions requiring explicit cost–benefit assessment to maximize social welfare [2,3]. In the ALARP region, safety measures should be implemented to reduce the risk to ALARP so the design can be considered acceptable.

- The F-N curve moves upward when HOEs are considered indicating increasing risks and greater severity in terms of frequency and number of fatalities.

ABCB tolerability curves are represented graphically in Figure 5 and the bounds set by BSI 7974 for their tolerance are superimposed using black solid and dashed lines. Overall, the limits set by ABCB are similar to BSI PD-7974-7:2019. However, the rate of change in allowable frequency is also much faster (steeper slope) than BSI. The ABCB slope of −1.5 indicates a higher risk aversion that BSI's neutral risk aversion slope of −1. Following are observations from Figure 5:

- Generally, HOEs result in an increase in risk levels for all seven case studies.

In TD01 (with all active systems present), only Case #7 exceeded the upper tolerability limit of 1×10^{-4} based on BSI PD7974-7 tolerability. Against ABCB tolerability bounds, Case #7 did not exceed the upper tolerance while it is at the borderline of the upper Kaneko curve. For Case #7, the difference in risk with and without HOEs is ~33%.

On the other hand, the risk levels in Cases #1, #2, #3, #5, and #6 (with sprinkler systems, BOWS, smoke detection, and natural ventilation in corridors), stayed within the ALARP region even when HOEs were considered.

- Societal risks remain high if no active safety systems are present.

For TD04, the F-N curve exceeds the ABCB tolerability curve for cases #1, 3, 6, and 7 (noHOE). In addition, the curves for these cases (noHOE) gradually move upward from TD01 to TD04, indicating that as the number of active systems is reduced; the system becomes risker for no human intervention case. Also, for all cases in TD16 (no active system), the F-N curve remains above the tolerability limit (Supplementary Material—Figures S1–S10). For partial or standalone active systems (TD5 to TD15) again, parts of F-N curve remain above tolerability limits prescribed by ABCB and PD7974-7:2019 resulting in unacceptable societal risks.

- By and large, risk is lower for cases where stairwells and active safety systems are present.

The lowest risk levels were realized in Case #1 and #5 (with two stairwells and installation of sprinklers, smoke detection, and BOWS) and Case #2 (with single stairwell, sprinklers, smoke detection, and BOWs). Risk levels did not exceed the tolerability limit in these cases when HOEs were included. In cases (#1, 2, and 5) risk only increased by 20% for with and without HOEs (nearly half that of Cases #4 and #7).

- To lower the curve to an acceptable ALARP region, additional fire safety measures or alternatives are required.

So, for Case #4 where HOEs edged the F-N curve towards the tolerability limit and also Case #7, additional fire safety measures. However, if the installation of further fire safety features is no longer available, alternatives might be to improve the reliability of active systems, accept a lower reliability interval or redesign the building plans to introduce passive means to improve tenability.

- As all cases fall within the ALARP region, Cost-Benefit Analysis (CBA) will need to be carried out

The CBA would use disproportionality factor, D set as 1 per PD7974-7:2019 guidelines [6], however, this is beyond the scope of this paper.

4.5. System Dynamics Modelling Results

System dynamics modelling considers risk variation over time and examines the dynamic effects of human and organisational factors on component reliability. It is observed that the reliability of safety systems such as detection or suppression systems varies with time, as illustrated by Case #1 in the graph on the left in Figure 6. The curve shows the effect of perceived safety on the building management team. There is an initial period (0 to 5 years) in which the reliability declines slowly, thus causing the number of accidents to increase (Figure 6a). The excessive number of accidents compel the building management to implement new safety measures that improve the reliability from year 5 to 7. The peak of the reliability reassures the building management team so that safety measures are then relaxed, and reliability declines again from year 7 to year 10. So there is a bottom value for reliability before 5 years, then a reaction from the organization is expected with improvements in safety being implemented along the next 2 years, peaking at 0.95 before lax safety behaviour causes the downward trend again till year 10. The ERL curve in Figure 6b indicates an opposite behaviour to reliability over the 10-year period reaching a low risk level of 5.9×10^{-6} in Year 7 before trending up. The detection probability curve in Figure 6c exhibits similar behaviour to the reliability curve over this period. The accident rate increases until year 5 when safety measures cause a downward dip until year 7 when it begins to slope up again.

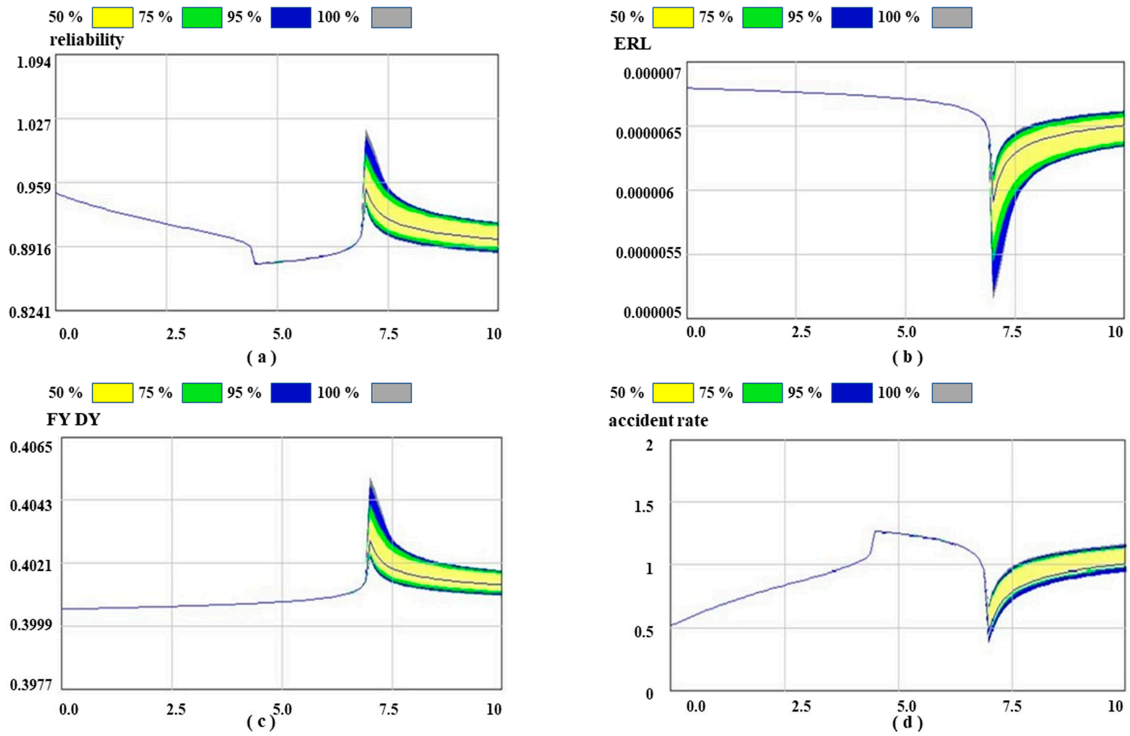


Figure 6. Sensitivity analysis: ERL and Reliability- TD01, Case #1. Note: SD Individual ERL sensitivity plots for all other Trial Designs for Case #1 to #7 are provided in Supplementary Material—Figures S11–S24. (**a**): reliability; (**b**): ERL; (**c**): FYDY; (**d**): accident rate.

A sensitivity analysis for the SD model is then performed for the dynamic response of the system over 10 years. Sensitivity analysis is used to determine how the model behaves and responds to a change in a parameter. Each simulation with changed parameters and slope of the nonlinear relationship was compared with the base run simulation to determine whether the parameters and nonlinear relationships exhibited sensitive behavior. If the model behavior only changes numerically with the values of parameters, it indicates that the underlying behavior is not sensitive to changes in parameters. In fact, most of the input parameters will not have a great influence on the model behavior, except for critical variables in the model. The sensitivity of a parameter is given by the following equation:

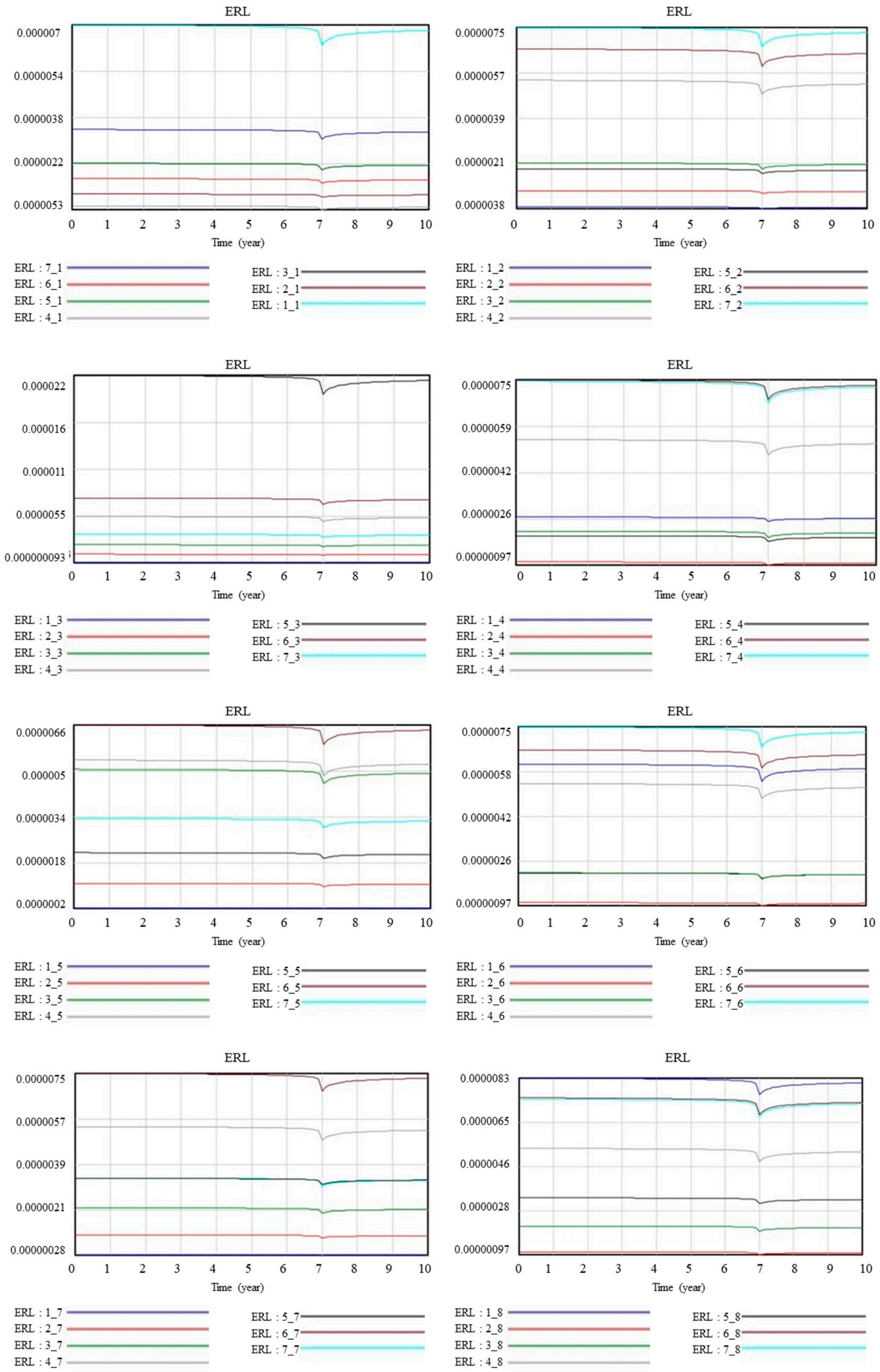
$$S(t)\left|\frac{(Y(t+1)-Y(t))/Y(t)}{(X(t+1)-X(t))/X(t)}\right. \tag{11}$$

where S is the sensitivity function, Y is the output behavior variable, X is the model parameter and t is time.

The sensitivity analysis tests are carried out in Vensim to provide a comparative graph of final results, which cause the simulation results to be displayed as confidence bounds ranging from 0 to 100 percentages. Confidence bounds are used to represent the sensitivity of the variable. The analysis is computed at each point in time by ordering and sampling all the simulation runs (1000 Monte Carlo simulation runs). The color area in the sensitivity graph indicates whether the specified variable may affect the simulation results to a great extent. For the confidence bounds color in Figure 6, yellow represents 50%, green represents 75%, blue represents 95% and grey represents 100%. The 'risk perception' variable of the socio-technical loop has been taken as the input variable and its range of variation is between 0.99999 to 1.00001 (the range is very small, in the order of 1×10^{-5}). Monte Carlo simulation with 1000 iterations was run and the resulting behaviour of the reliability variable is represented by the sensitivity curve in Figure 6a. It can be noted that the effect of the variations on the input variable deploy only after an initial period in which the input has no influence on the reliability outcome. This can be explained by the dynamic character of the high-level loop. For the same input variable 'perception' the ERL and accident rate exhibit large variations in behaviour after year 7.

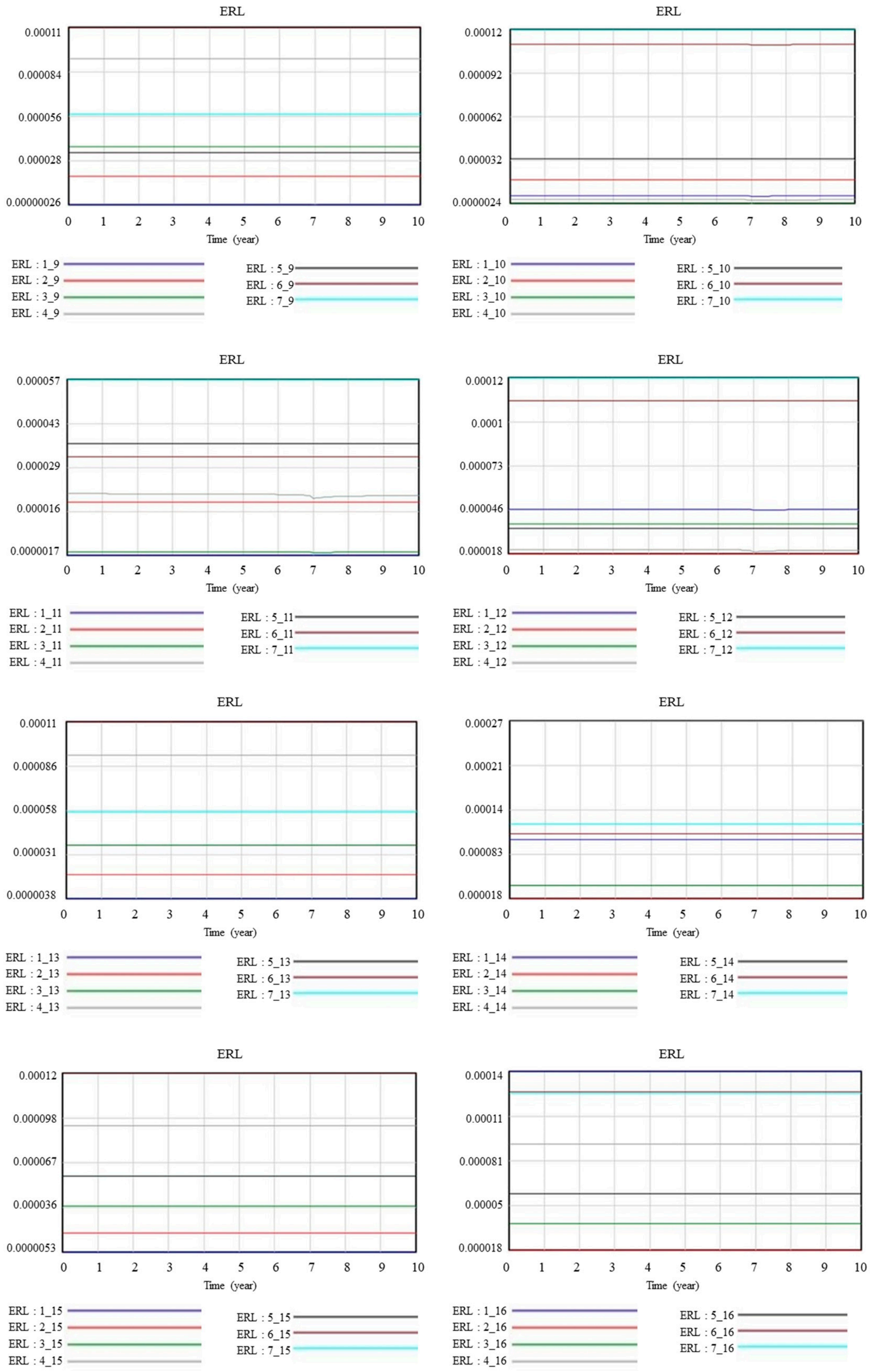
For the detection node 'fire yes, detection yes' (FYDY), the sensitivity to the 'perception' factor is extremely low, with variations in the range from 40.05% to 40.50% as shown in the curve of Figure 6c. The detection node (right side) shows that variations occur after about 7 years, meaning that the influence of the human and organization factors on technical systems develops after a certain period of time. The results indicate that a very small variation in the input variable 'risk perception' generates very large variations in the output ERL value. It can thus be concluded from the sensitivity analysis that a very small behavioural change in risk perception of a building management team can lead to a very large risk to life variations over time through the self-reinforcing feedback loop.

Figure 7a,b indicate the SD plots for ERL variations over time for each Trial Design (TD01-16) for case #1 to #7. The magnitude of the ERLs is different for different test cases and for different trial designs. It can be noted that the main trends in the ERL curves are maintained throughout all cases and determined by the HOE loop which the dynamic behaviour of the model is based on. Changes in ignition frequencies do not impact the evolution of the risk curve, although variations in absolute values are given. Dynamic risk variations are noticeable in the first 8 trial designs (TD01-08) with various active systems ON: in Year 6, risk levels improve due to improving safety measures from building management team peaking in year 7. Thereafter, lax safety behaviour is to be expected following the good outcome in the first six years, leading to risk levels increasing again. This behaviour is not as pronounced in Trial Designs TD09 to TD12 and is not present in TD13 to TD16 due to an absence of various active systems sensitive to HOEs. In summary, the high-level cycle, with its HOEs variables, is responsible for the dynamic risk curve behaviour while fire ignition frequency, building population, and consequences are parameters that impact only the absolute value of ERL at each time step.



(a)

Figure 7. *Cont*.



(b)

Figure 7. (**a**): SD plots—ERL variations over time for Trial Designs 01–08, Case #1 to #7. (**b**): SD plots—ERL variations over time for Trial Designs 09–16, Case #1 to #7.

5. Conclusions

The literature review suggests that it is necessary to adopt both technical and human organizational errors for realistic risk assessment of building design from a practical viewpoint. Furthermore, during the operational phase of the building, it is not reasonable to assume that the reliability of the fire equipment remains constant and its aging over time will need to be considered to derive more realistic risk assessment values. To address the literature gaps and follow the suggestions made by researchers in their studies, we developed a Technical-Human-Organizational Risk (T-H-O-Risk) methodology in [12].

In this paper, our aim is to employ T-H-O-Risk methodology of [12] to seven buildings in various geographical locations with different climatic conditions to assess and compare HOE risks due to fires in high-rise residential buildings. Particular focus is given to active fire safety systems in high-rise residential buildings by comparing the impact of HOEs on individual and/or combinations of active fire safety systems. This study breaks down the impact of HOEs on sprinklers, building occupant warning systems (BOWS), smoke detectors, and smoke control systems. For each of seven buildings (cases), 16 trial designs are considered. The building risk levels are compared to each other and against the absolute benchmark criteria to determine if they exceed the acceptable risk threshold. It is hypothesized that the ERL for each building design has different human and organizational scenarios based on either no HOEs or with HOEs-where organizational standards such as maintenance, safety culture, and emergency planning are determined to be low and human errors occur routinely. The quantification of difference in ERL for seven buildings for each of 16 trial designs is a novel aspect of this study.

The T-H-O-Risk model addresses the methodological gap in quantifying technical, human, and organizational risks and uncertainties in PRAs of high-rise residential buildings. To keep the study focused, we selected buildings in geographical locations with representative non-extreme climatic conditions of temperate, sub-tropical, and tropical zones and while we applied the BCA as the reference code for all seven cases, the T-H-O-Risk methodology can be applied to any other jurisdictions. The methodology incorporates HOEs by utilizing BN, while employing SD modelling to account for risk variations over time. Results are presented using multiple F-N curves encompassing ALARP criteria. Key outcomes are:

- The influence of HOEs increases with the complexity of the system. The increase in ERL can reach 33% in a design with the full set of safety provisions while the simpler designs with only the sprinkler system have a +20% increase in the ERL.
- HOEs have a significant risk impact on active safety systems with combinations of sprinklers. BOWS, smoke detectors, and smoke control systems. HOEs have limited or no impact on passive protection systems. Active systems require regular maintenance which increase the likelihood of human and organizational errors and increase in corresponding risk.
- Strong positive correlation exists between the ratio HOE/ERL with the number of active systems. With one active system, the HOE values range from 8–13% and increased to 25–38% when all four active systems are present in the trial design.
- For active systems, ERL values obtained from this study matches reasonably well with those obtained from the literature.
- For all cases, trial design 1 which consists of all active systems results in the lowest ERL, but this design is also most influenced by HOEs.
- Tenability conditions remain infinite for corridors having natural ventilation.
- Case #7 has the highest overall risk on account of the sole stairwell and low tenability due to the corridors filling up with smoke rapidly.
- The F-N curve with HOE is at a higher level than without HOE case indicating that risks increased with HOEs.

- SD uncertainty modelling indicates large variations in reliability and risk levels of active systems due to the influence on HOEs over time. The results show the effect of perceived safety on the building management team. There is an initial period (0 to 5 years) in which the reliability declines slowly, thus causing the number of accidents to increase.
- The reliability of active components gradually decreases with time and at about 5–7 years, there is a need to carry out maintenance activities.
- It can be noted that the effect of the variations on the input variable deploy only after an initial period in which the input has no influence on the reliability outcome. This can be explained by the dynamic character of the high-level loop.

Prior studies provide estimated effects of HOEs on risk in other industries such as nuclear plans and offshore oil platforms, and estimated effects of technical factors only on risks during a fire event in high-rise buildings, but existing literature does not address or quantify the impact of HOEs on risks during fire events in high-rise buildings. The T-H-O-Risk approach demonstrates how technical, human, and organizational risks can be quantified in a comprehensive probabilistic framework for high-rise residential buildings and is an important contribution to the development of the next generation building codes and risk assessment methods.

Future work will focus on simplifying the model for wider applications to other building occupancies as well as on expanding the sensitivity and uncertainty analysis. In addition, cost-benefit analysis (CBA) should be carried out. The application of the model to the reliability of other safety systems is a further area of development. Another area is the research for other HOE variables applicable to the building sector.

Supplementary Materials: The following are available online at http://www.mdpi.com/2076-3417/10/24/8918/s1, Figures S1–S3: F-N Curves for TD05-TD16, Case #1 to #7; Figures S4–S10: Individual F-N Curves for TD01-16, Case #1–#7; Figures S11–S24: SD Individual ERL plots for all Trial Designs TD01-16, Case #1–#7.

Author Contributions: Conceptualization, S.T. and K.M.; methodology, S.T. and Moinuddin; software, S.T.; validation, S.T., D.W., P.J. and K.M.; formal analysis, S.T. and K.M.; investigation, S.T.; resources, S.T. and K.M.; data curation, S.T.; writing—original draft preparation, S.T.; writing—review and editing, S.T., D.W., P.J. and K.M.; visualization, S.T.; supervision, D.W., P.J. and K.M.; project administration, K.M.; funding acquisition, S.T. and K.M. All authors have read and agreed to the published version of the manuscript.

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Appendix A. Bayesian Network Equations

The equations that govern the relationships among nodes in the BN are listed below:

For HOE-variables, the equations represent the OR Boolean logic:

$$\text{P(Inefficient timely control)} = \text{P(deficient training)} \cup \text{P(inefficient emergency plan)} \cup \text{P(not comply with instruction)}$$

$$\text{P(Deficient check)} = \text{P(no check rules)} \cup \text{P(not comply with instruction)}$$

$$\text{P(Equipment ageing)} = \text{P(deficient maintenance)} \cup \text{P(wrong risk assessment)}$$

$$\text{P(Adopt unsuitable equipment)} = \text{P(obeying standard)} \cup \text{P(improper safety organization)}$$

For other variables of the main net the Bayes' rule is used:

$$P(A) = P(A \backslash B)^{*}P(B)$$

For multiple causal events, the rule can be extended as follows:

$$P(A) = \sum_{i=1}^{N} P(A|C_i)$$

where C_i is the combination of states of causal events.

In general:

$$P(A) = \sum_{i=1} P(C_i) * a_i$$

where *P(Ci)* is the probability of occurrence of the *i*-th combination of states of the causative variables for the outcome *A*, calculated as:

$$P(C_i) = \prod_{j=1} P\left(c_j\right)$$

c_j is the state of the *j*-th root variable that constitutes the *i*-th combination.

a_i is the vector of the probabilities of the outcome *A* given the combinations of factors C_i

$$a_i = P\left(A\middle|C_i\right)$$

For example, for the node Fire Detected:

$$P(firedetected) = \sum_{i=1}^{N} P(firedetected|(fire, inefficient\_timelycontrol, deficientcheck, equipmentageing)$$

Appendix B. System Dynamics Mapping

Figure A1. This dynamic model is based on the BN and the HOE variables defined in the data analysis step: deficient training, inefficient emergency plan, not comply with instruction, no check rules, deficient maintenance, incorrect risk assessment, not following standards and improper safety organization.

These variables directly impact two safety systems: detection and suppression, and a fault tree analysis is implemented for smoke spread causes and frequency of occurrence of such events. The first step for the analysis is the definition of a high-level feedback loop describing the fundamental system adaptation modes responsible for the reliability of the safety measures as shown in Figure A2.

Two cycles are represented-one for perceived safety, which is a factor that impacts organizations after a long time without any fire events, and one for the organization itself. The high-level cycle is linked to the previous structure through the 'reliability' node, and to the nodes related to HOEs, such as deficient training. This variable is inversely proportional to the level of organization, and in turn, impacts the reliability of the system, hence the number of fire events. When the level of the organization is low, deficient training increases the number of fire events. This fact causes a sense of danger that tends to increase the level of organizational focus on safety issues reducing the level of deficient training. Quantitatively, perceived safety is assumed to vary from 0 to 4 (low = 0, high = 4); to obtain a level of organization of the same range it is important to avoid large variations in the rate of change. The level of organization is set initially to high (4) and the rate of change is inversely proportional to perceived safety. If perceived safety increases, the rate of change decreases as represented by the following:

$$rate\ of\ change = -0.1 \times perceived\ safety$$

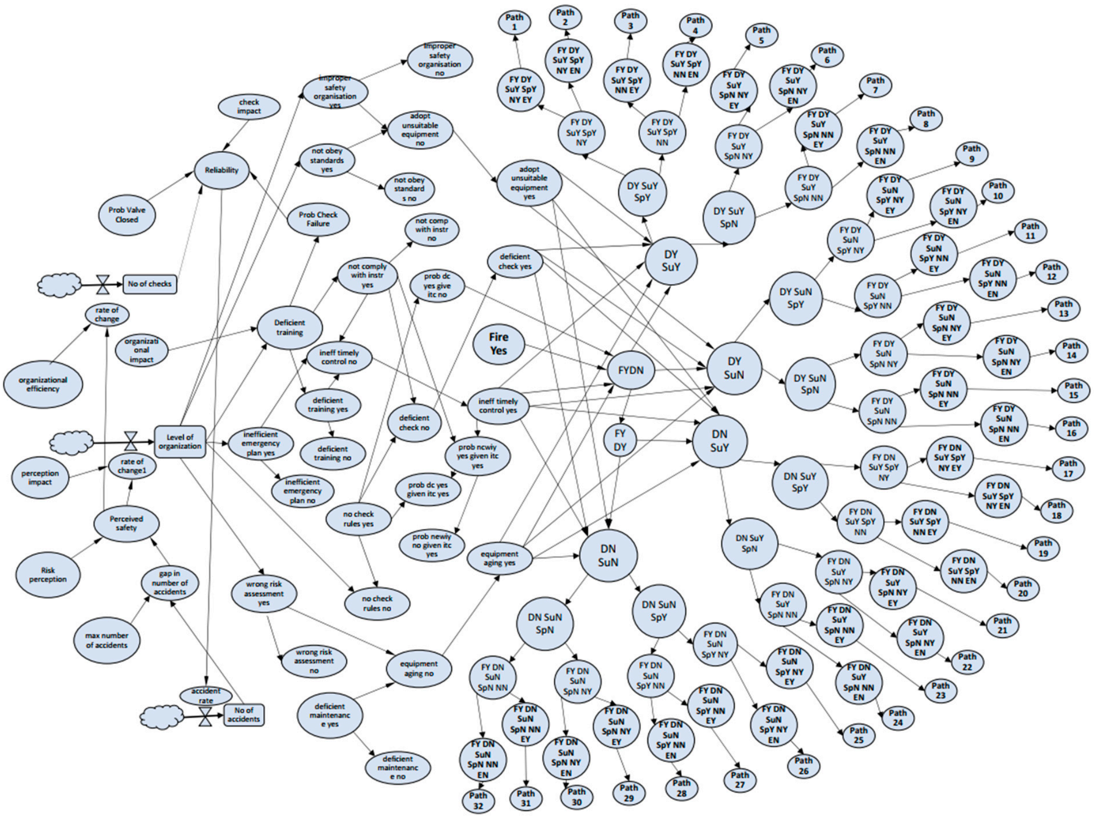

Figure A1. Visual representation of mapped SD model.

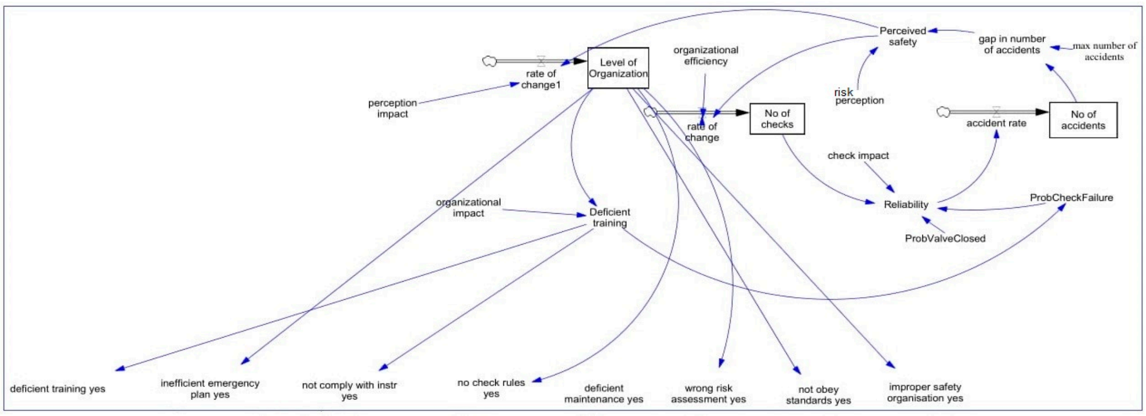

Figure A2. System adaptation models.

Deficient training is the opposite of level of organization and varies from 0 to 4 Hence, the relationship with the level of organization is as follows: if the level of organization is 0, deficient training is 1, when the level of organization is 4, deficient training is 0 (Assuming a linear function: $y = \frac{-x}{4} + 1$, where x is the value of the level of organization and y is the probability of deficient training). Deficient training influences the probability of check failure, which is set to an initial value of 1. With reduction in deficient training, the probability of check failure improves.

Appendix C. Tolerability Limit Curve–Equations

The equations mentioned here are based on Kaneko et al. [49]. The minimization of the squared differences is obtained through the Davidson–Fletcher–Powell method [29].

$$F = \sum_{j=1}^{N_{data}} \left(ln(CCDF_{Aprx-ALL}\ (k(j)) - ln(CCFD_{data-ALL}\ (k(j)))\right)^2$$

where $k(j)$ represents the j-th number of victims resulting from data and N_{data} represents the total number of number of victims, Ln is the natural logarithm and the $CCDF_{data\text{-}ALL}$ (Complementary Cumulative Distribution Function) is derived from statistical accident data. The approximating function to be determined is $CCDF_{Aprx\text{-}ALL}$, in the form of:

$$CCDF_{\{Aprx-ALL\}} = \sum_{i=1}^{M} r_i \frac{\zeta(b_i, n) - \zeta(b_i, N_{MAX-i} + 1)}{\zeta(b_i, N_{MIN-i}) - \zeta(b_i, N_{MAX-i} + 1)}$$

The parameters in the definition of F are calculated iteratively till the minimum is reached. An example of an approximating function determined with the above method could be the following:

$$CCDF_{\{Aprx-ALL\}} = 0.5\frac{\zeta(5, n) - \zeta(5, 100 + 1)}{\zeta(5, 1) - \zeta(5, 100 + 1)} + 0.2\frac{\zeta(0.5, n) - \zeta(0.5, 100 + 1)}{\zeta(0.5, 1) - \zeta(0.5, 100 + 1)}$$

with

$$\zeta(5, n) = \sum_{i=0}^{\infty} (i + n)^{-5}$$

and

$$\zeta(0.5, n) = \sum_{i=0}^{\infty} (i + n)^{-0.5}$$

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Impact of Technical, Human, and Organizational Risks on Reliability of Fire Safety Systems in High-Rise Residential Buildings—Applications of an Integrated Probabilistic Risk Assessment Model

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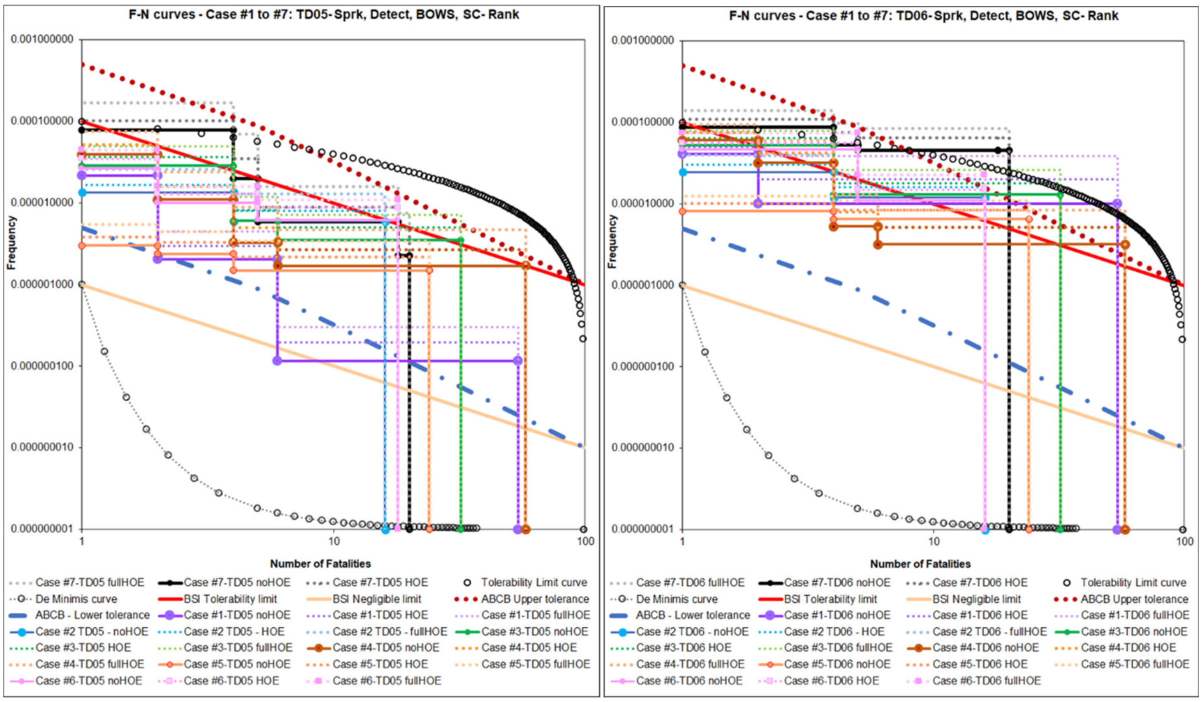
Supplementary Material

1. Figures S1-S3–F-N Curves for TD05-TD16, Case #1 to #7



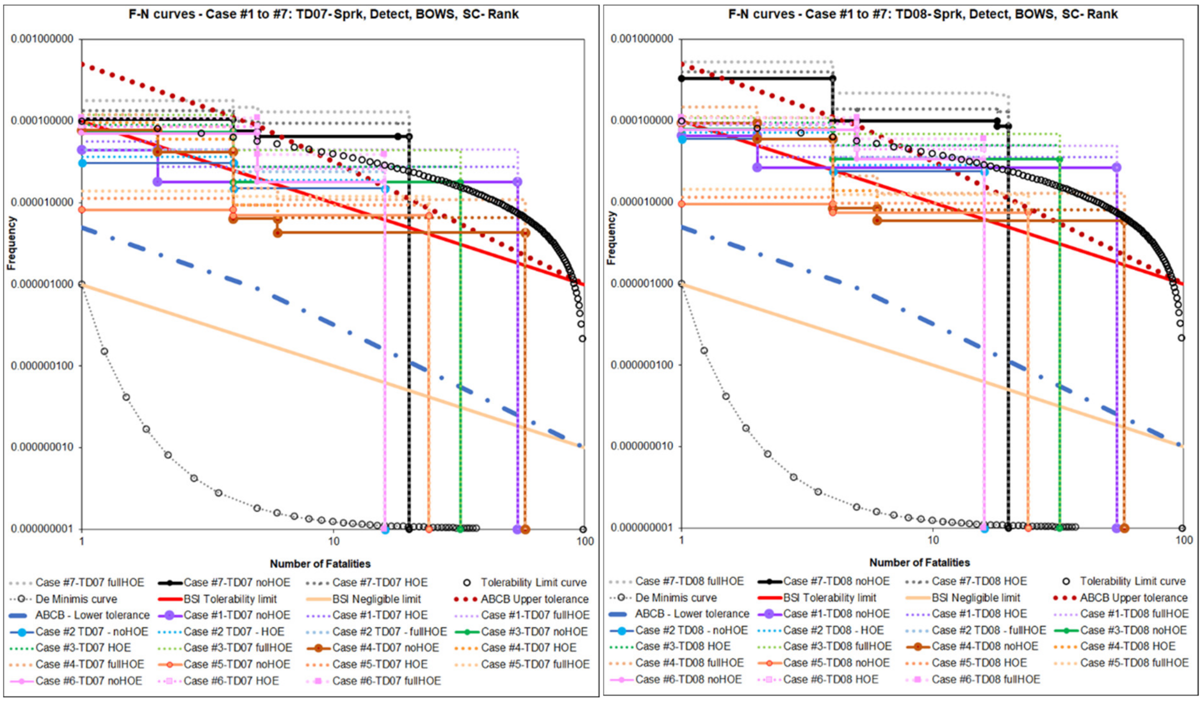
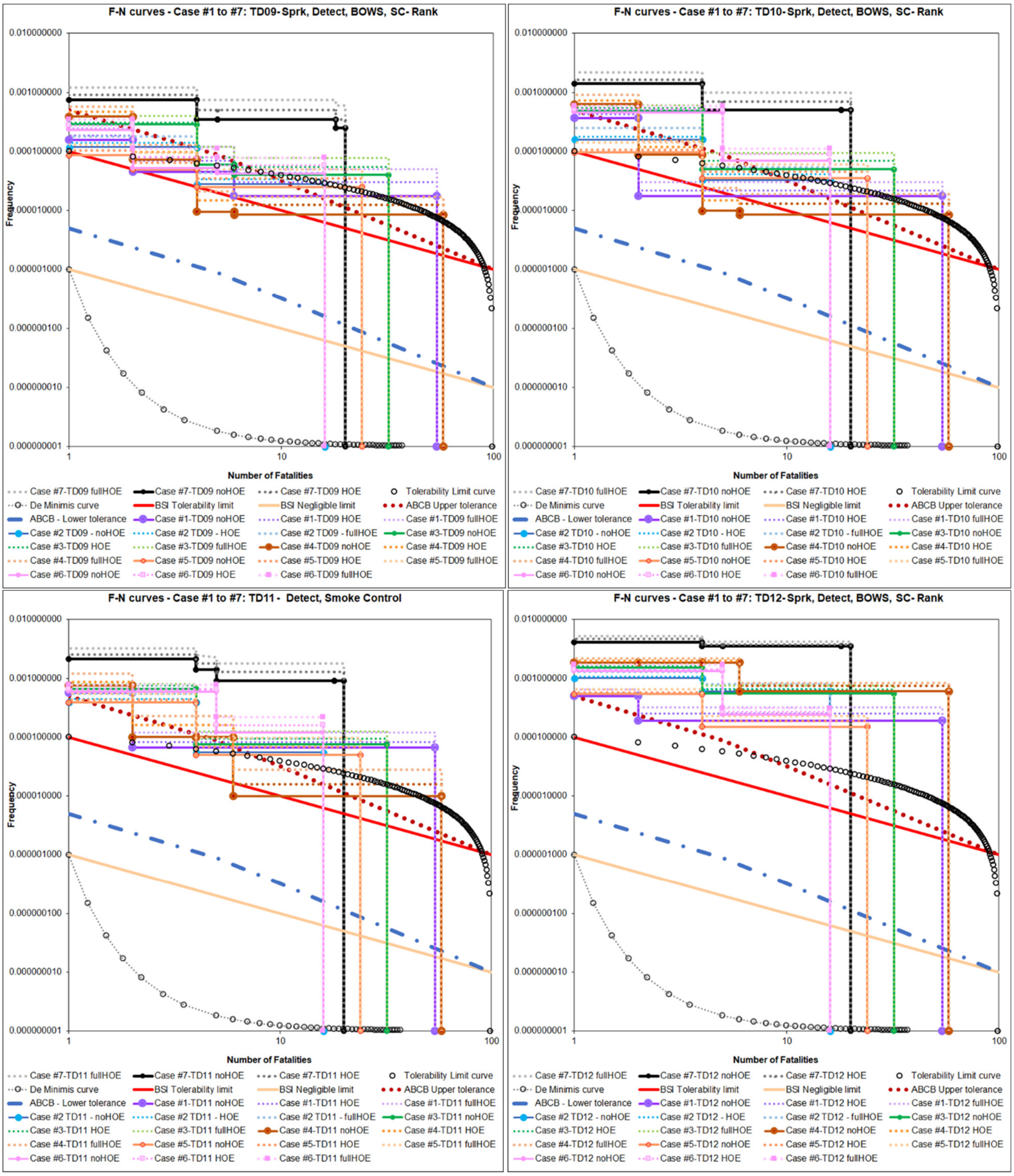


Figure S1. TD05 to TD08.



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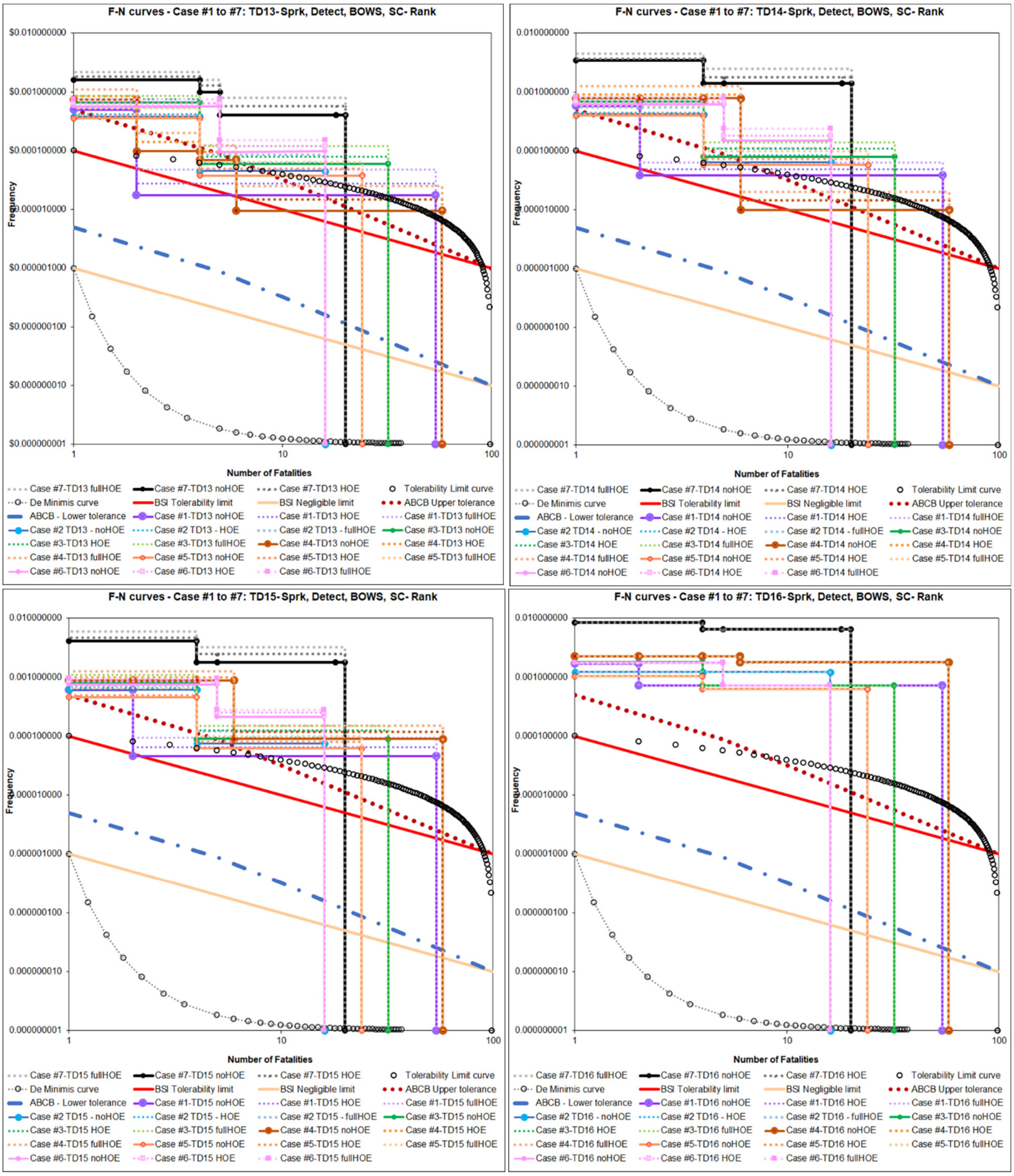

Figure S3. TD13 to TD16.

3. Figures S11-S24: SD Individual ERL plots for all Trial Designs TD01-16, Case #1-#7

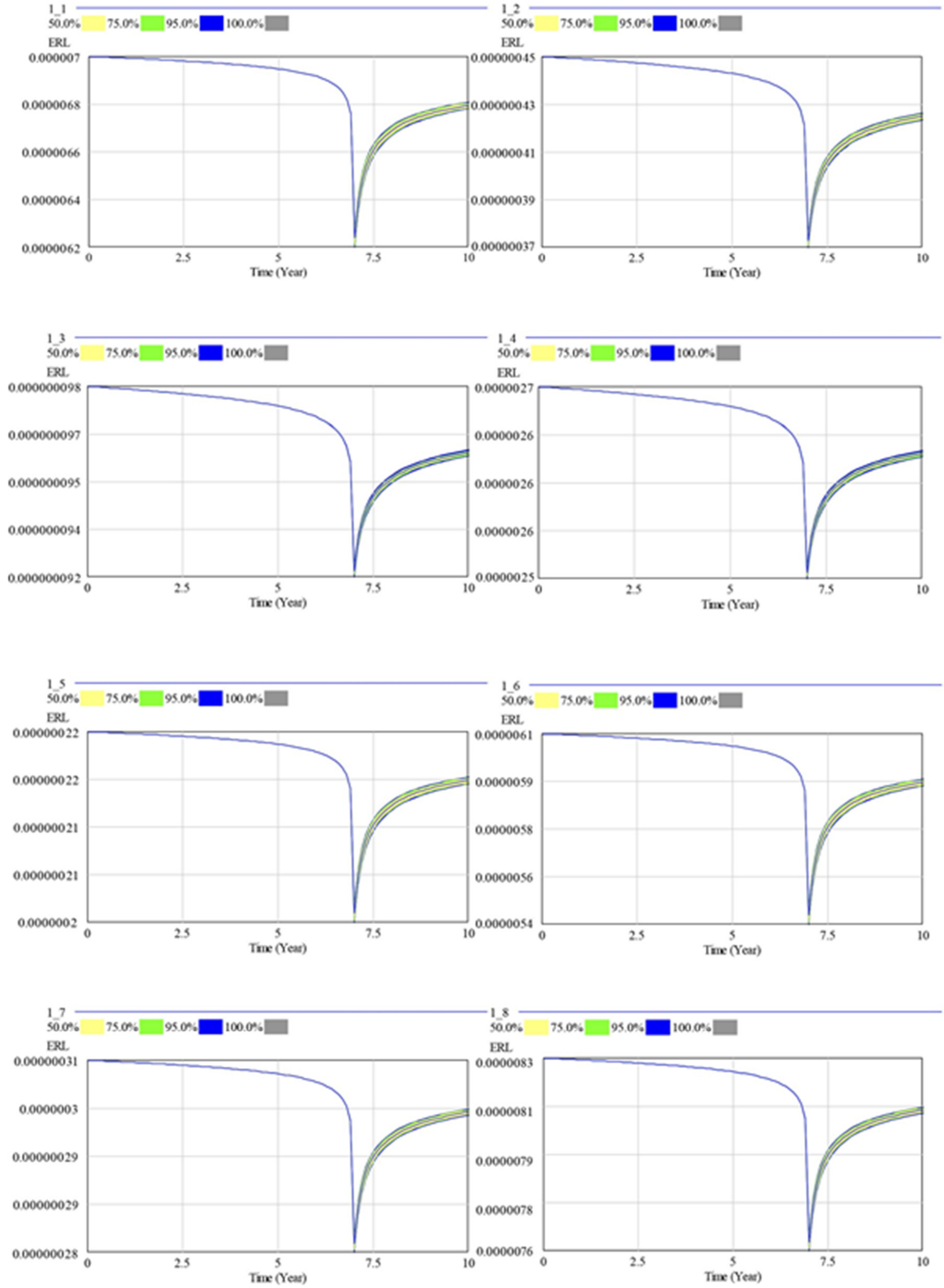

Figure S11. SD Individual ERL plots-Trial Designs 01-08, Case #1.

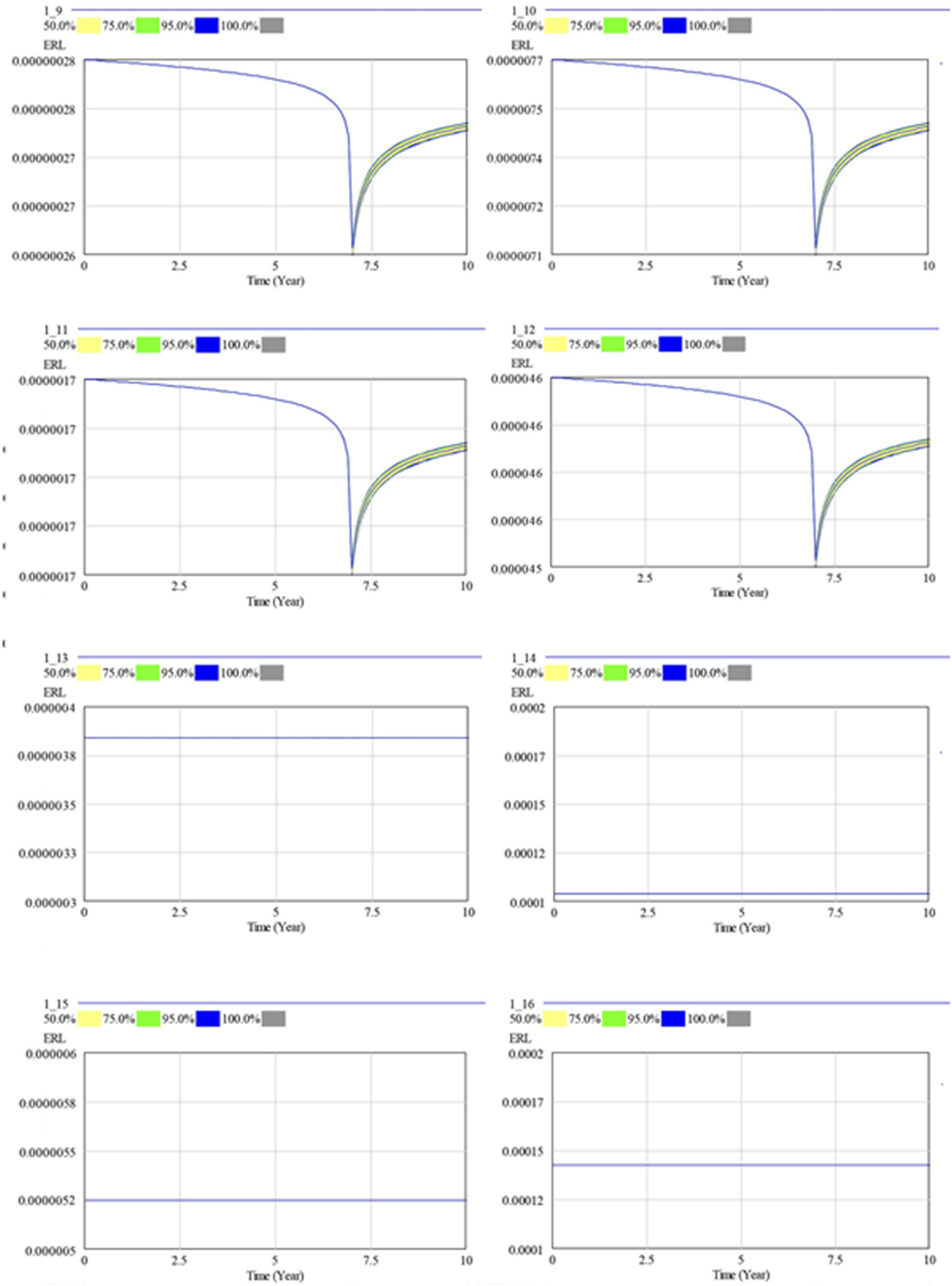

Figure S12. SD Individual ERL plots-Trial Design 9-16, Case #1.

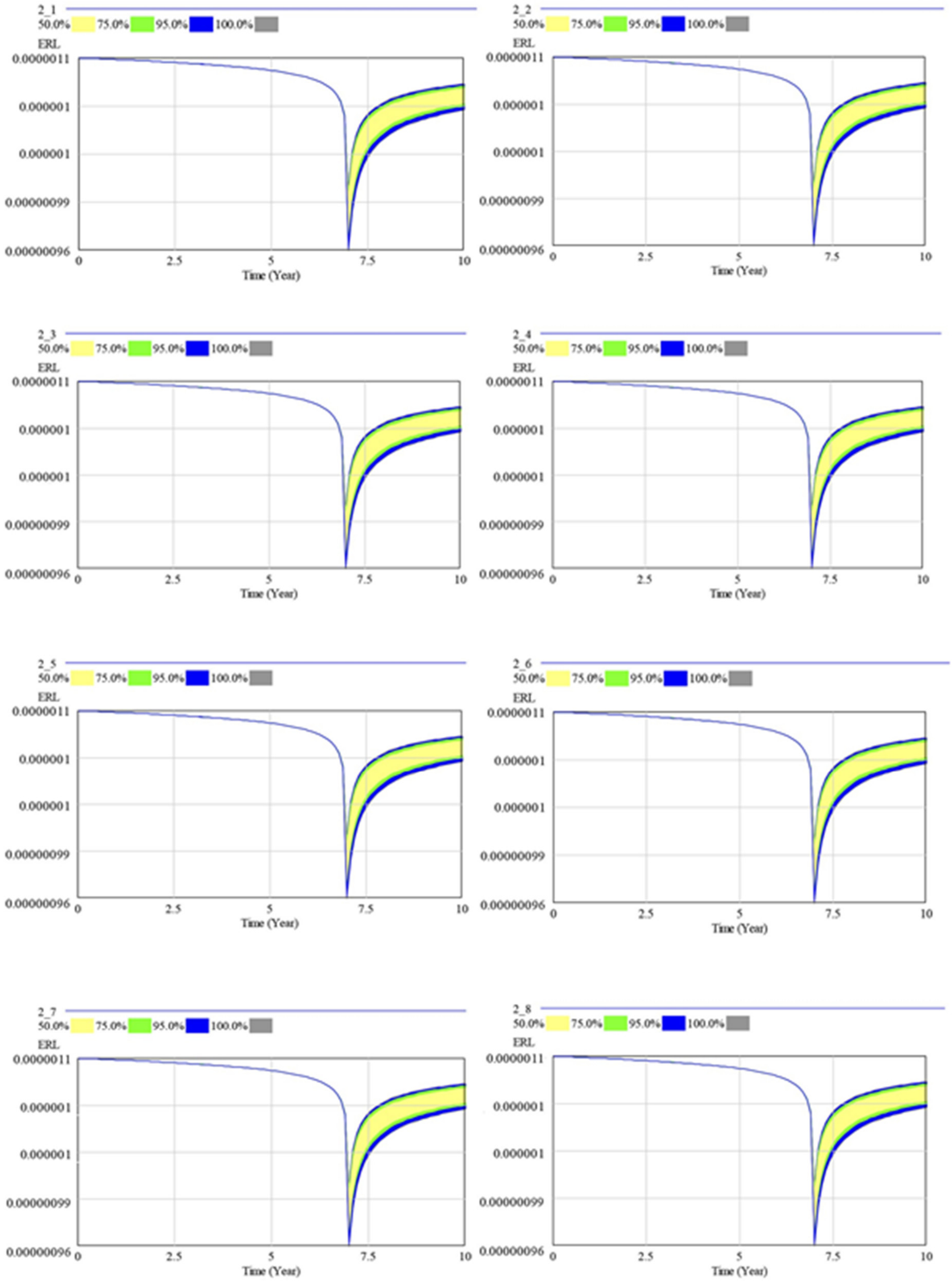

Figure S13. SD Individual ERL plots-Trial Designs 01-08, Case #2.

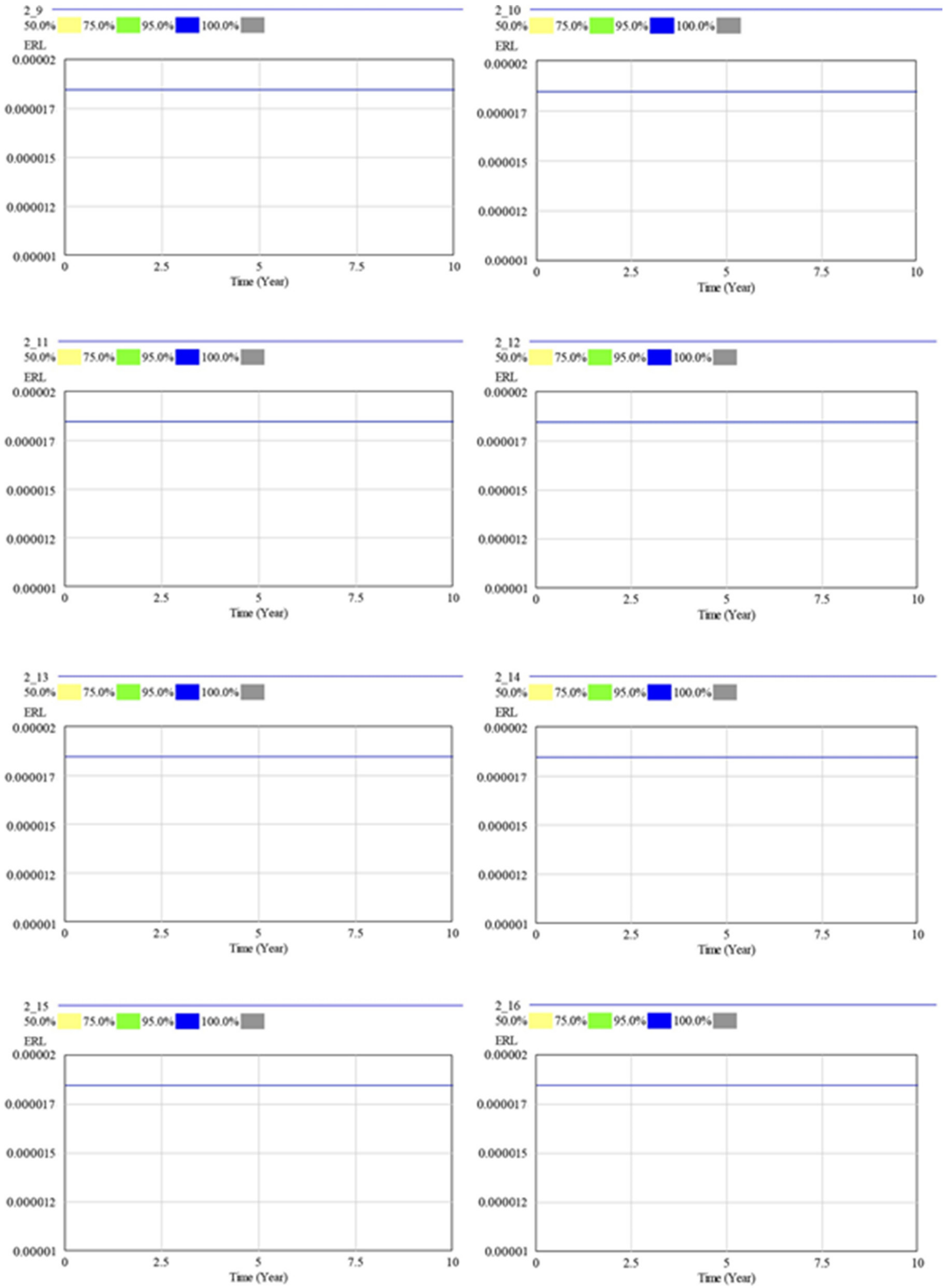

Figure S14. **SD Individual ERL plots-Trial Design 9-16, Case #2.**

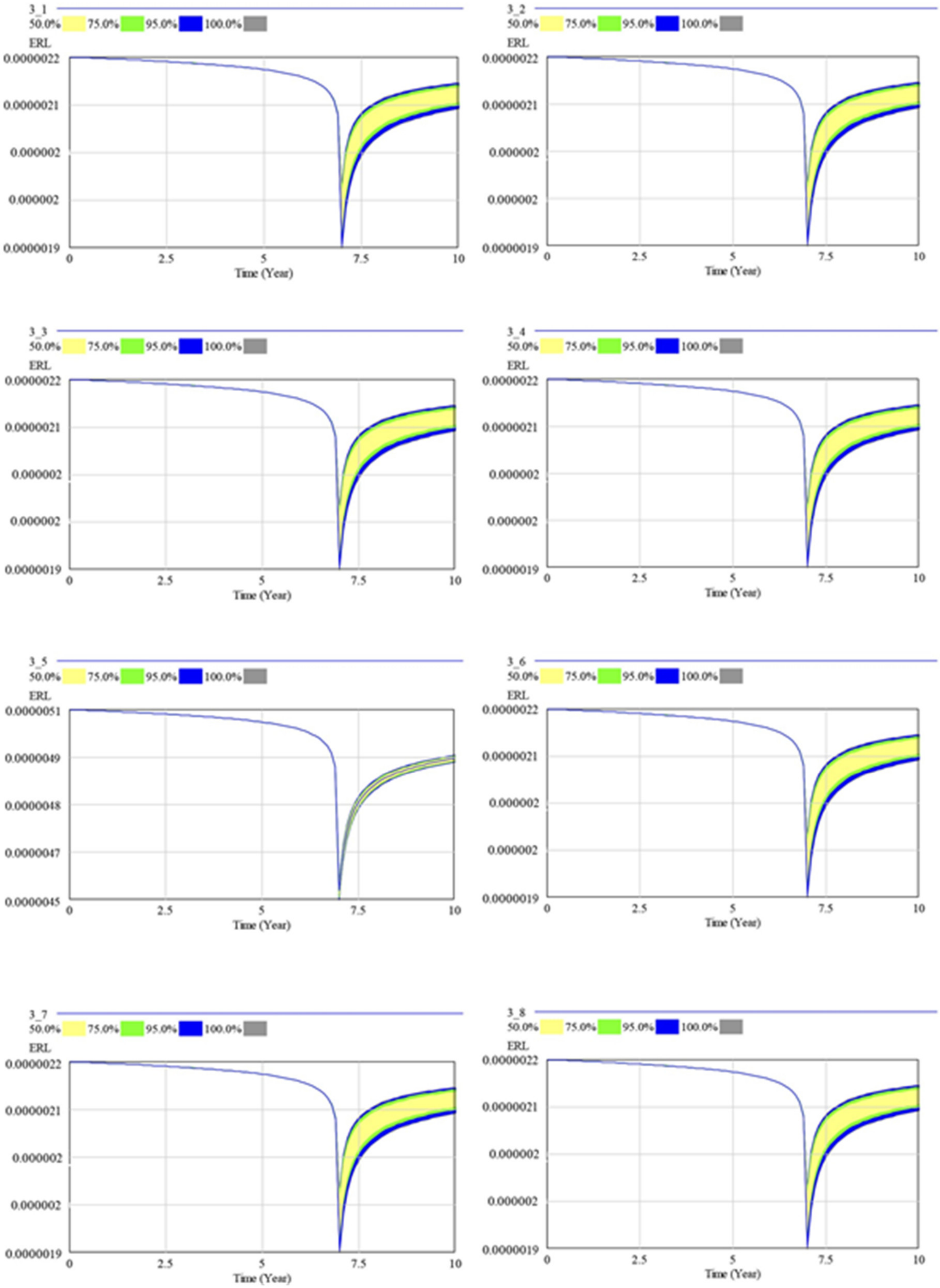

Figure S15. SD Individual ERL plots-Trial Designs 01-08, Case #3.

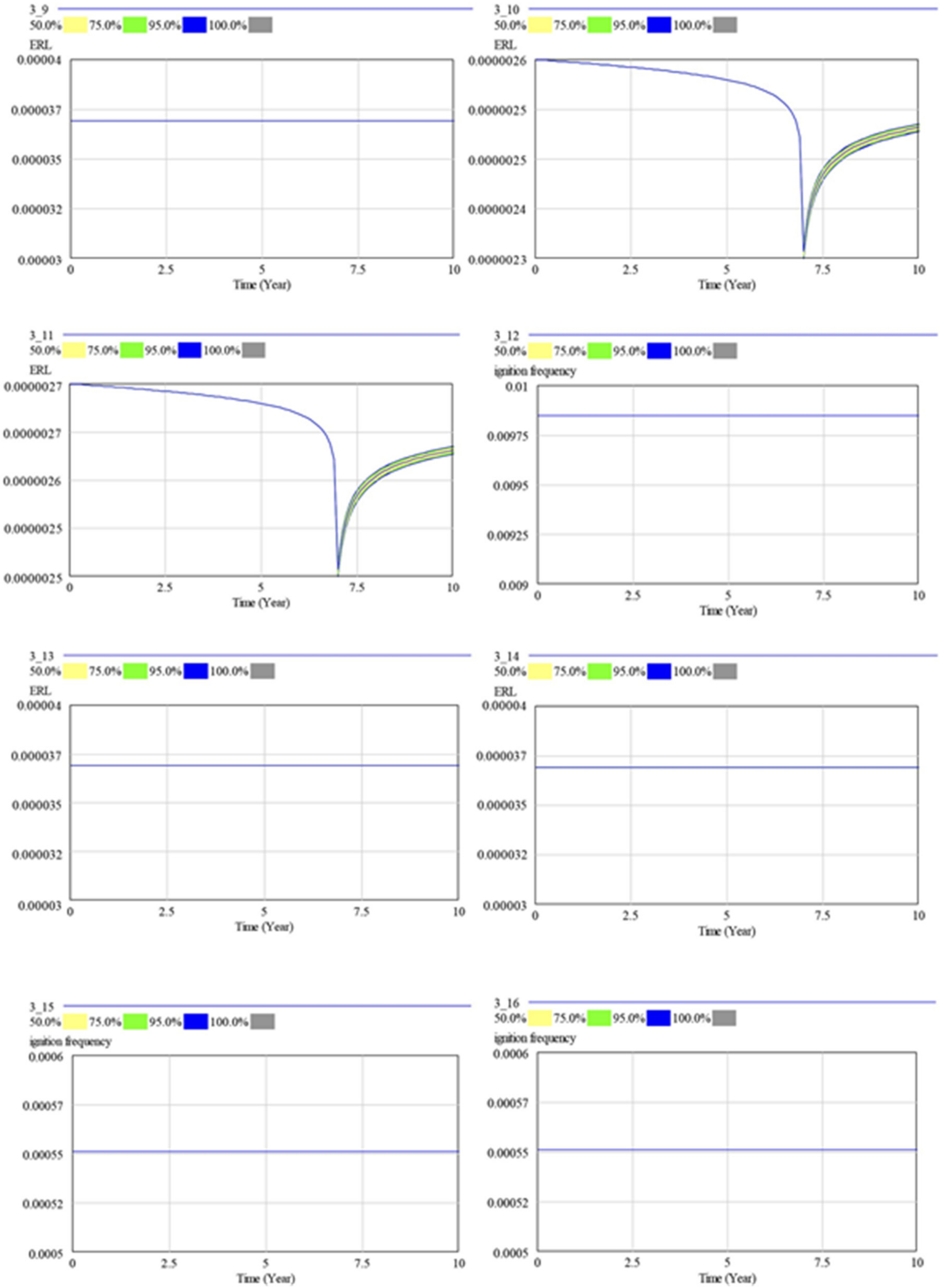

Figure S16. SD Individual ERL plots-Trial Design 9-16, Case #3.

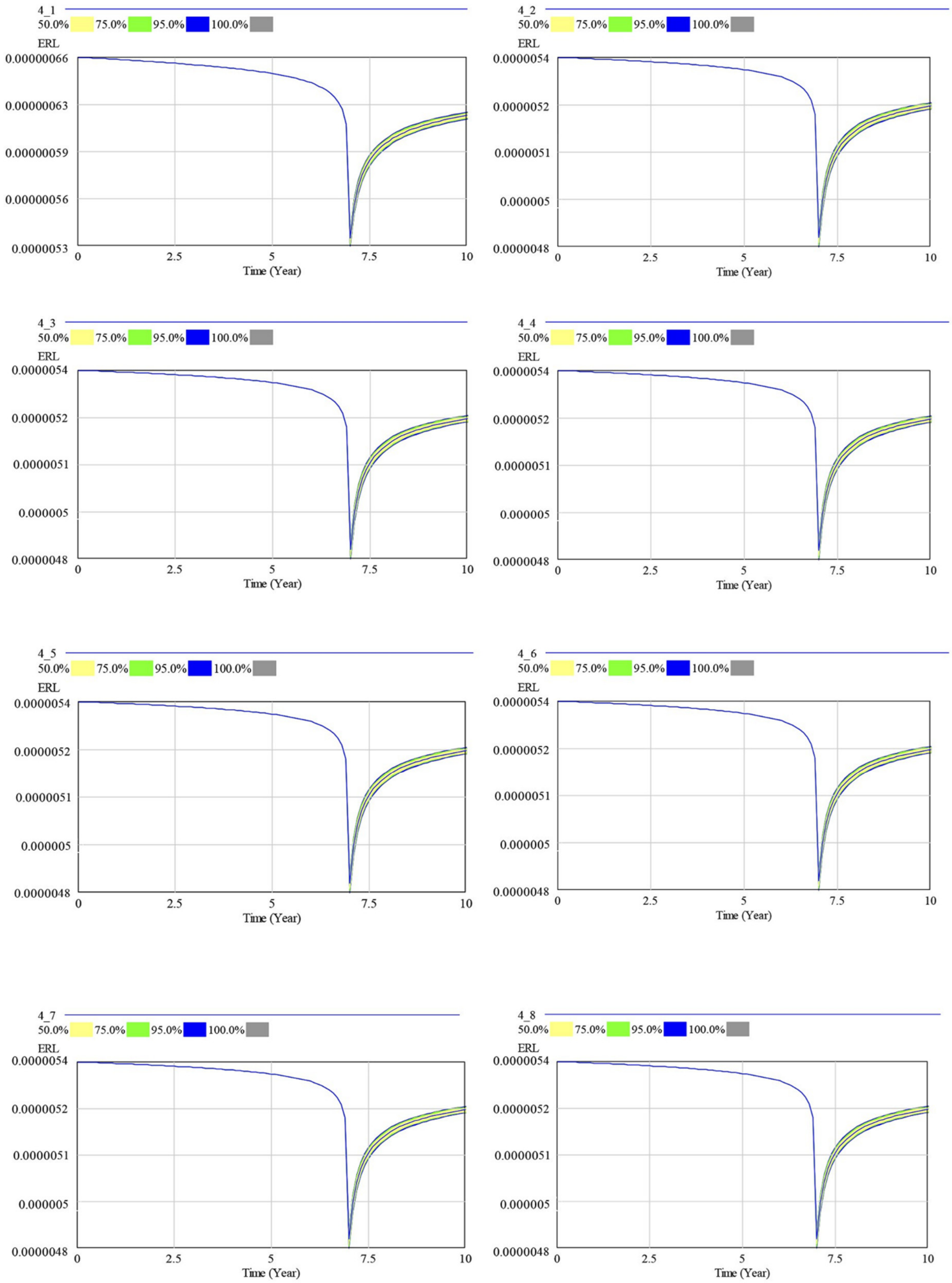

Figure S17. SD Individual ERL plots-Trial Designs 01-08, Case #4.

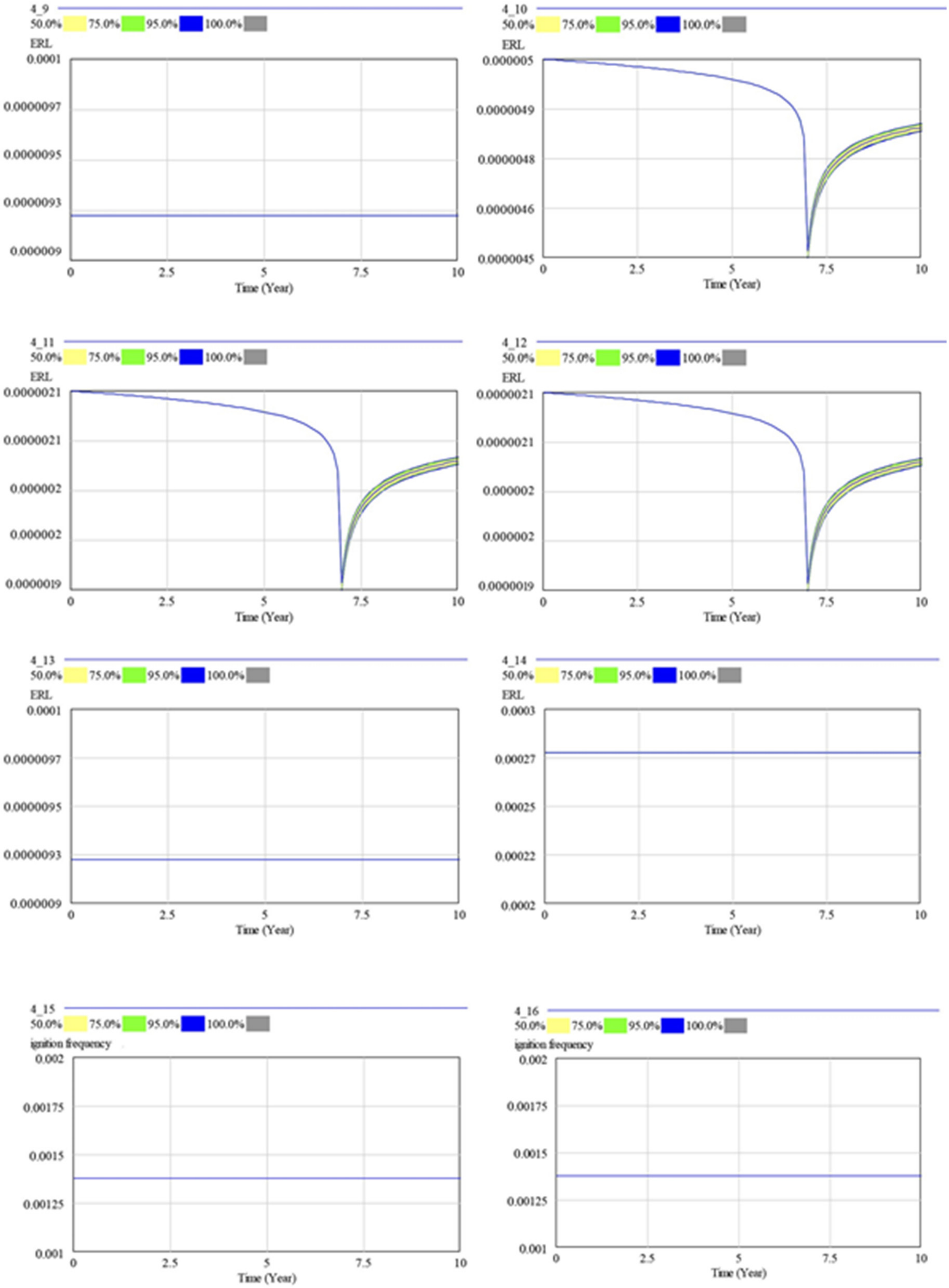

Figure S18. SD Individual ERL plots-Trial Design 9-16, Case #4.

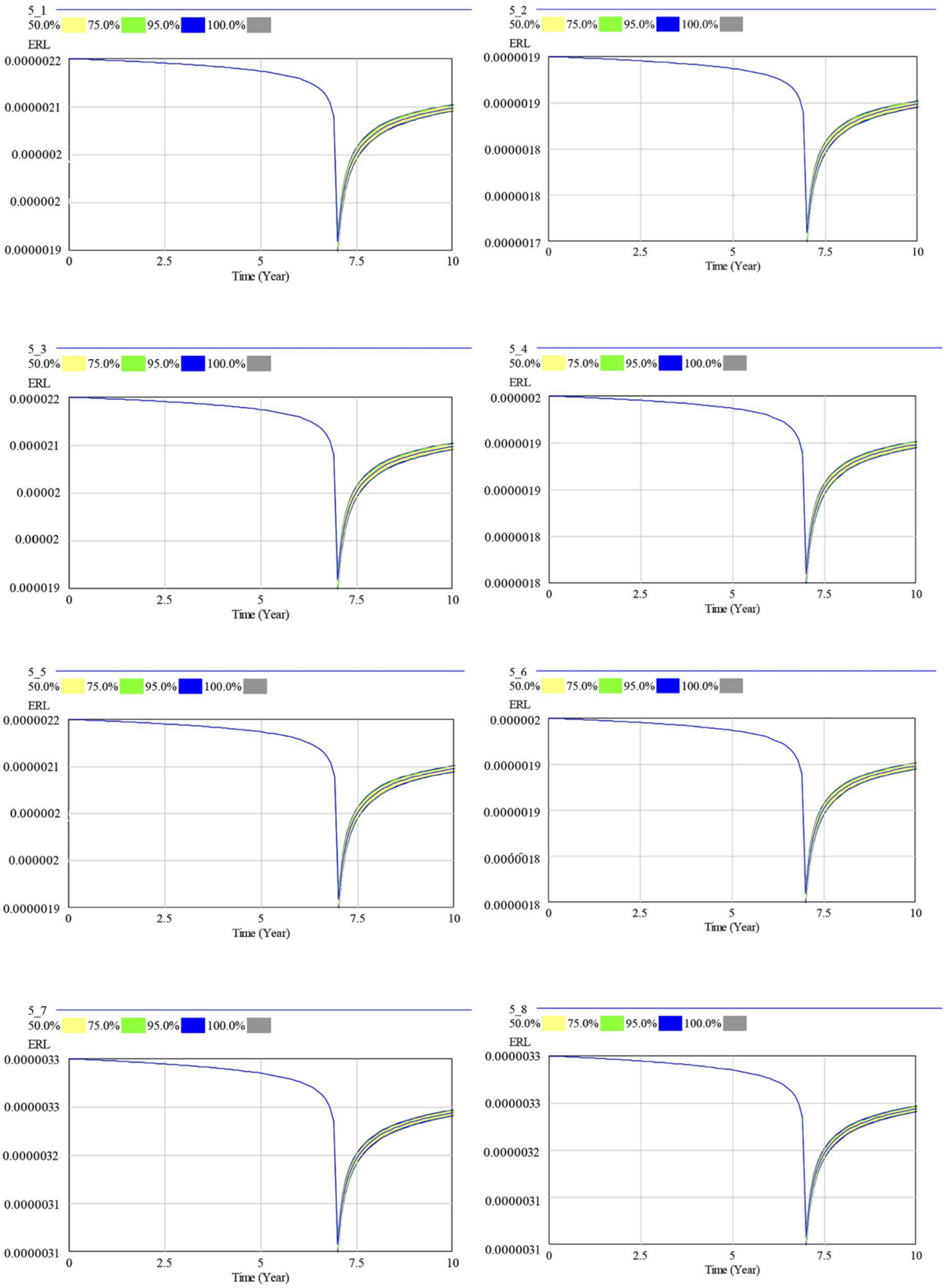

Figure S19. SD Individual ERL plots-Trial Designs 01-08, Case #5.

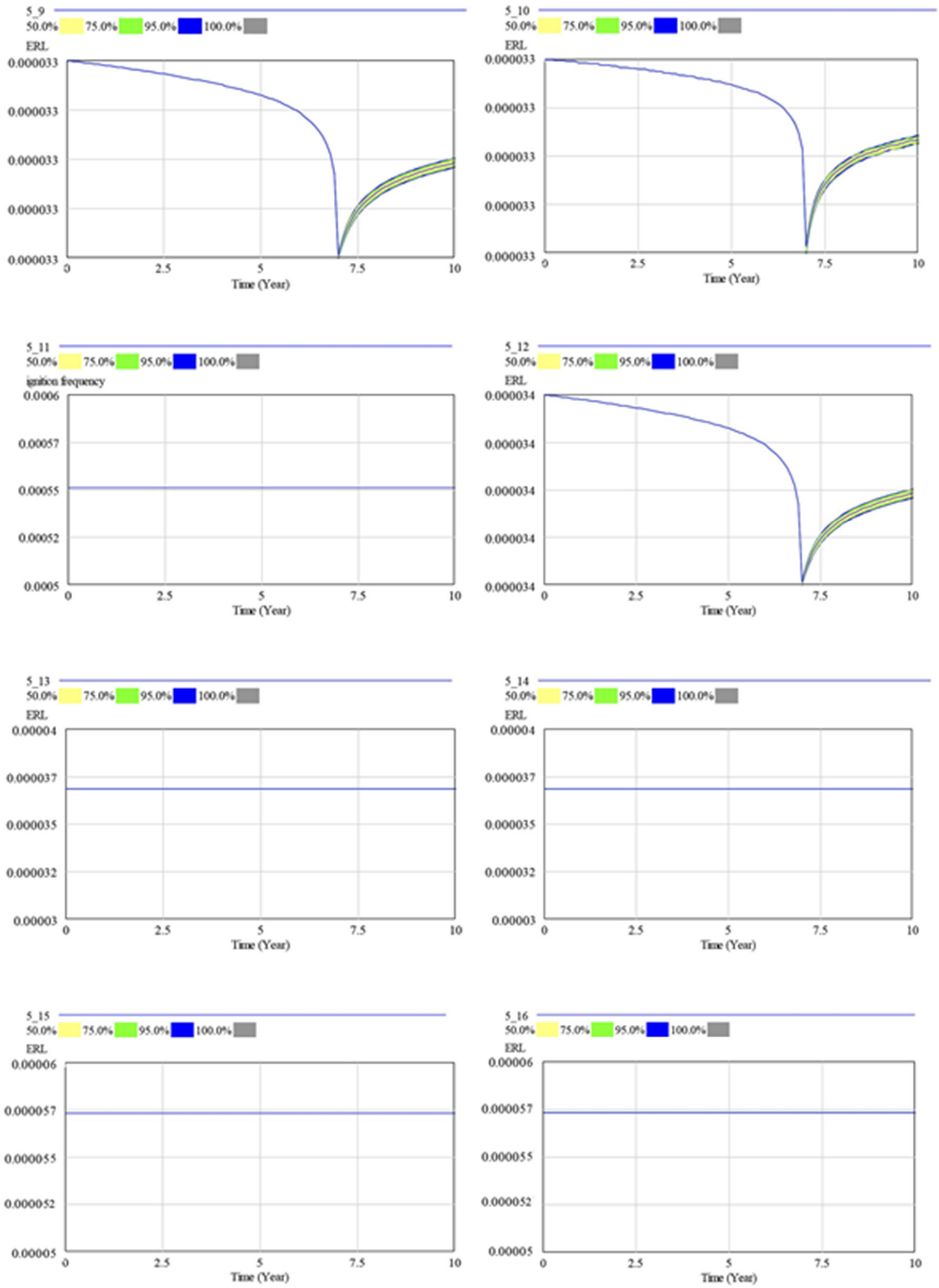

Figure S20. SD Individual ERL plots-Trial Design 9-16, Case #5.

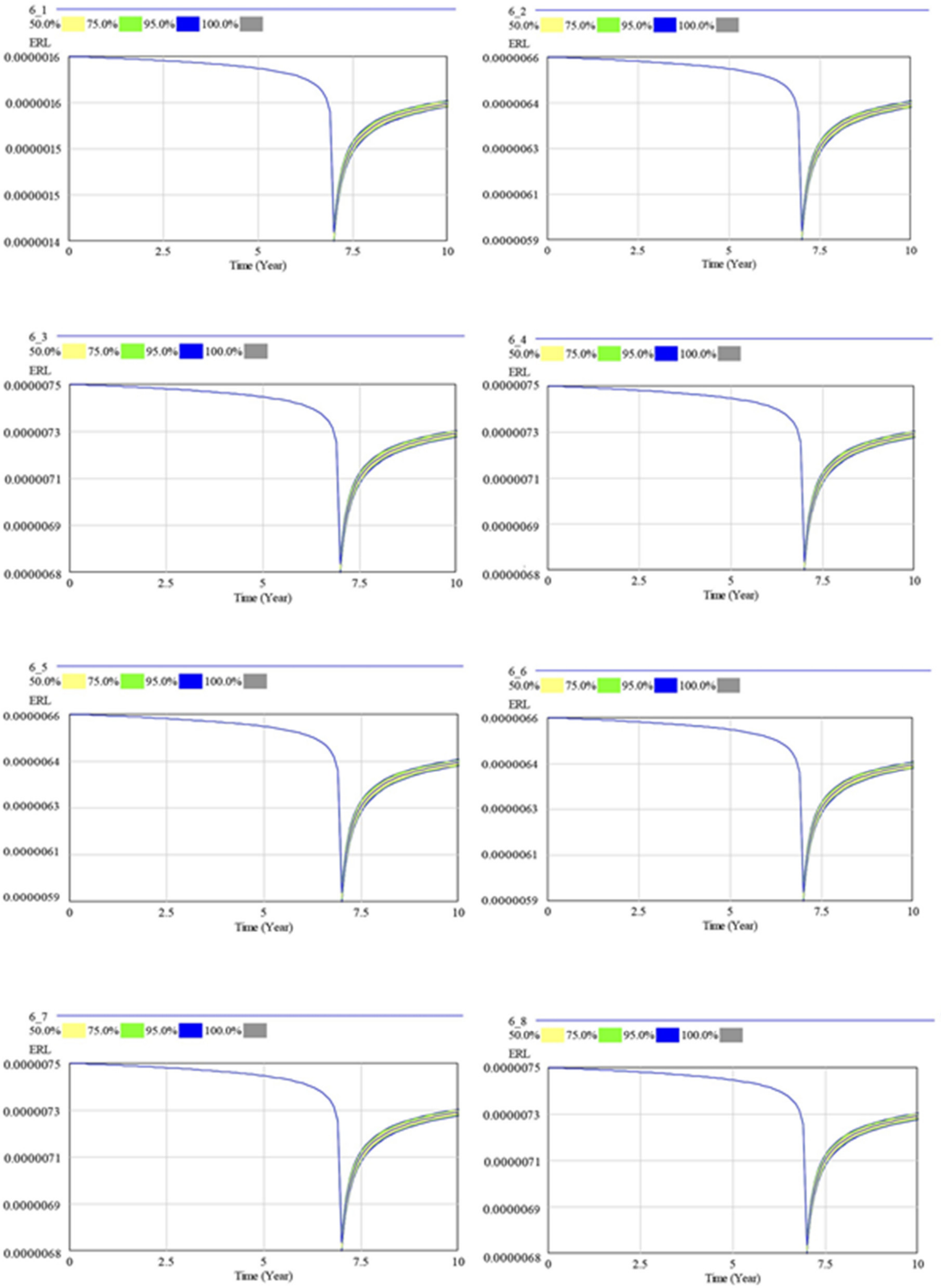

Figure S21. SD Individual ERL plots-Trial Designs 01-08, Case #6.

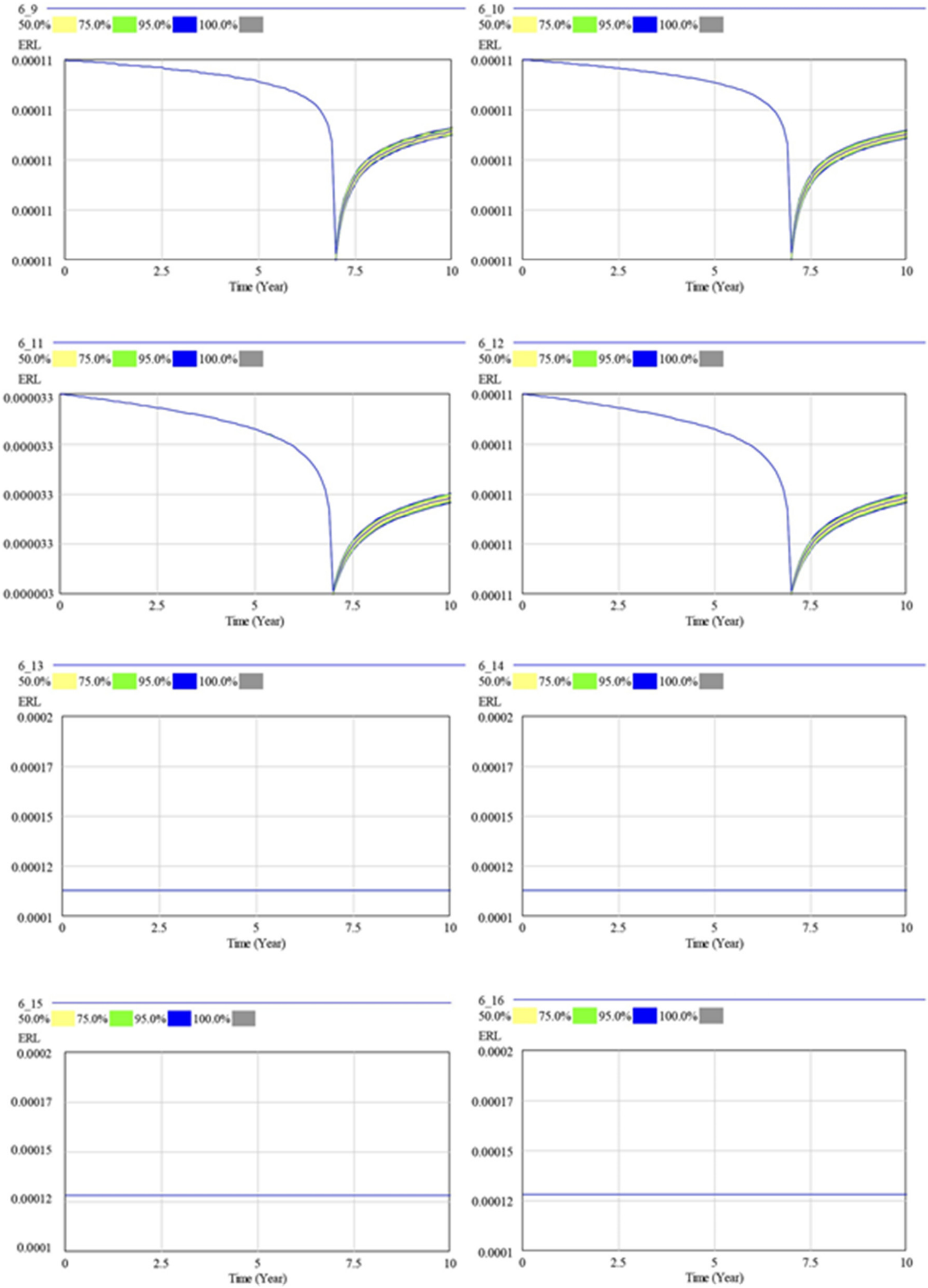

Figure S22. SD Individual ERL plots-Trial Design 9-16, Case #6.

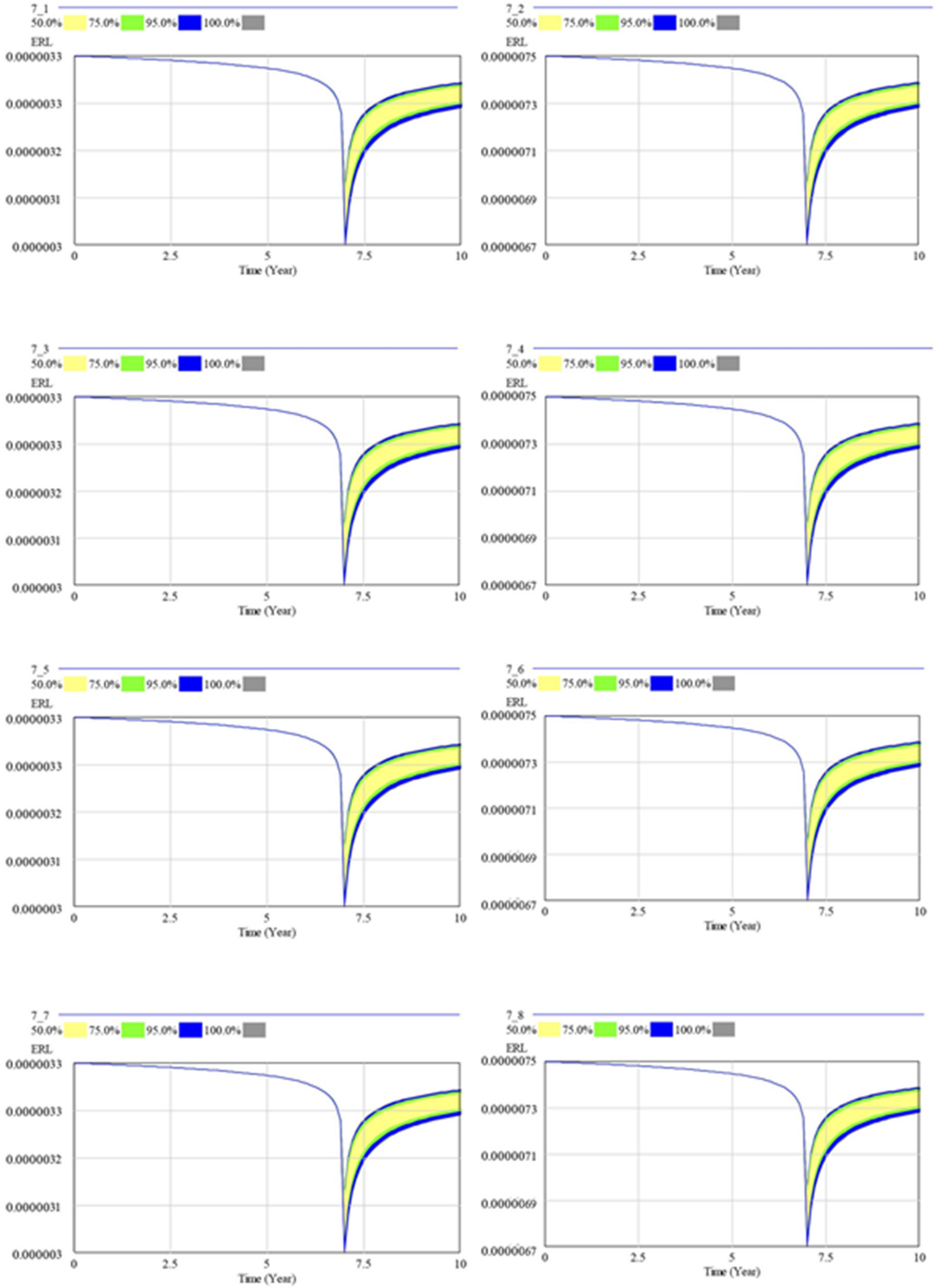

Figure S23. SD Individual ERL plots- Trial Designs 01-08, Case #7.

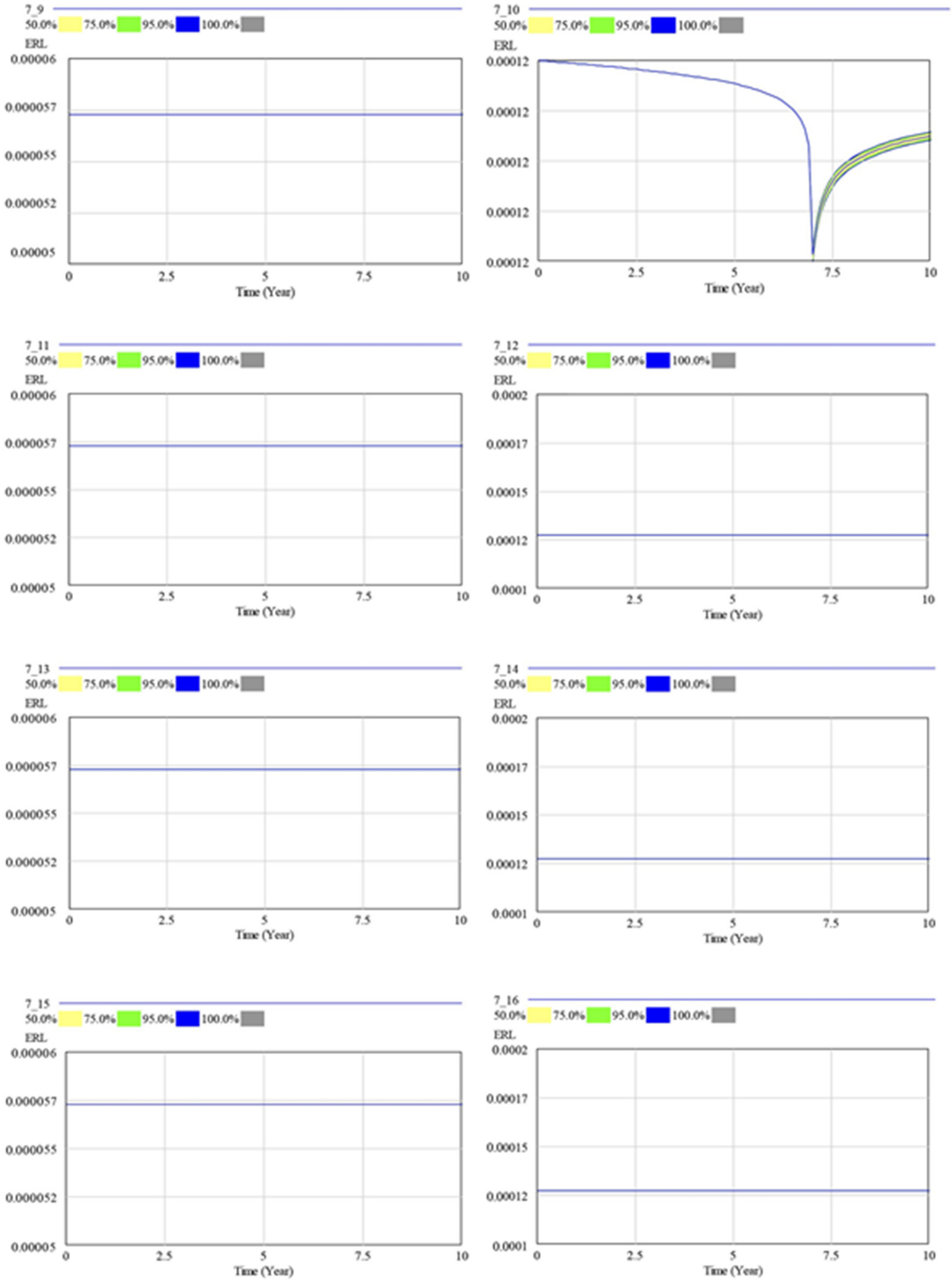

Figure S24. SD Individual ERL plots- Trial Design 9-16, Case #7.

4.6 Synopsis of Chapter 4

In this chapter, the T-H-O-Risk methodology was applied to seven case studies to determine the impact of HOEs on the reliability of active fire safety systems. The results demonstrate that HOEs can have a significant impact on fire risks in high-rise residential buildings; increase in ERL increased in the range of 6% to 38% due to the influence of HOEs in buildings with active systems of sprinklers, BOWS, smoke control systems and smoke detectors. HOEs have a limited or no impact on passive protection systems. Societal risks remain high in the absence of active safety systems and generally risk is lower where stairwells and active safety systems are present. SD modelling indicated large variations in the reliability of active systems due to HOEs over time. The reliability of safety systems such as detection or suppression systems varied with time as well as the effect of perceived safety impacted the actions of safety personnel. An initial sensitivity analysis on HOE variables performed in Chapters 3 indicates that deficient training, poor safety culture and ineffective emergency plans have a significant impact on the overall risk. The SD simulation results in Chapter 4 further show that the dynamic effects of human, organizational, and social factors alter component reliability and that the influence of these factors develops over time. Small behavioural changes in risk perception of a building management team can lead to large variations in risk for an individual (ERL) over time. In the next chapter, detailed sensitivity and uncertainty analyses on HOEs are explored within the T-H-O-Risk model and will be discussed later.

Chapter 5

Sensitivity and uncertainty analyses of human and organizational risks in fire safety systems for high-rise residential buildings with probabilistic T-H-O-Risk methodology

Overview

Chapter 5 presents the sensitivity and uncertainty analyses of the T-H-O-Risk model. In Chapter 3, an initial sensitivity analysis on HOE variables was performed but was limited to three case studies to establish what the significant variables were. In Chapter 4, the sensitivity analysis was limited to the dynamic response of the SD model. In this chapter, detailed sensitivity analyses are performed to determine the most influential HOE variables on the outcome and as precursors to more comprehensive uncertainty analyses to quantify the impacts on risk due to uncertainty associated with these HOE variables. This uncertainty analysis covers three aspects of the (i) expected risk to life (ERL) point estimates (ii) Societal Risk in the F-N curve assessment, and (iii) time varying reliability in the SD model.

The Australian Fire Safety Verification Method (FSVM) is the assumed verification method as it is more quantifiable from risk point of view. However, it is a bit of a simplification since it is a deterministic method. The T-H-O-Risk methodology extends the FSVM approach through PRA and incorporates technical risks as well as HOEs risks for a more inclusive view of risk as well as overcoming the deterministic nature of the current Australian FSVM. While FSVM provides fire engineers and building authorities with a clear set of assessment criteria so that the resultant fire engineering designs are more consistent, it does not incorporate quantitative risk, reliability and uncertainty analysis. The T-H-O-Risk model improves on these verification methods by enabling the quantification of individual and societal risks to facilitate absolute risk ranking of various design scenarios solution for more rigorous analysis and development of building codes and risk assessment methodologies The main focus of this chapter is to identify the most influential HOE variables through sensitivity analysis and the treatment of uncertainties regarding numerical values of the HOE parameters used in fault/event trees, Bayesian network (BN) and system dynamics (SD) in the PRA and their propagation in these models.

The T-H-O-Risk/FSVM framework is applied to four high-rise buildings that are used as case studies where the performance solution is assessed against a reference deemed-to-satisfy (DTS) solution to determine and compare the level of risk. By assuming different fire locations, 16 trial designs are simulated for each case. To determine the impacting factors, detailed sensitivity analysis was carried out. Uncertainties in point estimates of ERL in the model are analysed through appropriate probability distributions and Monte Carlo simulations while uncertainties in societal risks and risk variations over time are propagated with confidence-interval-based uncertainty diagrams. Additionally, separate sensitivity and uncertainty analyses are also performed on key variables in the SD model to assess model robustness and to explore how uncertainty affects the assessment of different safety systems and time-varying reliability of model outputs.

Results indicate that the most influential HOE variables are 'not complying with instructions', 'deficient training' and 'inefficient emergency plan'. The uncertainty analysis of the ERL indicates that the significant HOE variables determine important variations in the ERL value of the system by up to 30% of the reference value. The minimum amount of variation associated with these HOEs is approximately 3–5% indicating that HOEs impact global risk levels; the F-N curves for all cases and scenarios with HOEs shift upwards indicating risk is underestimated when HOEs are ignored. As system complexity increases, so does the influence of HOEs on risk primarily due to increasing numbers of fire safety measures and maintenance regimes. Sensitivity and uncertainty analyses in SD risk modelling indicate that risk thresholds oscillate or spike at year seven over the 10-year cycle. Risk variation over time analysis indicates that maintenance of an active safety system is required within five to seven years due to the degrading influence of HOEs on the reliability of the system.

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1. PUBLICATION DETAILS (to be completed by the candidate)

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Surname: Tan First name: Samson, Boon Hua

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Status:

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Name(s) of Co-Author(s)	**Contribution (%)**	**Nature of Contribution**	**Signature**	**Date**
Samson Boon Hua Tan	75	Conceptualization, methodology, software modelling, validation, formal analysis, original draft, writing- review & editing	[redacted]	04-Mar-2021
Khalid Moinuddin	15	Conceptualization, methodology, validation, resources, writing-review & editing, supervision	[redacted]	08/03/21
Paul Joseph	5	Validation, writing- review & editing, project administration, supervision	[redacted]	08-03-21
Darryl Weinert	5	Validation, writing - review & editing, supervision	[redacted]	

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Article

Sensitivity and Uncertainty Analyses of Human and Organizational Risks in Fire Safety Systems for High-Rise Residential Buildings with Probabilistic T-H-O-Risk Methodology

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Abstract: Given that existing fire risk models often ignore human and organizational errors (HOEs) ultimately leading to underestimation of risks by as much as 80%, this study employs a technical-human-organizational risk (T-H-O-Risk) methodology to address knowledge gaps in current state-of-the-art probabilistic risk analysis (PRA) for high-rise residential buildings with the following goals: (1) Develop an improved PRA methodology to address concerns that deterministic, fire engineering approaches significantly underestimate safety levels that lead to inaccurate fire safety levels. (2) Enhance existing fire safety verification methods by incorporating probabilistic risk approach and HOEs for (i) a more inclusive view of risk, and (ii) to overcome the deterministic nature of current verification methods. (3) Perform comprehensive sensitivity and uncertainty analyses to address uncertainties in numerical estimates used in fault tree/event trees, Bayesian network and system dynamics and their propagation in a probabilistic model. (4) Quantification of human and organizational risks for high-rise residential buildings which contributes towards a policy agenda in the direction of a sustainable, risk-based regulatory regime. This research contributes to the development of the next-generation building codes and risk assessment methodologies.

Keywords: human and organizational risks ; probabilistic risk assessment; high-rise residential buildings; fire risk; human and organizational errors; time varying reliability; fire safety engineering

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1. Introduction

Probabilistic modelling of fire safety risks in high-rise residential buildings typically has included technical risks and errors, while ignoring the impacts of human and organizational risks resulting in significant underestimation of overall risks. It has been well recognized that human and organizational factors (HOFs) are the leading causes of most accidents, and literature in other related industries indicates that existing models that ignore human and organizational errors (HOEs) underestimate risk, possibly by as much as 80% [1–3]. From a practical viewpoint, it is essential to adopt technical, human, and organizational risks for a realistic fire risk assessment of a building design [2]. Moreover, during the operational phase of a building, the reliability of the fire equipment should not be considered constant, and its aging over time must be addressed to derive more realistic risk values [4]. Prior studies provide estimated effects of HOEs on risk in other industries such as nuclear plants, aviation and offshore oil platforms, but existing literature does not address or quantify the impact of HOEs on risks during fire events in high-rise buildings.

Recent fatalities in high-rise residential fires, e.g., Grenfell, London, have demonstrated the urgent need to consider HOEs in probabilistic risk assessments (PRA) for high-rise residential buildings [2,5]. However, this is yet to be reflected in the current state-of-the-art PRA for high-rise buildings given that current models still consider only technical factors [6]. Meanwhile, various frameworks and models are available in other industries such as nuclear plants, aviation or offshore platforms, e.g., Pence et al.[7], Mohaghegh and Mosleh [8], Mohaghegh [9], Groth et al. [10], Lin et al. [11] and Wang et al. [12]. Recently, Meacham et al. [13] have proposed a socio-technical system (STS) approach to characterize and incorporate risk measures into building regulation by viewing building regulatory systems (BRS) as complex STSs, where institutions, technology and people interact to mitigate risk to a societally tolerable level. Meacham and Straalen assert the importance of human and organizational risk to the development of new building codes[14]. In another study [15], cultural factors, barriers and influences, training, communication, supervisor role, employee participation and risk-taking behaviours were considered in fire safety analysis in a mining industry. Similar to high rise buildings, safety analysis of wildfire is equally challenging. In [16], risk assessment and risk elimination (like administrative control) models are used in a dynamic environment of wildfires. However, to date, there is a dearth of studies that incorporate technical, human and organizational risks in a PRA specific to the building domain. Therefore, the aim of this study is to address this methodological gap.

Deterministic and probabilistic analysis are two common methods to perform fire risk assessment [17]. In a deterministic fire engineering approach, worst-case scenarios are considered, and it is assumed that there will be no failure of fire safety systems such as sprinklers or smoke detectors. This oversight results in a failure to account for the reliability of such systems. In addition, uncertainties are not explicitly considered in deterministic approaches. On the other hand, probabilistic fire safety engineering approaches consider all possible scenarios, as well as their consequences and likelihood of occurrences [18]. Probabilistic approaches deploy tools like fault tree analysis (FTA) and event tree analysis (ETA) to analyse the cause of a failure and its consequences if a failure occurs. Prescriptive building codes may include provisions that result from immediate reactions after major fire incidents, can be difficult to use with new technologies and do not adequately address new building innovations. The limitations of prescriptive building codes instigated a paradigm shift from prescriptive to performance-based design (PBD) methods where the desired safety level in a building is ensured while enabling the use of newer technologies. However, the proliferation of different PBD approaches necessitated a framework to bring uniformity to PBD which is achieved using verification methods (VM). VM is a tool to verify compliance with the performance requirements of building codes by taking a performance solution through a detailed verification process to ensure it meets the acceptance criteria [19]. These VMs are merely tests to be carried out after a performance solution has been developed, without interfering with the PBD process itself [20]. The fire safety verification method (FSVM) was introduced into the Australian National Construction Code (NCC) in 2019, following the need to reduce the 'reliance' on prescriptive regulations [21]. Internationally, New Zealand already has VM within their building codes, Scotland and Spain are considering them and Sweden has a similar scenario-based fire safety engineering process document [22–24]. Both the FSVM [21] and the earlier New Zealand Verification Method C/ VM2 [22] describe procedures for validation and verification of models. There have been various recent studies on VM [20,25,26] and while the next iteration is expected to incorporate a risk-based approach, current VMs are largely deterministic in nature. However, the Australian Building Codes Board (ABCB) is keen to bring PRA into practice within next few years albeit without considering HOEs.

The present Australian FSVM framework is deterministic in nature, does not consider failure modes of components, and risk is estimated from worst credible case scenarios. Often such scenarios are not practical, resulting in underestimation of risk. Furthermore, the literature review suggests that it is necessary to consider the time varying reliability of safety systems for more realistic view of risk. To address the methodological gap in the lack of methods available to incorporate human and organizational risks specifically for high-rise residential buildings, we developed the technical-human-organizational risk (T-H-O-Risk) model that considers technical, human and organizational risks for a more inclusive estimate of overall fire risk [27–29]. While this approach enables an integrated analysis of HOEs and their nonlinear interactions and feedbacks, it generally results in a higher level of uncertainty, hence, detailed sensitivity and uncertainty analyses are performed to assess the model robustness and reliability of model outputs. Sensitivity analysis assesses which input parameters contribute the most towards the total uncertainty in analysis outcomes, while uncertainty analysis assesses the uncertainty in model outputs derived from using a range of values of a particular input parameter.

Uncertainty plays an important role in the T-H-O-Risk model which can arise from incomplete modelling, assumptions and human errors. The main sources of uncertainty are inadequate conceptual, mathematical or computational models [30]. Some parameters in the event/fault trees, Bayesian networks (BN) and system dynamics (SD) variables for estimation of probabilities can be uncertain due to lack of data or availability of information. Data used to quantify fire scenarios include reliability and failure rates of safety system components and HOE probabilities. They are usually represented by probability density function or uncertainty bounds. Uncertainties can be significant in HOE variables and hence, are important for determining the reliability of T-H-O-Risk model. For technical factors where statistical data is largely available, uncertainties may be small but for HOE variables where limited data is available, uncertainties can be significant. The event pathways in T-H-O-Risk methodology introduce uncertainties into probabilities and consequence which can be either aleatory uncertainty or epistemic uncertainty. Aleatory uncertainty is due to randomness in the process while epistemic uncertainty is a result of lack of knowledge in the system. Reliability data and failure rates of safety components are typically uncertain due to lack of information. In Pate-Cornell's [31] uncertainty framework, Level 5 uses the same kind of framework as Level 4 uncertainty but risk that is typically expressed in point estimates are replaced with probability distributions instead and confidence intervals are added to the results—this is investigated in this study. It is important to determine the degree of uncertainty in the T-H-O-Risk methodology to assess the efficacy and reliability of the model for effective fire safety measures in high-rise residential buildings. It is to be noted that sensitivity and uncertainty analysis in this article will be confined to HOEs only.

Due to the highly publicized high-rise fires in recent years such as the Grenfell Tower fire in London and the Lacrosse Dockland Fire in Melbourne, fire risk is vitally important to occupants and regulators. Much of the recent research in building fire risk is heavily focused on reducing risk and developing risk-informed oversight by improving technical systems in fire risk assessments. Risks in building fires include the systems, organizations and humans and by excluding HOEs, risk is likely to be underestimated. Equipment maintenance and operation, and procedural factors have a human component, as well as building occupant behaviour during a fire event. Current methods do not include the possible impact of explicit human and organizational errors on safety performance of equipment and personnel. Stakeholders in Australia are progressively shifting towards quantifying performance in the building codes by evaluating risk levels and their tolerability levels [21].

To address the knowledge gaps in current state-of-the-art PRA for high-rise buildings identified in the literature review above, the main goals of this paper are as follows:

- Develop an improved PRA methodology to address concerns that deterministic, fire engineering approaches significantly underestimate safety levels that lead to inaccurate fire safety levels.
- Enhance existing verification methods by incorporating probabilistic risk approach and HOEs for (i) a more inclusive view of risk, and (ii) to overcome the deterministic nature of Australian verification method.

- Perform comprehensive sensitivity and uncertainty analyses to address uncertainties in numerical estimates used in fault tree/event trees (FT/ET), BN and SD and their propagation in T-H-O-Risk model.
- Quantification of human and organizational risks for high-rise residential buildings which contributes towards Australia's agenda that is moving in the direction of a sustainable, risk-based regulatory approach.

The paper proceeds as follows: Section 2 presents the methodology and materials used; case studies are explained in detail in Section 3; analysis, sensitivity, uncertainty studies are presented in Section 4 and finally, conclusions and implications are discussed in Section 5.

2. Materials and Methods

2.1. Characteristic Overview

The Australian FSVM specifies twelve typical design scenarios for establishing if a building solution satisfies the relevant performance requirements. The proposed solution is then compared against a reference design which complies fully with the NCC Deemed-to-Satisfy (DTS) requirements. As the performance requirements are not quantified, the DTS building serves as a benchmark for acceptable safety level. The development of the FSVM process takes place in two different documents; a performance-based design brief (PBDB), which contains a description of all decisions of the stakeholders to perform the assessment, and a report which illustrates the execution and results from the risk assessment. To assess compliance with NCC, the required steps for completing the PBDB are shown in Figure 1 which enhances existing FSVM by incorporating T-H-O-Risk methodology.

Note that the developed T-H-O-Risk model is incorporated in the last step of the flowchart for comparison of technical, human and organizational risk levels of the performance building and reference DTS building. The choice of reference building should be based on an agreement with all the stakeholders and will have the following characteristics:

- Fully comply with the NCC DTS provisions;
- Comply with other relevant regulations;
- Have the same footprint, floor area and volume as the proposed building;
- Be of the same NCC classes as the proposed building;
- Have the same effective height;
- Have the same occupant load and occupant characteristics;
- Have the same fire load and design fire.

2.2. Methodology

The Australian FSVM provides a deterministic assessment of risk estimation in high-rise buildings. It provides standard design scenarios covering different fire safety aspects of a building. If the criteria fulfilled for these design scenarios are within certain thresholds, the design of building is considered safe. The limitations of this approach are that only technical factors are considered in the model and component reliability and failure rates are not accounted for in the framework. The T-H-O-Risk model improves on the existing FSVM by incorporating both technical and human errors into the simulations. Since HOEs are accounted for in this model, the T-H-O-risk model provides more accurate and realistic estimates of risk. The methodology develops a risk-based performance-based approach to generate alternate solutions, amongst which lower risk designs can be selected which enhances existing FSVM solutions while providing flexibility to fire safety engineers. In the next sections, the incorporation of the T-H-O-Risk model into the Australian framework is assessed.

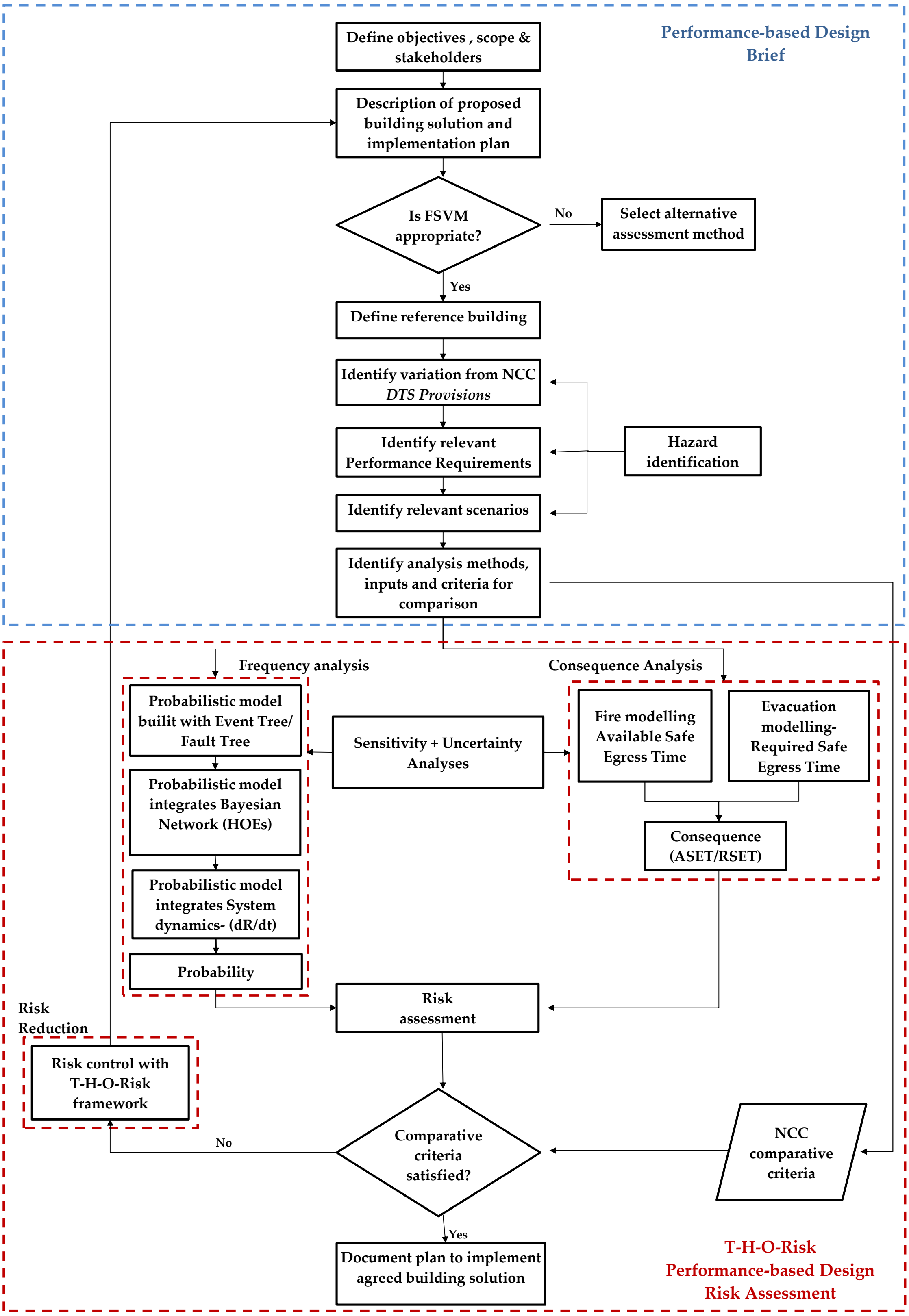


Figure 1. Technical-Human-Organizational Risk (T-H-O-Risk) FSVM (fire safety verification method) process flow chart. NCC: National Construction Code.

2.3. FSVM

The FVSM requires several phases to be accomplished before conducting the risk analysis, among which the most relevant are the definition of the proposed building design and the corresponding DTS solution, the variations from the DTS solution and the identification of the relevant performance requirements. The FSVM presents twelve design scenarios that cover fire engineering design compliance on egress, active and passive systems, fire spread and fire brigade intervention and safety systems redundancy. Some or all of these design scenarios may be considered for the performance solutions, depending on the scope of the assessment and the desired fire safety level. The performance solution must be at least equivalent to that of the DTS solution. The description and analytical process of the design scenarios applicable to the fire engineering design of the case studies are presented in the following subsections. The fire engineering design is comprised of quantitative assessments utilising current fire and evacuation modelling and risk assessments tools.

2.4. T-H-O-Risk Framework

The PRA-based T-H-O-Risk methodology includes a set of sequentially linked tools and techniques. These are used to estimate probabilities and consequences for several fire scenarios and provide output in the form of both individual and societal risk. The process is described concisely here while the complete methodology can be found in our earlier papers [27–29]. Appendix A provides more details on the T-H-O-Risk methodology that incorporates ETA, FTA, Bayesian networks, system dynamics, and fire and evacuation modelling to determine available safe egress time (ASET) and required safe egress time (RSET). Briefly, the model involves the following steps:

I. Calculation of the frequency of ignition: the calculation is based on [32]. The resulting value is then multiplied by the probability of a fire located in a sole-occupancy unit (SOU), in other words an apartment fire, or in the corridor (corridor fire).

II. Deployment of the accident scenarios and calculation of the associated probability using ETA: starting from the initiating event, the possible scenarios are derived by assuming a set of events that could or could not happen. The events are related to the effectiveness of the safety countermeasures (detection, notification, sprinkler, smoke management system) hat is linked to the type of fire (flaming or smouldering). FTA, a top-down failure analysis tool, is used to estimate the effectiveness of the safety measures.

III. Calculation of the consequences for each scenario using ASET/RSET analysis: as described elsewhere, consequences are estimated by comparison of the ASET and the RSET. The first parameter is obtained from the B-Risk fire modelling simulation by determination of the time available before untenable conditions occur; the second is obtained as the sum of the time to complete different evacuation phases (detection, notification, pre-movement, and movement). Those times are derived partly from analytical calculations (hydraulic model), and partly via B-Risk simulation.

IV. Introduction of HOEs through a BN: a static evaluation of the effects of human and organisational failures is performed through a BN. The ET structure of the model is converted into the more flexible BN which allows the description of multiple relationships between variables.

V. Calculation of the individual and societal risk for different contexts (level of organization): the impact on the risk of a good or bad safety organisation is investigated using two different indicators. The first indicator is a single risk value, the Expected Risk to Life (ERL), which expresses the risk in deaths/year*building; the second risk indicator, the SR is represented using the Frequency—Consequences (F-N) curves. F-N curves allow a comparison of the different solutions on Societal Risk which reflects average risk, in terms of death that a whole group of occupants is exposed to a fire scenario instead of looking at individual occupant. This second indicator is helpful in the decision-making process, introducing the possibility of adopting human-related countermeasures.

VI. Dynamic modelling of risk variations in the system using SD: to include future changes of the various components of a complex system, the evolution along its entire life cycle should be investigated. The analysis incorporating changes over time is performed with SD: each parameter of the system is checked along a period of ten years and hypotheses are made on the evolution of their values in relationships with all other parameters. A 'societal' loop is created which enables the modelling of HOEs in response to changes in the perception of the risk in the system.

VII. Calculation of the time—risk curve for the entire lifecycle of the building.

VIII. Sensitivity and uncertainty analyses using a Monte Carlo approach. Uncertainties in point estimates of ERL values are propagated through probability distributions with Monte Carlo simulations while a family of F-N curves and confidence intervals propagate epistemic uncertainty on SRs. Sensitivity and uncertainty analyses are also performed on key variables in the SD model to assess model robustness and to explore how uncertainty affects the assessment of different safety systems and reliability of model outputs.

2.5. Sensitivity and Uncertainty Analysis

A sensitivity analysis is conducted to determine the most influential HOE variables on the model outputs while uncertainty analysis is used to assess how much uncertainty is associated with these influential variables. The purpose of these analyses is to determine the HOE-related influence on risk. A Monte Carlo approach is adopted to perform the analysis; a sampling is generated from the probability distributions and the output of the model is determined and represented in different graphs. The number of samples has been fixed to 1000 samples for an acceptable level of confidence. The following steps are performed for the sensitivity and uncertainty analyses.

First, the responsive parameters are identified. Second, for each of the responsive human and organizational parameters, a univariate analysis is performed to assess the sensitivity of the target variables to characterize which variables are more sensitive to the organisational response. The quantification of the uncertainty allows for both comparative and absolute risk analysis; when using the comparative approach, it ensures that the point value of the individual risk of the performance solution is below that of the DTS solution even if HOE-related errors are taken into account for both designs. It can be possible, in theory, that the first of the two solutions is more prone to be influenced by human factors than the second, or vice versa. For the performance solution to be approved, it is therefore important to find the upper and lower limits for both the risk values and verify that the upper bound value of the performance solution is below the lower bound solution of the DTS solution. When risk evaluation is conducted in absolute terms, the oscillations of the risk value should never trigger the reference value. The uncertainty analysis allows a deeper understanding of the propagation of HOEs through a risk model for high-rise buildings subject to fire.

In the sensitivity analysis, a simple mono-dimensional analysis is conducted based on point values. The HOEs (deficient training, inefficient emergency plan, not comply with instruction, no check rules, deficient maintenance, wrong risk assessment, not obey standard, improper safety organisation) are attributed with a probability distribution built based on a three-point estimation method. In a multivariate analysis, the sensitivity is represented in a tornado graph showing the variables with major impacts on the final risk value. When considering a single parameter, the relative amplitude of the variation of the global risk value is compared to the relative amplitude of the variation of the parameter value (sensitivity). Moreover, the model is used to determine the amplitude of the risk variations in cumulative terms. This in fact can be beneficial for more detailed analysis of the risk in relationship to the entire society.

Sensitivity analysis is further conducted on key variables in the SD model to assess model robustness and to explore how uncertainty affects the assessment of different safety systems and reliability of model outputs. Once the sensitive parameters for each HOE variable have been identified in the previous steps, a Monte Carlo simulation is carried out. The linkage of these variables to their parent nodes is the focus of this analysis. The causal loop in the SD model consists of all the variable and their interactions with each other including feedback loops and time delays. Stocks are accumulations in the system used to represent variables that change with time and flows are entities that control these stocks. The behaviour of the HOE variables depends on the parent variables connected to them in the causal loop and delays are to be expected in the response to safety issues due to feedback loops occurring over a period of time. Therefore, if the system is observed on a wider time scale over ten years, oscillations in the final output are possible, generating phases during which the risk could vary greatly with respect to the static value. To develop a better understanding of those dynamic phenomena, parent nodes, are varied and the corresponding variation in the value of the target variables (children nodes) is investigated.

The propagation of uncertainty is modelled using the Monte Carlo technique applied to the ET to calculate uncertainty related to the probability of accidents (ordinate of the F-N curve). The same approach is then used to model the uncertainty related to the number of deaths, in the abscissa of the F-N curve. This allows an expansion of the single F-N curve to a family of curves that can be considered representative of the effective SR. In this way, the confidence of the model output can be increased.

3. Case Studies

Four cases have been selected for this study. Three of the cases are taken from our previous studies [27–29]. The fourth case is an ABCB FSVM Handbook reference case study. The ABCB case will enable us to benchmark against the other three selected cases.

3.1. Objectives and Performance Requirements

The first proposed design (Case 1—ABCB) is a 20-storey residential occupancy building with twelve units per floor. The performance solution provides a single fire stair for each floor while the DTS solution provides a double exit stair in compliance with the requirements from NCC. Both designs are taken from the FSVM Handbook and are shown in Figure 2. Table 1 summarizes the main characteristics and differences between the two solutions. When examining the floor plan of a single floor, space saving by using a single fire stair does not appear to be significant, however the space savings over twenty floors can be quite significant. Additionally, construction cost savings from not constructing the second stair compartment is also substantial.

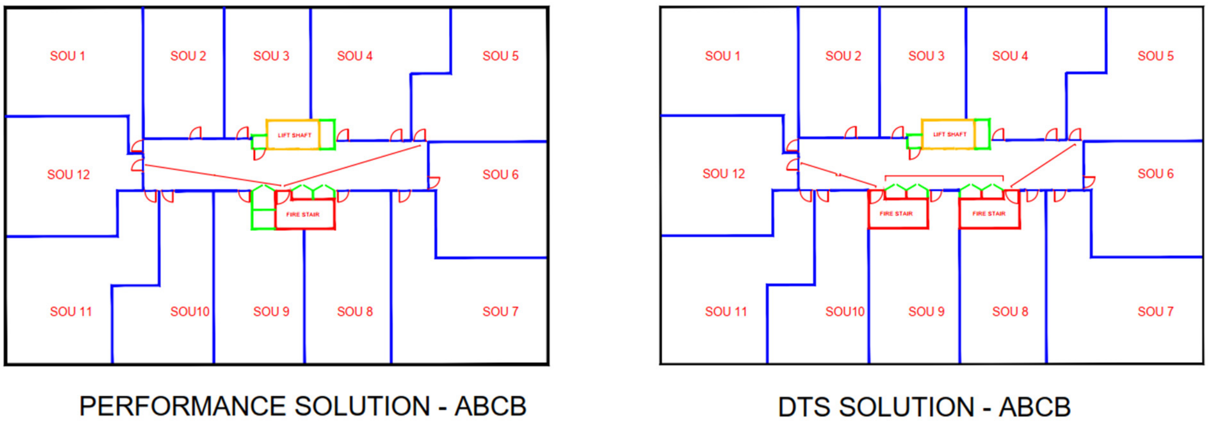


Figure 2. Two solutions for Case #1 Australian Building Codes Board (ABCB) model residential building.

Table 1. Characteristics of Case #1- Australian Building Codes Board (ABCB) Deemed-to-Satisfy (DTS) and Performance solutions.

Building Characteristics	ABCB DTS	ABCB Performance
Occupants per floor	36	36
Number of floors	20	20
Floorplate area (m^2)	702	702
Number of units per floor	12	12

The comparison of the two designs shows that the performance requirement that is not met by the proposed design is the DP6 (Paths of Travel to Exits) requirement. The building is classified as a Class 2 building according to the NCC, Volume 1. Given the height of more than 25 m, the DTS design shall have at least two exits from each storey. The second element of non-compliance for the performance solution is the exit travel distance (D1.4) [21]. The DTS condition requires that the 'entrance doorway of any sole-occupancy unit must be not more than 6 m from an exit or from a point from which travel in different directions to two exits is available'. Moreover, the distance between alternative exits must be not less than 9 m and not more than 45 m.

These DTS requirements are expected to be compensated by introducing other safety measures that are not contemplated in the DTS solution. The method used to compare the risk in the two buildings is the T-H-O-Risk method. The output from the application of the method to the two solutions will generate two risk values that will be compared to assess the level of safety of the performance solution. Using the FSVM, a selection of the design scenarios can be made based on the performance requirement that is violated (using Table 1.2 of the Handbook for FSVM [21] as a guide). Consequently, the design scenarios that need to be modelled are as follows:

- BE—Blocked Exit, a fire blocks the evacuation route; it is necessary to demonstrate through ASET/RSET and ERL analysis that the level of safety is at least equivalent to the DTS provisions.
- CS—Concealed Space, a fire starts in a concealed space that can spread and harm several people in a room. The solution might include fire suppression or automatic detection.
- SF—Smouldering Fire, a fire is smouldering close to a sleeping area. The solution may provide a detection and alarm system.
- IS—Internal Surfaces, interior surfaces are exposed to a growing fire that potentially endangers occupants.
- CF—Challenging Fire, the worst credible fire in an occupied space.
- RC—Robustness Check, failure of a critical part of the fire safety system will not result in the design not meeting objectives of the NCC (modified ASET/RSET analysis to demonstrate that the remaining floors or fire compartments are robust).

For each of the fire scenarios, a fire modelling simulation based on fast t-squared fire ($\alpha = 0.0469$) up to flashover will be performed to determine ASET based on tenability limits. The same approach is used for the other three cases (Figures 3–5), with characteristics shown in Table 2.

In Case #2, as shown in Figure 3 the performance solution has only a single exit stair similar to Case #1, while for Cases #3 and #4 (Figures 4 and 5, respectively); the performance solutions deviate from the required 6 m dead end travel distance. As described in [29], Case#2 is located in UK and Cases #3 and #4 are in Australia—all in a temperate climate.

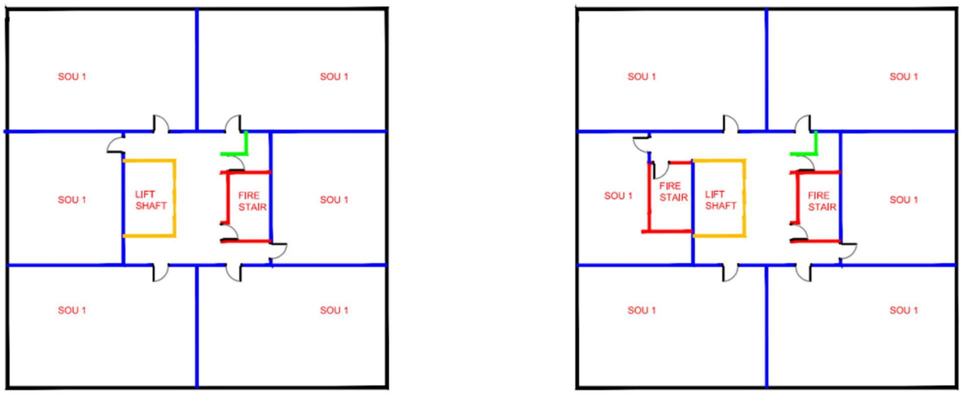


Figure 3. Case #2—Performance (**left**) and DTS (**right**) solutions.

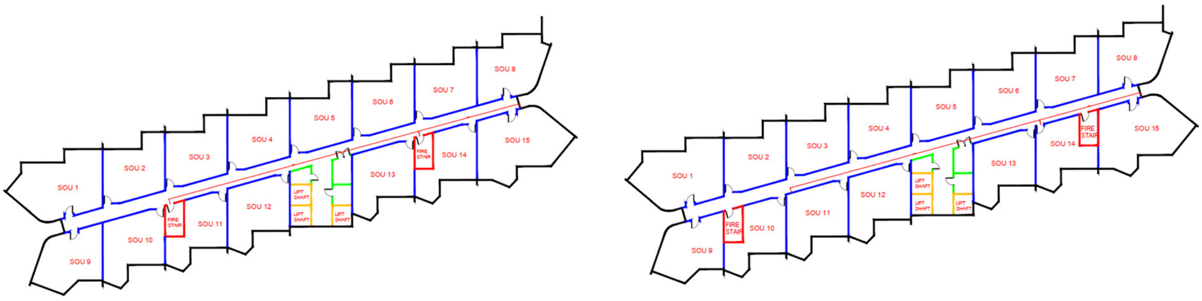


Figure 4. Case #3—Performance (**left**) and DTS (**right**) solutions.

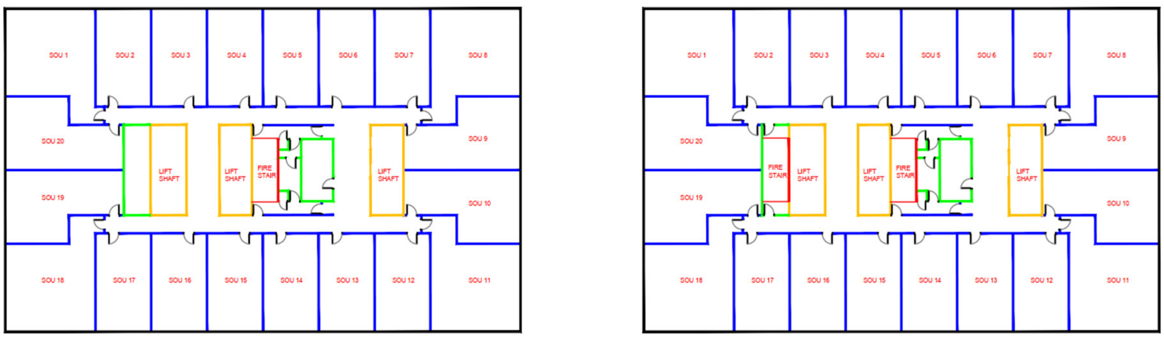


Figure 5. Case #4—Performance (**left**) and DTS (**right**) solutions.

Table 2. Characteristics of the building case studies.

Building	Case #2		Case #3		Case #4	
Characteristics	Performance	DTS	Performance	DTS	Performance	DTS
Occupants per floor	24	24	54	54	58	58
Number of floors	24	24	23	23	21	21
Floorplate area (m^2)	484	484	1099	1099	1343	1343
Number of units/floor	6	6	15	15	20	20

3.2. Probability Analysis of Human and Organizational Errors

In addition to technical factors, a review and analysis of the literature is performed to obtain probabilities and frequencies of the important HOEs. These probabilities and frequencies are assigned to initiating events and basic events in the model to carry out a quantitative analysis of the frequency of occurrence. The Fussel-Vesely method [33] is used to determine the important HOEs as described in Appendix A.

3.3. Event and Fault Tree

The ETA uses a logical technique to examine the failure and success of technical risks emanating from an event. The initial and subsequent events are assigned probabilities and possible outcomes contributing to computations of expected number of consequences. Typical fire safety sub-systems used in high rise buildings are fire detection systems, emergency notification systems, fire suppression systems, interior fire barriers, floor compartmentation (vertical barriers) and building egress systems. The ET incorporates all fire safety sub-systems expected to be present within the high-rise residential buildings as they relate to occupant evacuation as well as the relevant FSVM design scenarios that are applicable to the case studies as follows: (i) CS—Concealed Space (ii) CF—Challenging Fire (iii) BE—Blocked Exit and (iv) Robustness Checks where RC1 is failure of detection, RC2 is failure of sprinklers and RC3 is failure of building alarm. Events are assumed to be independent of each other. The fire safety sub-systems in high-rise buildings are often provided with redundancies to avoid a single point failure. An efficient fire safety system will increase ASET and reduce RSET. The ET helps in identifying the critical sub-system path of fire safety that leads to better mitigation measures.

A typical ET is shown in Figure 6. After the fire is initiated, the first branch is whether fire is in a concealed space or SOU/corridor with a probability of 0.2 and 0.8, respectively. In the next event, this fire can develop into a challenging fire (>5 MW) or a smouldering fire with a probability of 0.45 and 0.55, respectively. Further in the next event, failure of fire detection occurs with a probability of 0.1. Next in the chain comes the sprinkler system with a failure probability of 0.10. A building alarm failure occurs with a probability of 0.1. The probability of the next event, which is blocking of an exit, has a failure probability of 0.2. The failure probabilities assumed are slightly conservative compared to the literature (Appendix B, Table A4) and so will likely result in slightly higher, yet acceptable ERL values. In the worst credible case, the fire ignition occurs in a concealed space, developed into a full CF, the sprinkler system fails (robustness check) and the emergency exit is blocked (BE). In the best case scenario, the fire does not occur in a concealed space, but in the living room of the SOU, does not develop into a full CF, there is no failure in sprinkler or alarm or detection and the emergency exit is not blocked.

The frequency and number of fatalities are also shown in Figure 6. The two most critical events resulting into maximum number of deaths are CF and sprinkler failure. That is, if fire develops into a CF and sprinkler fails, it leads to maximum fatalities. A fire will not be controlled if the fire sprinkler system is not functioning properly. When the sprinkler system is activated, fire growth is controlled or extinguished. If the sprinkler system fails, the fire continues to grow until untenable conditions occur. The negative effects of a fire spreading throughout the building are directly related to the failure of each sub-system. Systems performing as intended will elongate the ASET giving occupants more time to reach safety. The number of consequences is dependent on the reliability of the detection, suppression, notification, containment, robustness and egress sub-system systems. (The failure probabilities for sub-systems assumed in this study are provided in Appendix B, Table A4)

The first node of the ET is the ignition frequency; using the Barrois model [32] equation as:

$$P_1(A) = c_1 A^r + c_2 A^s \quad (1)$$

where $P_1(A)$ is the ignition frequency of a building with floor area A/year, c_1, c_2, s and r constants based on [32] (refer Appendix A).

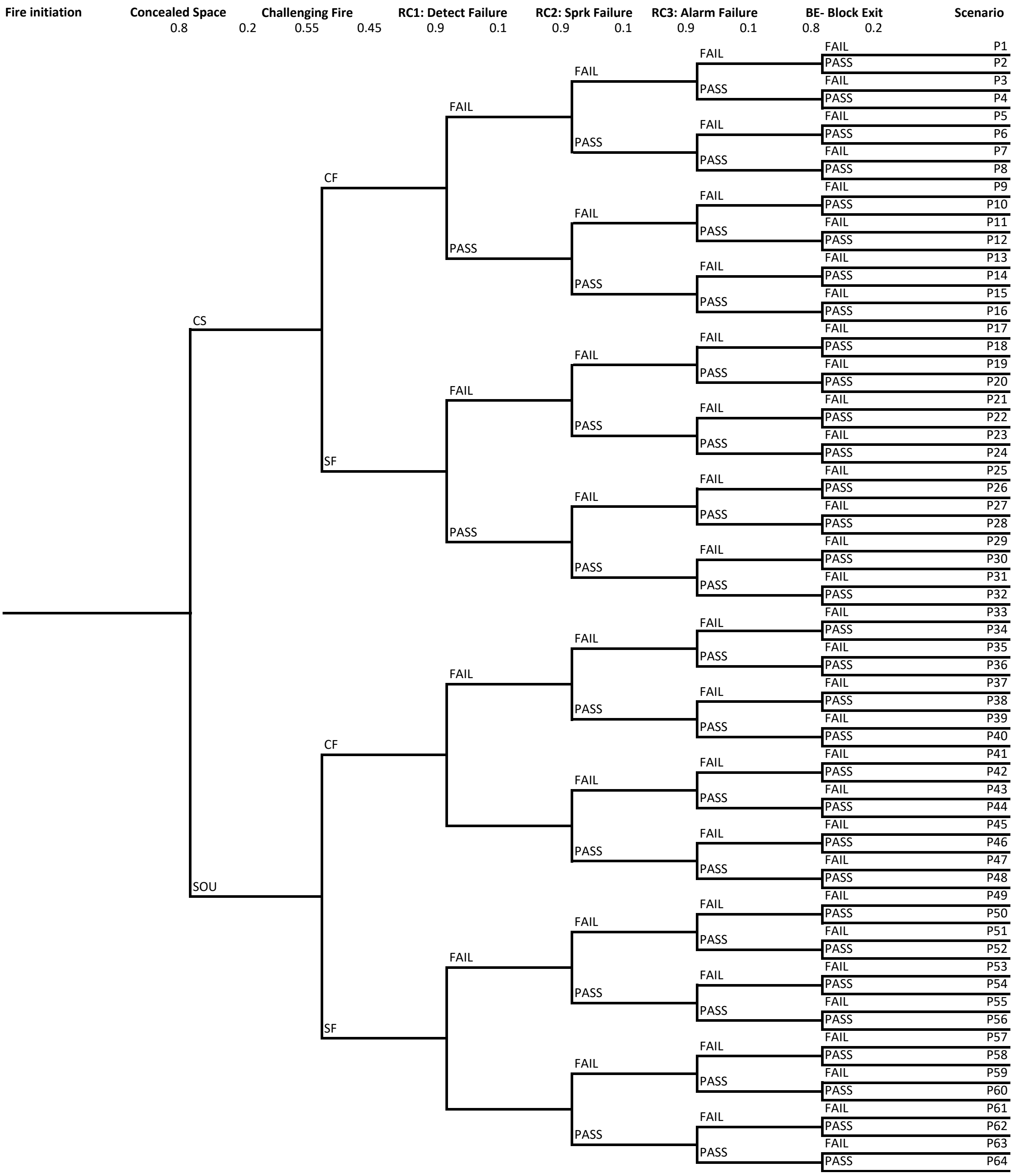


Figure 6. Typical Event Tree—apartment fire.

3.4. Bayesian Network

As the FT/ET can only handle technical factors primarily in Boolean form, HOEs are introduced into the model through BNs. The FT/ET used to determine the probabilities for each possible outcome of the fire event is mapped into a BN for the incorporation of HOEs.

The inclusion of the FT/ET in the BN is shown in Figure A2 and described in Appendix A.

3.5. System Dynamics

System dynamics modelling is used to obtain time-varying probabilities which allows for the representation of feedback loops and delays and to allow for the estimation of risk variations over time of the system. The SD model is shown in Figure A5 and described in Appendix A.

3.6. Consequence Analysis & Design Scenarios

To estimate the consequences, different characteristics of the various fires are analyzed. This includes exits blocked by a fire, fire in concealed spaces, smouldering fires, challenging fires and a robustness check. These characteristics are described in further detail below.

The FSVM associates each performance requirement that has been individuated with the hazard identification process to a certain number of design scenarios to be tested (see Table 1.2 of FSVM Handbook [21]). In the specific case, the performance requirement is the DP6 (Paths of Travel to Exits), which requires only 4 design scenarios to be modeled (BE, CS, CF, RC). The SF scenario in our model is assumed to produce no casualties and has been not modelled. The RC scenario is required to be one where a safety measure (e.g., detection, sprinkler, alarm) is not working as expected; in the T-H-O-Risk model the RC event is included in the analysis of the DTS and performance solution. The details of the numerical experiments are shown in Table 3 and the simulations yield the results as presented in Table 4.

Table 3. Table of experiments for FSVM design scenarios.

Design Scenario	Numerical Experiment #	Solution	Fire Spread
Fire blocks evacuation route	BE1	Performance	Yes
	BE2	Performance	No
	BE3	DTS	Yes
	BE4	DTS	No
Fire starts in concealed space	CS1	Performance	Yes
	CS2	Performance	No
	CS3	DTS	Yes
	CS4	DTS	No
Robustness Check	RC1	Performance	Yes
	RC2	Performance	No
	RC3	DTS	Yes
	RC4	DTS	No
Challenging fire	CF1	Performance	Yes
	CF2	Performance	No
	CF3	DTS	Yes
	CF4	DTS	No
Fire in a normally unoccupied room threatens occupants of other rooms	UT	Not required	
Smouldering fire	SF	Not required	
Internal surfaces	IS	Not required	
Structural stability and other properties	SS	Not required	
Horizontal fire spread	HS	Not required	
Vertical fire spread involving cladding or arrangement of openings in walls	VS	Not required	
Fire brigade intervention	FI	Not required	
Unexpected catastrophic failure	UF	Not required	

Table 4. Results from B-Risk simulation for case #1 Blocked Exit fire.

Tenability Criteria	Sole Occupant Unit	Corridor	Stairway
Upper Layer temperature	n	n	150 s
Lower layer temperature	n	n	90 s
Visibility	240 s	150 s	59 s
FED thermal	n	n	135 s
FED asphyxiant	n	n	1011 s

3.7. Fire Safety Verification Methods – Applicable Design Scenarios

3.7.1. Exit Blocked by a Fire

The fire in a blocked exit scenario is assumed to occur in the stairway where a low fire load is expected. Hence, it can be estimated that a fire has a peak heat release rate (HRR) of 2500 kW. The DTS building shows an individual risk indicator largely greater than the performance solution, hence for this scenario the performance design is verified.

3.7.2. Concealed Space

In this design scenario, the fire starts in a concealed space between two rooms. This fire can be electrical in origin and develop behind a curtain or within a wall with a slow-growth fire (α = 0.0117 kW/s^2). It is assumed that the initial fire is in the bedroom and the fire develops to engulf the mattresses (data from fire test from mattresses re-reported in SFPE Handbook [8] to be around 2 MW).

3.7.3. Smouldering Fire

The assumption in the model is that the smouldering fire is readily cured by occupants and extinguished. Hence, no simulation is determined for this scenario.

3.7.4. Internal Surfaces

The design scenario of a fire igniting internal surfaces of a compartment can become risky for occupants. The fire is then determined to be a fast-growing fire (time to growth is 150 s, so α = 0.0469 kW/s^2). This scenario affects fire growth and fuel load in a fire compartment and is addressed in the consequence modelling.

3.7.5. Challenging Fire

The worst-case fire is a fire that develops into a flashover and involves all combustible materials in a dwelling. The fire could be modelled as a fast-growth fire (NFPA 72 [34], 150 s) with a peak of 10 MW. The fire burns at 10 MW HRR until the end of the simulation.

3.7.6. Robustness Check

This scenario tests the robustness of the design by assuming that a key component of the fire safety system fails. The required outcome is that if a single fire safety system fails, the robustness of the building will prevent disproportionate spread of fire (e.g., by showing that ASET/RSET for the remaining fire compartments is satisfied).

3.8. PRA —ASET/RSET Analysis

To determine the associated risk, is necessary to calculate the expected consequences, expressed in casualties. The determination of the casualties is the result of an ASET/RSET analysis and is based on a computer simulation of the fire scenarios. To reduce the burden of the simulation work, the number of simulated scenarios can be reduced by making some assumptions:

- A smouldering fire yields no casualties as the fire is limited in size and generally its extinction is performed by occupants before the fire develops into flashover.
- When suppression systems work as expected, the fire is controlled, and there are no victims.
- When the egress protection system is working as expected, untenable conditions do not arise in the corridor, hence the ASET is infinite and there are no victims (all scenarios identified with an odd number).

The scenario where fire spreads is modelled with the following assumptions:

- The fire starts in the corridor/stairs; exit doors are not closed due to door blockade or due to failure of the self-closing mechanism. Smoke leakage through SOU doors.
- The fire starts in SOU; SOU doors remain open after the people have left the apartment (the self-closing mechanism is not working). Exit doors remain open due to door blockade or due to the failure of the self-closing mechanism.

With these assumptions, there are 8 scenarios for each fire location, resulting in a total of 16 scenarios for each design. The fire modelling simulations are performed using the B-Risk [35] fire modelling software as used in previous studies [27–29] and requires two different scenarios for each location, one with the fire spreading into common parts and the second with fire restricted to the area of fire origin. The application of FSVM implies that the selection of fire scenarios is based on the performance requirements that have been selected in the hazard identification phase (see Chapter 8 from the FSVM Handbook [21]).

The simulation output consists of a set of ASET values, each associated with a different scenario. The B-Risk software calculates in each time step the enclosure conditions in terms of five different tenability parameters: upper layer temperature below 200 °C, lower layer temperature below 60 °C, FED for asphyxiant gases below 0.3, FED for thermal effects below 0.3, and visibility above 10 m. The first value that triggers the above value determines the ASET, except for visibility, which is excluded in the room of fire origin and in the corridor. In these spaces, it is assumed that the occupants have familiarity with the exit route, so the visibility is not relevant. With stairs, visibility is an impeding factor as the occupants are assumed to be unfamiliar with the environment. B-Risk estimates the detection time by simulating the response time of smoke detectors or heat detectors. In one such simulation, detection time was computed as 187 s and 107 s for SOU and corridor compartments, respectively.

4. Analysis

4.1. Verification Method Incorporating T-H-O-Risk to Compare ERL and HOEs

The application of the methodology shows that the level of risk of the performance solution is lower than that of the DTS solution, as required by FSVM for the relevant fire scenarios. Table 5 presents the ERL results of the design scenarios for the DTS solution, the performance solution and the performance solution with HOEs.

Table 5. ERL results of design scenarios for Case #1 to #4 (DTS, Performance, HOE (human and organizational errors)).

Design	Case #1	Case #2	Case #3	Case #4
DTS	3.21×10^{-5}	4.02×10^{-5}	2.64×10^{-5}	3.98×10^{-5}
Performance	3.03×10^{-5}	3.91×10^{-5}	2.18×10^{-5}	2.98×10^{-5}
Performance HOE	4.36×10^{-5}	4.55×10^{-5}	3.14×10^{-5}	4.27×10^{-5}

Figure 7 shows the ERL of the various scenarios in which consequences occur. Results of the T-H-O-Risk analysis indicate that the influence of HOEs is significant for all cases. A fire initiating in a SOU (P33) has a significantly higher ERL, i.e., 7.8 times higher than the fire initiating in a concealed space (P1). P33 has the highest risk as the flaming fire occurs in the bedroom of the SOU where all safety systems fail. Moreover, when all the fire safety strategies including fire detection, alarm, sprinkler, and emergency doors fail, the probability of failure is increased substantially. However, if at least one of the fire safety systems is successful, the probability of failure is considerably reduced. Scenarios P2 & P3 and P34 & P35 indicate that a blocked exit results in a higher ERL than building alarm failure.

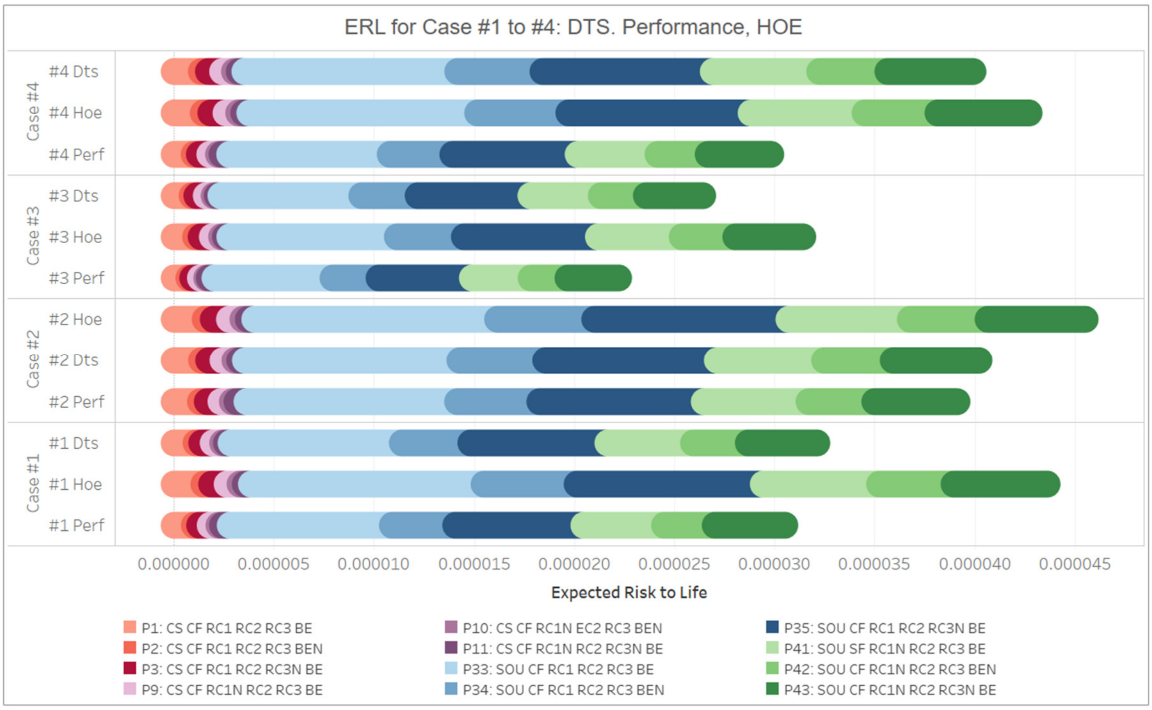


Figure 7. ERL for design scenarios for Case #1 to #4. Note: CS—Concealed Space, CF—Challenging Fire, RC1—Robustness Check Detection Failure, RC2—Robustness Check Sprinkler Failure, RC3—Robustness Check Building Alarm Failure, BE—Blocked Exit, SOU—Sole Occupancy Unit (not CS), BEN—Exit is NOT Blocked.

It is evident from the figure that there are severe consequences in all scenarios where a challenging fire occurs while sprinklers also fail. When the sprinkler system fails, the role of the emergency exit door becomes very important. On the contrary, when the sprinkler system is activated, the emergency doors will be less important, and no fatalities are anticipated, hence showing that the sprinklers are critical to helping occupants to evacuate safely. The alarm system is another important safety measure. As shown in Figure 7, the probability of failure is significantly increased if the alarm system fails. When the four case studies are compared with each other, the results in Figure 7 indicate that the ERL values in Case #3 for different scenarios that consider HOEs are the lowest while for Cases #1 and #4, the values fall into a similar range. Case #3 has a double-loaded straight corridor configuration with full-height window openings at either end which results in elongated ASET conditions. Case #2 has a higher ERL on account of the sole stairway for performance and HOE solutions and low tenability due to the small corridor area filling up with smoke rapidly. More results for the four cases indicating similar patterns are discussed later in Section 4.2.2.

4.2. Sensitivity and Uncertainty Analyses of HOE Variables and ERL

In this section, a sensitivity analysis is carried out for the main HOE variables to rank them from the most influencing to the least from a risk perspective. The most influencing variables are then associated with a probability distribution and quantification of uncertainties related to design variables are examined. T-H-O-Risk is used as a verification method to compare HOEs in the various design scenarios. This is followed by F-N curve assessment where uncertainties in SR due to HOEs are propagated as confidence-level-based SR followed by risk over time analysis in the SD model. Lastly, the T-H-O-Risk model is validated against the risk data obtained from the literature for high-rise building fires.

4.2.1. Sensitivity Analysis of HOE Variables and ERL

Different weights are used for different performance shaping factors (PSFs) in the analysis. The most influencing HOE variables are identified from the analysis. For each test case, ERL values and variations are estimated using the Monte Carlo approach. It is to be noted that the ERL values are necessarily point estimates, where the probabilities of events occurring do not take uncertainty into account. The uncertainty inherent in point estimates of HOEs can be considered by estimating a range or distribution in which the probabilities lie (various distributions are described in Appendix B, Table A5). Steijn et al. [36] have developed a method for the inclusion of uncertainty by adopting probability distributions in place of point values. This can be performed by transforming the point estimates into probability distributions. The number of parameters in the model is large, thus there is a need to focus on a narrow set of significant HOE variables. Consequently, a sensitivity analysis is conducted to determine the most influential HOE variables on the outcome. To analyze the uncertainty associated with the HOE variables, the beta distribution is assumed because this distribution allows for updating with new HOE data by combining prior with posterior probability; as the number of observations increase, the distribution will become narrower as there is less uncertainty in probability of errors [36]. Beta distributions are useful to express failure probability density functions (PDFs), described by the following equation:

$$f(x) = \frac{(x-p)^{(\alpha-1)}(q-x)^{(\beta-1)}}{B(\alpha,\beta)(q-p)^{(\alpha+\beta+1)}} \tag{2}$$

where α and β indicate the number of successes and failures, respectively. The conversion from point estimation to α and β values that are required to plot a beta distribution is possible using the three-point estimation method. These three points are the lowest realistic (min), the modal (mod), and the maximum (max); the normal value for each HOE is estimated by expert judgment. PSFs are then used to determine modal, the worst-case and the best-case probability of failure through multipliers that weigh the impact of each factor. The best-case estimation was based on a scenario with realistic HOEs while in the worst-case scenario, the HOEs were assumed to have deteriorated to a point that would still realistically allow an organization to remain functional. For simplicity, the nominal modal level for each HOE-variable is considered, as represented in Table 6:

Table 6. Performance shaping factors (PSFs) and range for associated multipliers.

PSF	Modal Level	Modal Multiplier	Best Case Multiplier	Worst Case Multiplier
Available time	Nominal	1	1	1
Stress and stressors	Nominal	1	1	2
Complexity	Nominal	1	1	1
Experience and training	Nominal	1	0.1	1
Procedures	Nominal	1	0.5	1
Ergonomics	Nominal	1	1	1
Fitness for duty	Nominal	1	1	1
Work processes	Nominal	1	0.8	2
Multipliers		1	0.04	4

Once the probability distribution of each HOE-variable is defined, the propagation of uncertainty is calculated. A beta distribution for each of the HOE variables in the BN is assumed, such as deficient maintenance as shown in Figure 8 where y-axis represents the probability and x-axis represents the ERL values. The beta distribution for the deficient maintenance variable uses the three points as follows: minimum value = 0.0032, modal value = 0.08, maximum value = 0.32. A similar analysis is performed for the other three cases. The results of the sensitivity analyses are summarized in the Tornado Plots presented in Figure 9.

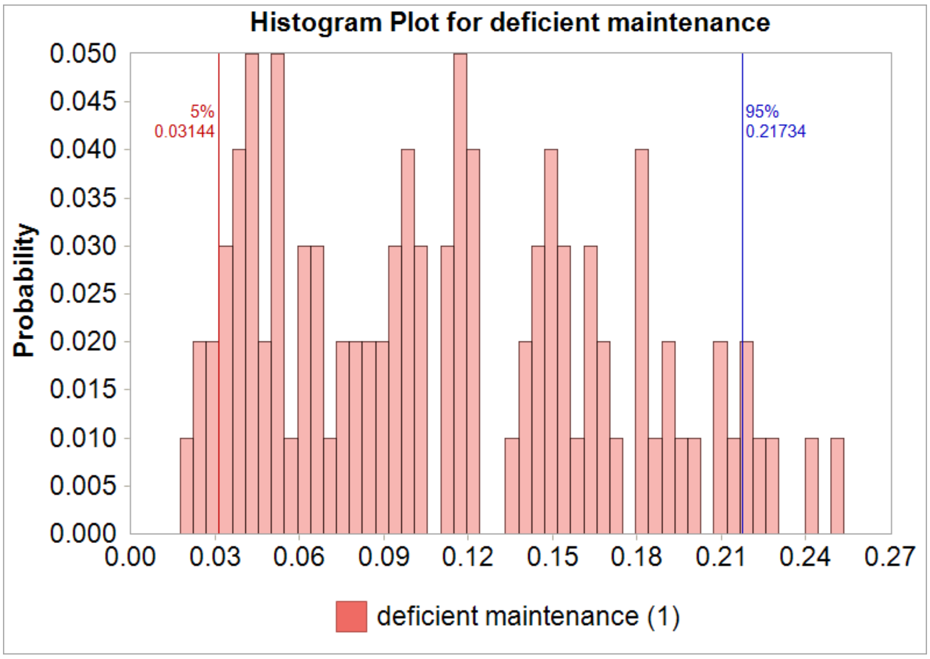


Figure 8. Sensitivity analysis (Probability distribution for input variable).

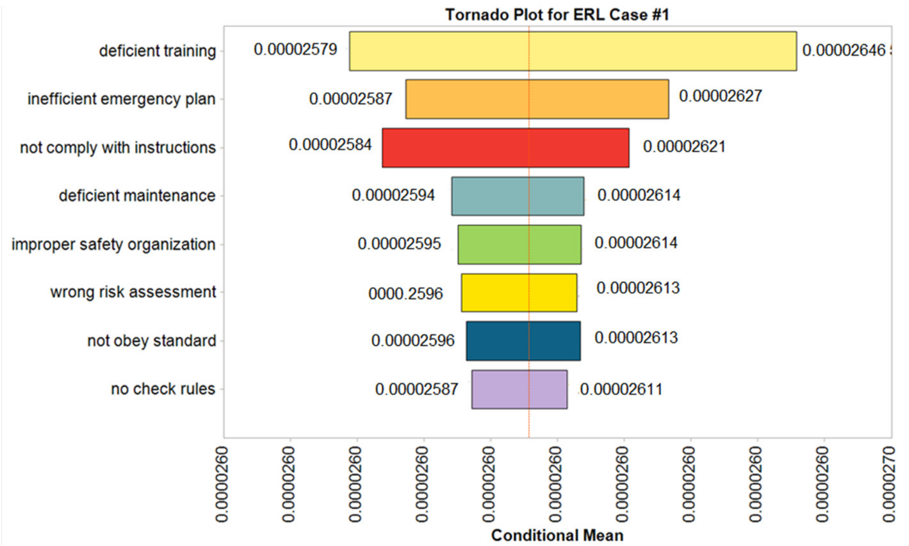


Figure 9. Sensitivity analysis of HOE variables -Tornado plots for case #1 to #4.

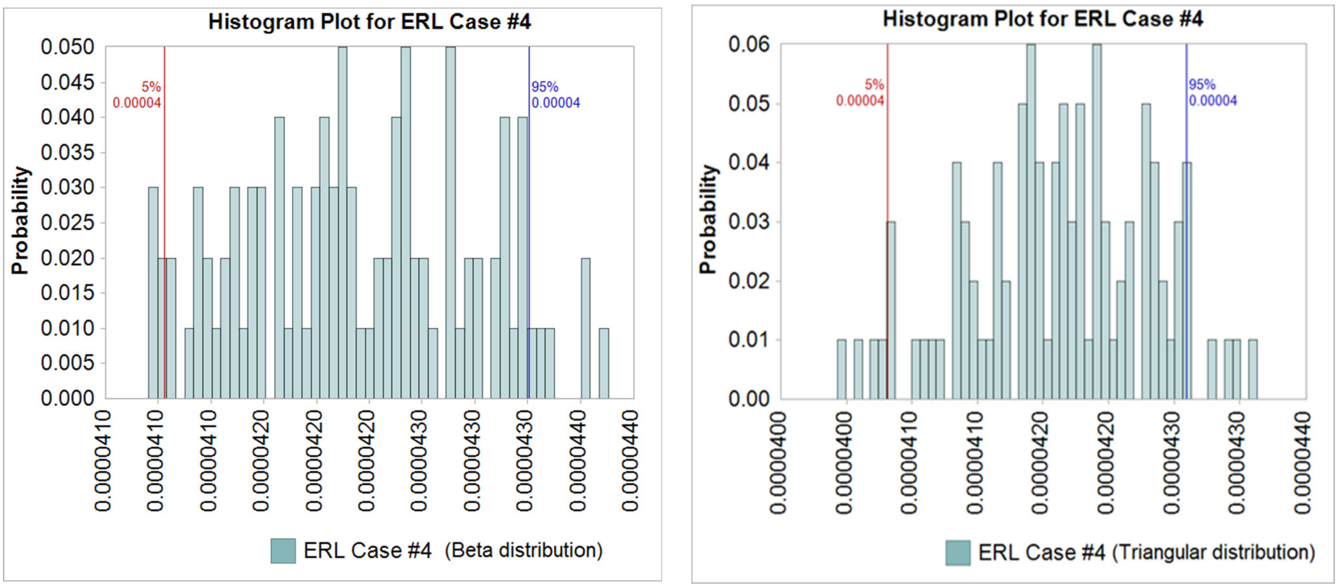
The results indicate that the most influencing HOE factors are 'not comply with instructions', 'deficient training', and 'inefficient emergency plan'. The mean value of the ERL is highest for Case #4 when considering the HOE 'not comply with the instruction'. The same trend is also observed for Case #4 for the other two critical HOE factors, 'deficient training' and 'inefficient emergency plan'. The main HOE variables impacting the final ERL are dependent on the design type. In those scenarios/designs where there are minimal active safety measures (DTS solutions), the impact of 'not comply with instruction' or 'inefficient emergency plan' are more significant. This is clearly because when no active fire safety measures are in place, the global safety of the building relies less on the activity of an operator that would periodically check on the safety systems than on the organisational efficiency required to determine the presence of ignition sources, combustible materials or working conditions of the fire doors. The other significant HOE factors considered in the analysis are 'no check rules', 'improper safety organization', 'wrong risk assessment', 'no check rules' and 'not obey standard'.

4.2.2. Uncertainty Analysis of HOE and ERL

The purpose of the uncertainty analysis of the ERL is to determine the HOE-related influence on risk variations in the model. While the sensitivity analysis previously conducted assesses the ranking of the contributions of the HOE inputs to the total ERL outcomes, an uncertainty analysis assesses the uncertainty in the model risk outputs that arise from the variations in HOE inputs. One of the procedural requirements in a PRA is the quantification of the uncertainties associated with the model variables. In particular, the probability values of human and organizational failures are affected by high levels of errors in estimations. There is limited literature data supporting their inclusion in a PRA, both in terms of absolute value and in terms of distribution through the probabilistic model. It is therefore of the utmost importance to estimate the distribution and range of those errors and their impact on the global level of risk.

The sensitivity results show that the most influencing HOE factors are 'not comply with instruction', 'deficient training' and 'inefficient emergency plan'. The three main variables determine important variations in the ERL of the system, up to 30% of the reference value. The minimum variations associated with the HOEs are in the order of 3–5%. The study indicates that HOEs have an important impact on the global risk level and cannot be neglected. Moreover, the more complex the system, the greater their influence. The complexity of the system is essentially due to the number of fire safety measures adopted, each of them subjected to varying maintenance regimes. The uncertainty analysis was performed based on the three most influencing HOEs identified in the sensitivity analysis in each case study. Using Case #4 as an example, when the most significant HOE factor of 'not comply with instruction' is simulated with 100 Monte Carlo simulations, the results are shown in Figure 10a where the y-axis represents probability values and x-axis represents the ERL values. It can be noted that the minimum probable ERL value with HOEs for Case #4 is 4.07×10^{-5} deaths/year while the maximum ERL value is 4.38×10^{-5} deaths/year. The mean value is 4.21×10^{-5} deaths/year and the standard deviation is 7.57×10^{-7}. The 5% and 95% confidence interval range for uncertainty is between 4.09×10^{-5} and 4.34×10^{-5}.

When limited information is available on the likely distributions of the key variables, the triangular distribution can be used to reflect the most likely, lowest, and highest outcomes. When using a triangular distribution for the variable 'not comply with the instruction', the 5% and 95% uncertainty ranges between 4.06×10^{-5} and 4.32×10^{-5} as shown in Figure 10b. This indicates that a beta or triangular distribution does not alter the uncertainty range significantly while the beta distribution produces a smoother curve.

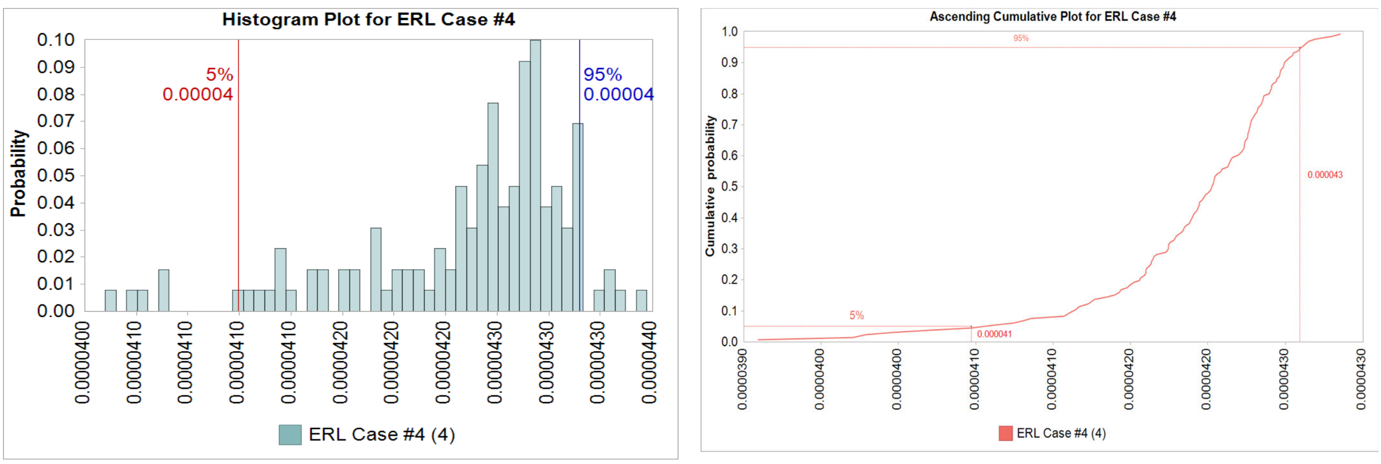


(**a**) (**b**)

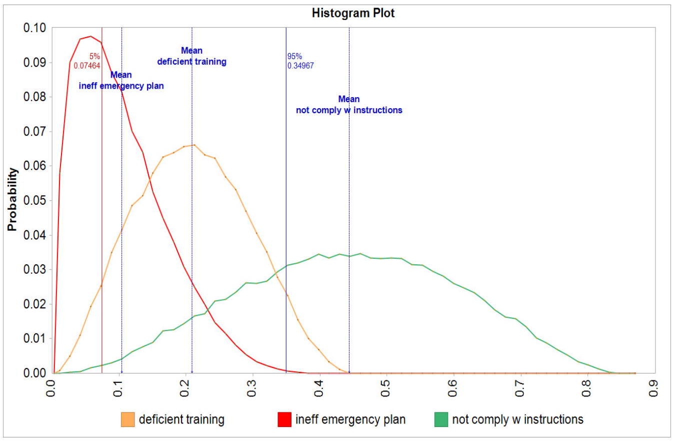
Figure 10. Case #4: Uncertainty analysis for 'not complying with instructions'. (**a**) ERL uncertainty analysis for Case #4 with beta distribution. (**b**) ERL uncertainty analysis for Case #4 with triangular distribution.

When considering the three main HOE variables and assuming a beta probability distribution, the result is shown in Figure 11a. The y-axis represents the probability and x-axis represents the ERL values. It can be noted that the outcomes of the simulations are concentrated on the right side of the histogram. The standard deviation is small at 5.40×10^{-7} with 5% and 95% uncertainty ranges from 4.15×10^{-5} to 4.30×10^{-5}. The cumulative probability distribution of the single-run curve (S-curve) for Case #4 is presented in Figure 11b where the mean ERL is 4.25×10^{-5}.

Figure 11c shows the probability density plot and Figure 11d shows the cumulative probability distribution of the three HOE input variables that have a major impact on the final ERL for Case #4. The cumulative probability plot in Figure 11d indicates that the distribution of the probability for 'not comply with the instruction' is centred on higher values than the other two HOE variables; its mean is 0.46 compared to 0.25 for 'deficient training' and 0.11 for 'inefficient emergency plan'. Moreover, it is evident that the HOE variable 'not comply with the instruction' has larger variations than the other two because the difference between the 95% and the 5%-percentiles is 0.49 in absolute terms (and 1.07 relative to the mean). (Refer to Appendix C for detailed calculations.)



(**a**) (**b**)



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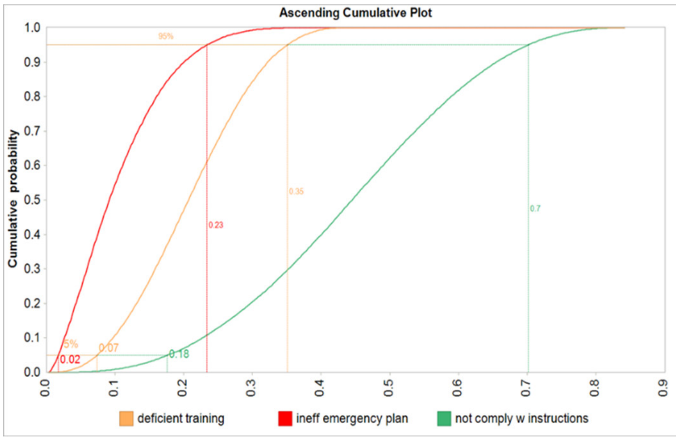

(**d**)

Figure 11. (**a**) Uncertainty analysis of 3 main HOE variables -Case #4. (**b**) Single Cumulative probability plot of ERL Case #4 HOE. (**c**) Probability plots of significant HOEs for Case #4 (**d**) Cumulative distribution plots for significant HOEs –Case #4.

To evaluate the uncertainty of the model due to the three variables, these values can be compared with the output of the model from the Monte Carlo simulation. In Figure 11d, the graph indicates that the difference between the 95% and the 5% value is 2.9×10^{-7}. (Refer to Appendix C for detailed calculations). As expected, the HOE variable 'not comply with instructions' has the greatest influence on the outcome with a sensitivity of 5% followed by 'deficient training at 4% and 'inefficient emergency plan' at 3%.

The Monte Carlo simulation runs for the ERL uncertainties for Case #1 to #4—DTS, performance and HOE solutions are plotted in the cumulative probability plots in Figure 12. It is observed that ERL for the performance solution with HOEs is higher as compared to the performance solution and DTS-based ERL values. Further, the performance solution (without HOEs) gives lower ERL as compared to the DTS solution. The results for different cases are summarized below:

- For Case#1 ERL values for the performance solution with HOEs for 5% and 95% bounds are 4.21×10^{-5} and 4.58×10^{-5}, respectively. ERL values for the DTS solution for 5% and 95% bounds are 3.10×10^{-5} and 3.37×10^{-5}, respectively. Similarly, ERL values for the performance solution for 5% and 95% bounds are 2.94×10^{-5} and 3.18×10^{-5}, respectively. From the average value, the ERL for the performance solution with HOEs is higher by 35% compared to the DTS solution and by about 44% as compared to performance solution.
- For Case#2 ERL values for the performance solution with HOEs for 5% and 95% bounds are 4.40×10^{-5} and 4.63×10^{-5}, respectively. ERL values for the DTS solution for 5% and 95% bounds are 3.91×10^{-5} and 4.10×10^{-5}, respectively. Similarly, ERL values for the performance solution for 5% and 95% bounds are 3.78×10^{-5} and 3.97×10^{-5}, respectively. From the average value, the ERL for the performance solution with HOEs is higher by 13% as compared to the DTS solution and by about 16% as compared to performance solution.
- For Case#3 ERL values for the performance solution with HOEs for 5% and 95% bounds are 3.01×10^{-5} and 3.15×10^{-5}, respectively. ERL values for the DTS solution for 5% and 95% bounds are 2.58×10^{-5} and 2.72×10^{-5}, respectively. Similarly, ERL values for the performance solution for 5% and 95% bounds are 2.10×10^{-5} and 2.22×10^{-5}, respectively. From the average value, the ERL for the performance solution with HOEs is higher by 16% as compared to the DTS solution and by about 41% as compared to performance solution.
- For Case#4 ERL values for the performance solution with HOEs for 5% and 95% bounds are 4.15×10^{-5} and 4.30×10^{-5}, respectively. ERL values for the DTS solution

for 5% and 95% bounds are 3.83×10^{-5} and 4.02×10^{-5}, respectively. Similarly, ERL values for the performance solution for 5% and 95% bounds are 2.92×10^{-5} and 3.03×10^{-5}, respectively. From the average value, the ERL for the performance solution with HOEs is higher by 7% as compared to the DTS solution and by about 42% as compared to the performance solution.

The results also indicate that uncertainties associated with the ERL point estimates are small. At the same time, the low standard deviations as shown in Table 7 signifies that the data points are closely distributed around the mean values.

Figures 13–15 show the ERL cumulative distribution plots for the DTS, performance and performance solution with HOEs to facilitate a direct comparison of the ERL for the case studies. The ERL uncertainty values are summarized in Table 7. Here again, ERL values are compared for DTS and performance solutions along with HOEs for four cases. The ERL is highest for the performance solution with HOEs followed by the DTS solution and then the performance solution. The ERL value is highest for Case #4 which has the largest floor area.

Table 7. Uncertainty analysis of ERL for Case #1 to #4.

Design	Sampling	Case #1	Case #2	Case #3	Case #4
DTS	Mean	3.25×10^{-5}	4.02×10^{-5}	2.66×10^{-5}	3.97×10^{-5}
	5%CI	3.10×10^{-5}	3.91×10^{-5}	2.58×10^{-5}	3.83×10^{-5}
	95%CI	3.37×10^{-5}	4.11×10^{-5}	2.72×10^{-5}	4.02×10^{-5}
	Standard deviation	7.66×10^{-7}	5.87×10^{-7}	4.37×10^{-7}	5.43×10^{-7}
Performance	Mean	3.05×10^{-5}	3.89×10^{-5}	2.17×10^{-5}	2.98×10^{-5}
	5%CI	2.94×10^{-5}	3.78×10^{-5}	2.10×10^{-5}	2.92×10^{-5}
	95%CI	3.18×10^{-5}	3.97×10^{-5}	2.22×10^{-5}	3.03×10^{-5}
	Standard deviation	7.78×10^{-7}	5.27×10^{-7}	3.56×10^{-7}	3.79×10^{-7}
HOE	Mean	4.39×10^{-5}	4.56×10^{-5}	3.09×10^{-5}	4.25×10^{-5}
	5%CI	4.21×10^{-5}	4.40×10^{-5}	3.01×10^{-5}	4.15×10^{-5}
	95%CI	4.58×10^{-5}	4.63×10^{-5}	3.15×10^{-5}	4.30×10^{-5}
	Standard deviation	1.14×10^{-6}	6.90×10^{-7}	4.18×10^{-7}	5.40×10^{-7}

Detailed results are summarized below:

- For the DTS solution, the ERL value is highest for Case #2 followed by Case #4, #1 and #3 in descending order.
- For the performance solutions, the ERL value is highest for Case #2 followed by Case #1, #4 and #3 in descending order.
- When HOEs are considered, the ERL value is highest for Case #2 followed by Case #1, #4 and #3 in descending order.
- The average across different cases shows that the performance solution gives the lowest ERL with an average value of 3.02×10^{-5} whereas for DTS solution it is 3.48×10^{-5}.

When HOEs are considered in the analysis, the ERL increases to 4.07×10^{-5}, considering it is average value across different cases. Thus, across different cases, HOEs can increase the ERL value by as much as 42% compared to the performance solution. Further, the performance solution gives a lower value of ERL by much as 33% as compared to DTS solution.

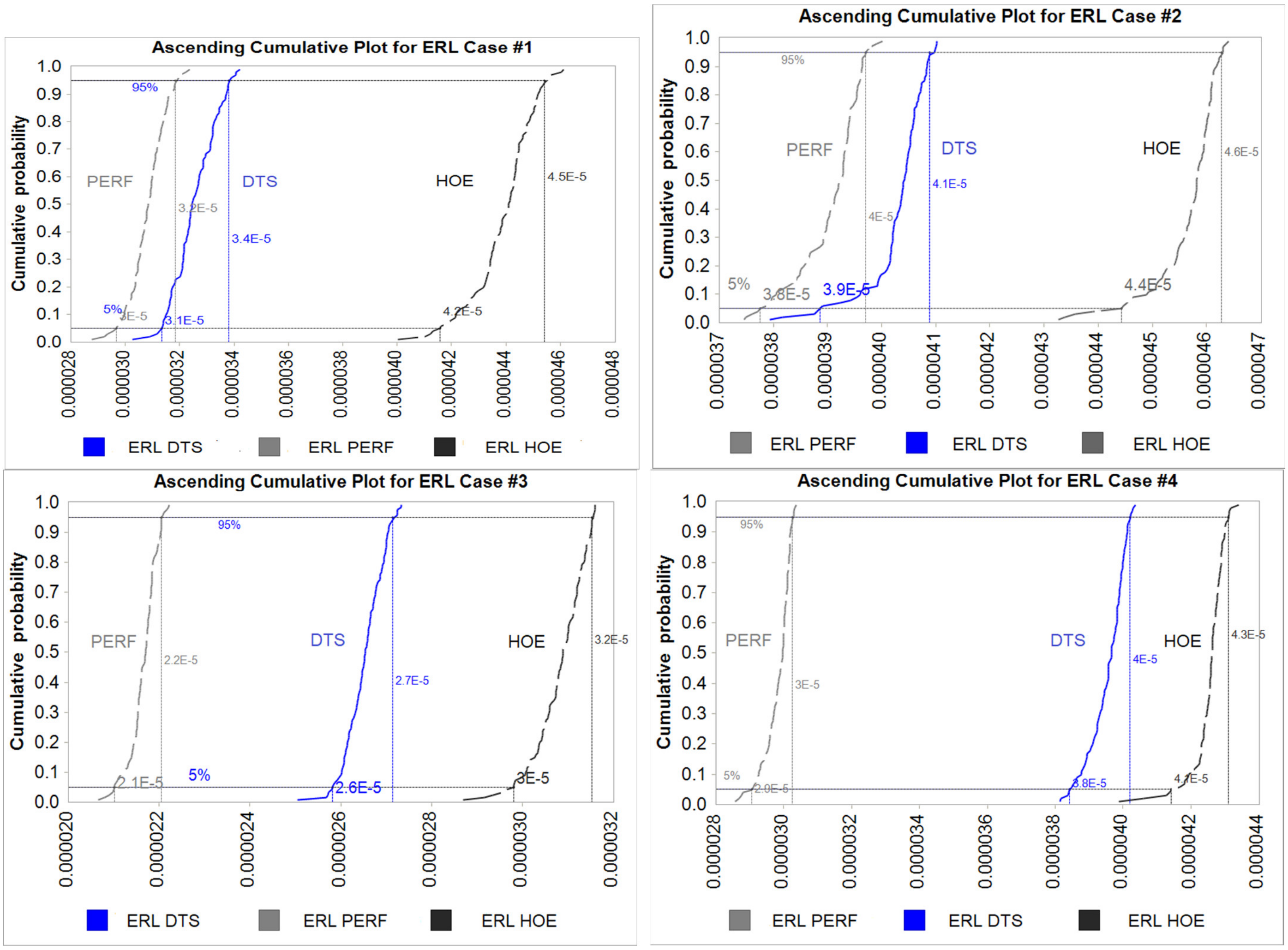

Figure 12. Cumulative Probability Distribution for Case #1 to #4—DTS, Performance & Performance with HOE.

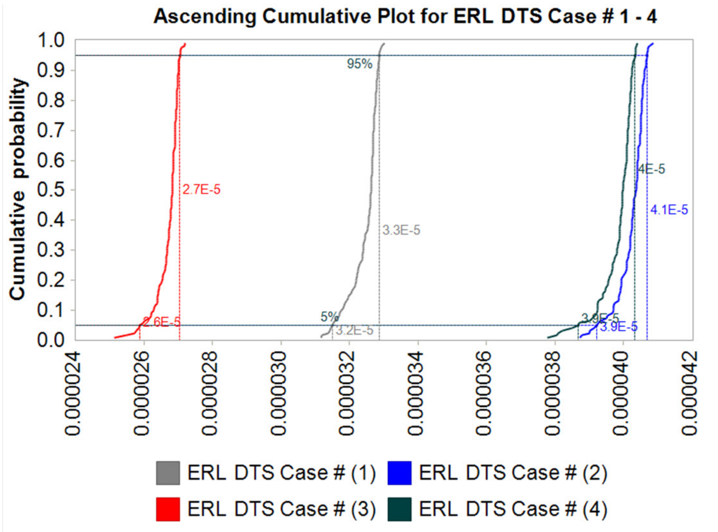

Figure 13. ERL Cumulative distribution plots—DTS Case #1 to #4.

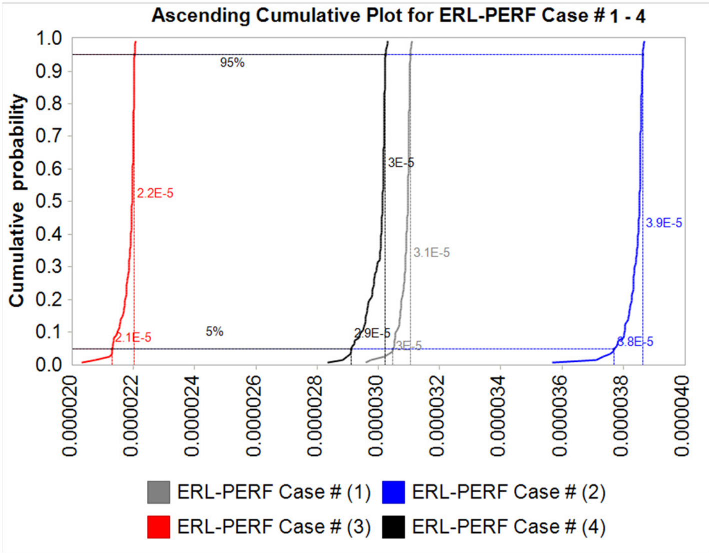

Figure 14. ERL Cumulative distribution plots—Performance solutions Case #1 to #4.

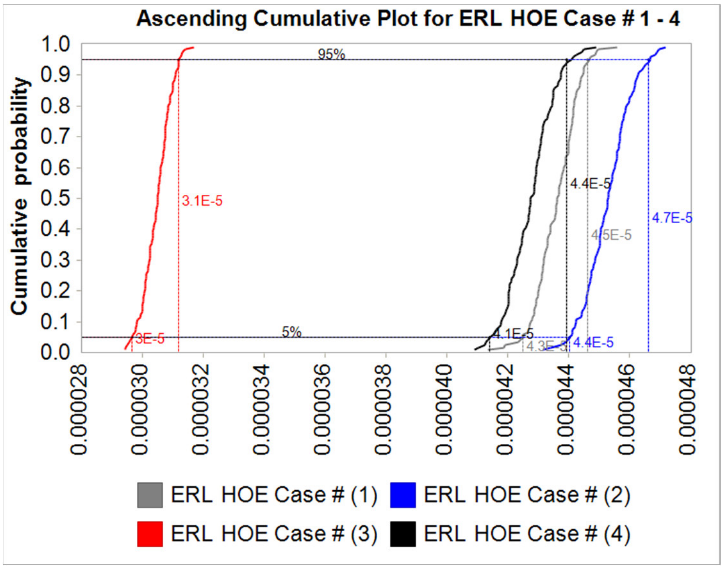

Figure 15. ERL Cumulative distribution plots—HOE Case #1 to #4.

4.3. Societal Risk Assessment and Uncertainty Analysis

To assess the risk tolerability of various design solutions, F-N curves are constructed to enable comparison of SR for each case study. Figure 16 shows the F-N curves with and without HOEs for Case #1 to #4. ABCB tolerability curves are represented graphically by red dotted and blue dot-dash diagonal lines and are similar to British Standards Institution Published Documents (BSI) PD–7974–7:2019 [37] tolerability limits which are represented by red and yellow diagonal lines. However, the rate of change in allowable frequency is much faster (steeper slope) than BSI. The ABCB slope of −1.5 indicates a higher risk aversion than BSI's neutral risk aversion slope of -1 [37]. The area between the tolerability curves defines the region where a design is considered to be safe, or as low as reasonably practicable (ALARP). The upper and lower bound uncertainties in SR are presented as 95% and 5% Confidence Intervals are represented by black dash-dot and grey dash-dot lines, respectively. The uncertainty analysis generates an area plot for a certain level of confidence in the F-N curve with upper (95%) and lower (5%) bounds of Societal Risk instead of only one mean F-N curve. The methodology to generate these uncertainty bounds is based on Sun et al. [38] described in Appendix D.

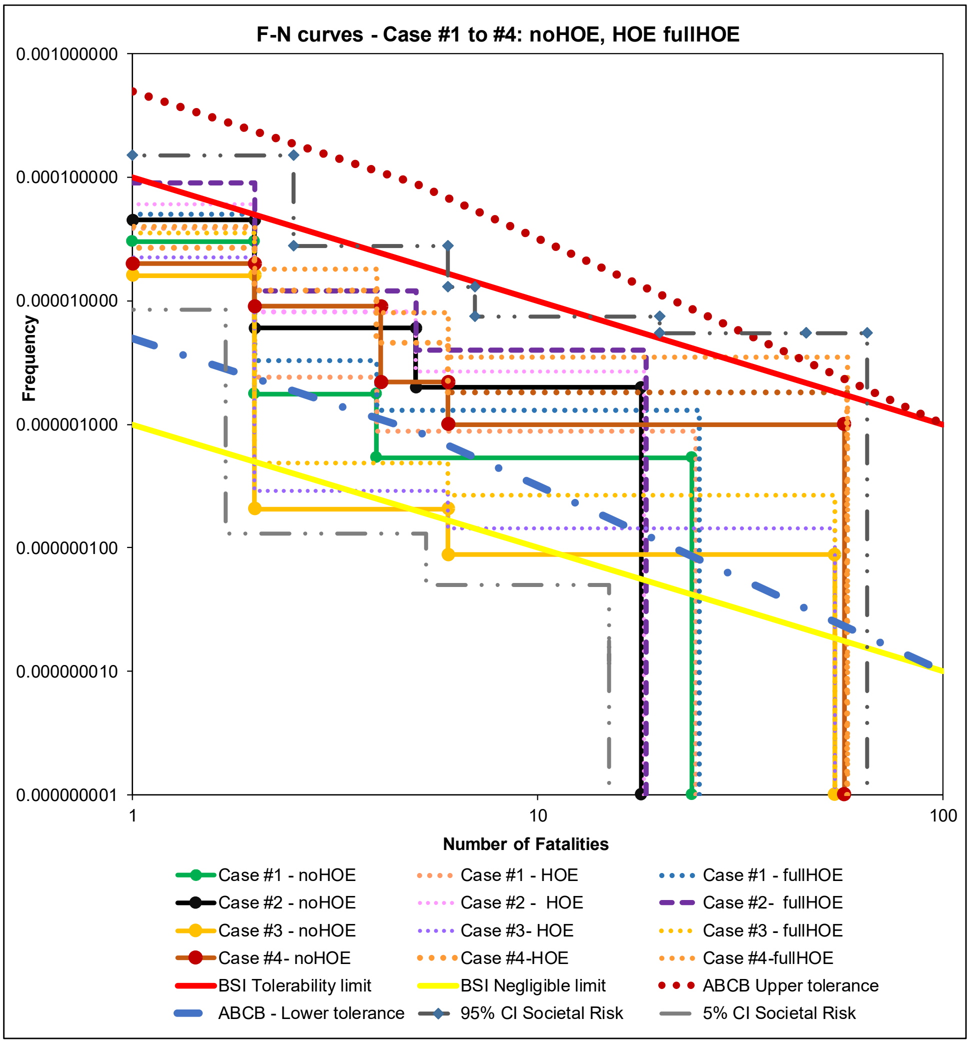

Figure 16. F-N curves for Case #1 to #4—Performance, HOE.

The inclusion of HOEs in the analysis results in variations to SR values as shown in the F-N plots in Figure 17 for Case #1 to #4. The following observations can be made from Figure 16. For all cases where HOEs are considered, SRs are higher than the corresponding case with no HOEs. All cases are below the upper tolerability bounds indicating acceptable SRs, however, when HOEs are considered, Case #2 marginally exceeds BSI tolerance but meets ABCB acceptable limits. Case #4 exceeds both BSI and ABCB tolerability limits. When confidence-interval uncertainty bounds are considered, Case #2 marginally meets ABCB upper tolerability limits while Case #4 clearly exceeds the tolerability limits. To lower the curve such that it falls in the ALARP region, either additional fire safety measures can be installed, or systems reliability can be improved. Among the four cases, Case #4 results in maximum SR. This is followed by Case #2, Case #1 and Case #3 in decreasing order. For case #3 and #4, the F-N curves are shifted to the right resulting in higher consequences even though frequencies are within similar range as the other two cases. The CI-95% uncertainty bounds indicate that Case #2 & #4 exceed the BSI upper tolerance limit but only Case #4 exceeds the ABCB upper tolerance limit. Thus, when uncertainty ranges are considered, tolerability thresholds can be exceeded in some cases (Case #2 & #4) when mean values do not.

4.4. System Dynamics Risk Modelling, Sensitivity and Uncertainty Analysis

The assessment of risk in the SD model allows for an integrated analysis of HOE factors and their nonlinear interactions and feedback loops. The SD model also accounts for the delays and more realistic analysis of risk variation over time. When maintenance of a safety system is not performed for prolonged periods, risk will trend upwards over time and there can be a duration in which risk exceeds a critical or safe value. The SD model identifies the point in which the maintenance regime of safety systems needs to be conducted. System dynamics describe the level of uncertainty of diverse situations. This technique is specifically useful when variables are interlinked, and data is indistinct. In this model, some variables vary with time and simultaneously interact with other variables. Thus, the state of a variable is both time dependent and state dependent with respect to other variables. The time slice in a SD model is a snapshot of the BN at different instances of time (Figure 17).

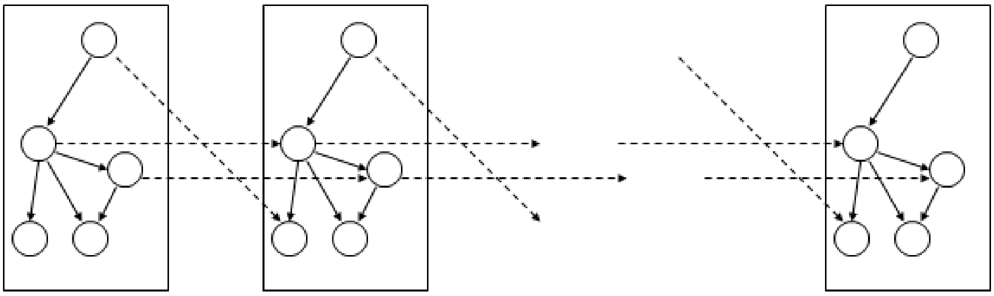

Figure 17. SD model at three different time instances showing variable dependencies.

The conditional probability table (CPT) is the transition matrix that represents the time slice and provides insights into the transformation of the different nodes across the model and describe the causal relationships within the nodes. The mathematical model describing the state and time dependency is given by:

$$P(X,Y) = \prod_{t=0}^{T} P(x_t|x_{t-1}) \prod_{t=0}^{T} P(y_t|x_t)P(x_0) \quad (3)$$

where:

X, x_t, x_{t-1} are state variables;;y, y_t, y_{t-1} are observable variables;
$P(x_t|x_{t-1})$ gives time dependencies between states;
$P(y_t|x_t)$ gives state dependencies between the variables;
$P(x_0)$ is initial state distribution.

In the SD model, the flow variables are time-varying terms. For example, the rate of change (RoC) of the number of checks (NoC)) for perceived safety (ps) is given by:

$$RoC(t) = 5\,\frac{d}{dt}(ps) \quad (4)$$

On the other hand, stock variables, refer to the integrated value of the flow variables. Thus, a stock variable refers to the accumulated value of the flow variable in a given time frame. For the above example, a stock variable NoC is given by:

$$NoC = 12 + \int RoC\,(t)dt \quad (5)$$

In the present analysis, random perturbations on input parameters are performed and risk is computed at each of the time instants. The nodes of the SD are mapped from the corresponding nodes in the BN model. The mapped SD model is represented in Figure

A5 in Appendix A. A sample schematic showing reliability change due to time and state change is shown in Figure 18. The SD model, thus, brings out the effects of deficient training and inefficient emergency plan from the analysis.

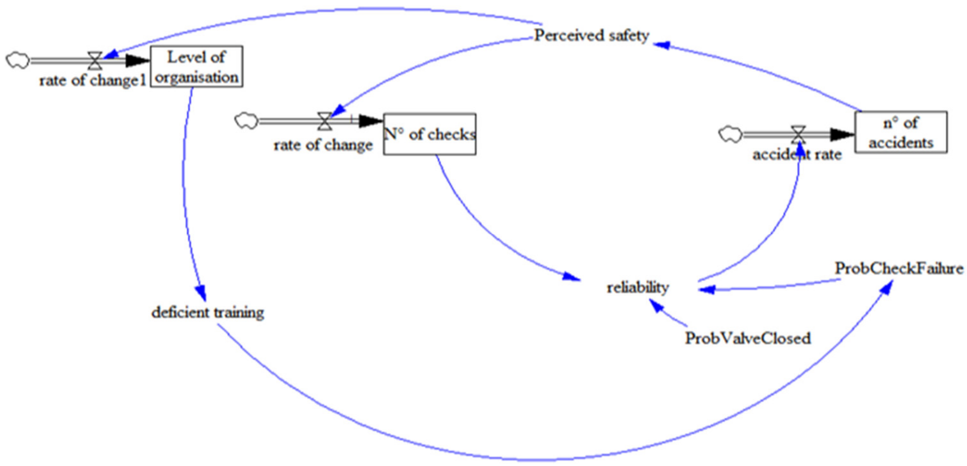

Figure 18. Sample schematic showing time and state affecting reliability.

The results from the SD simulation are reported in Figure 19 which compare the DTS to the performance solutions for each design scenario for Case #1 (ABCB).

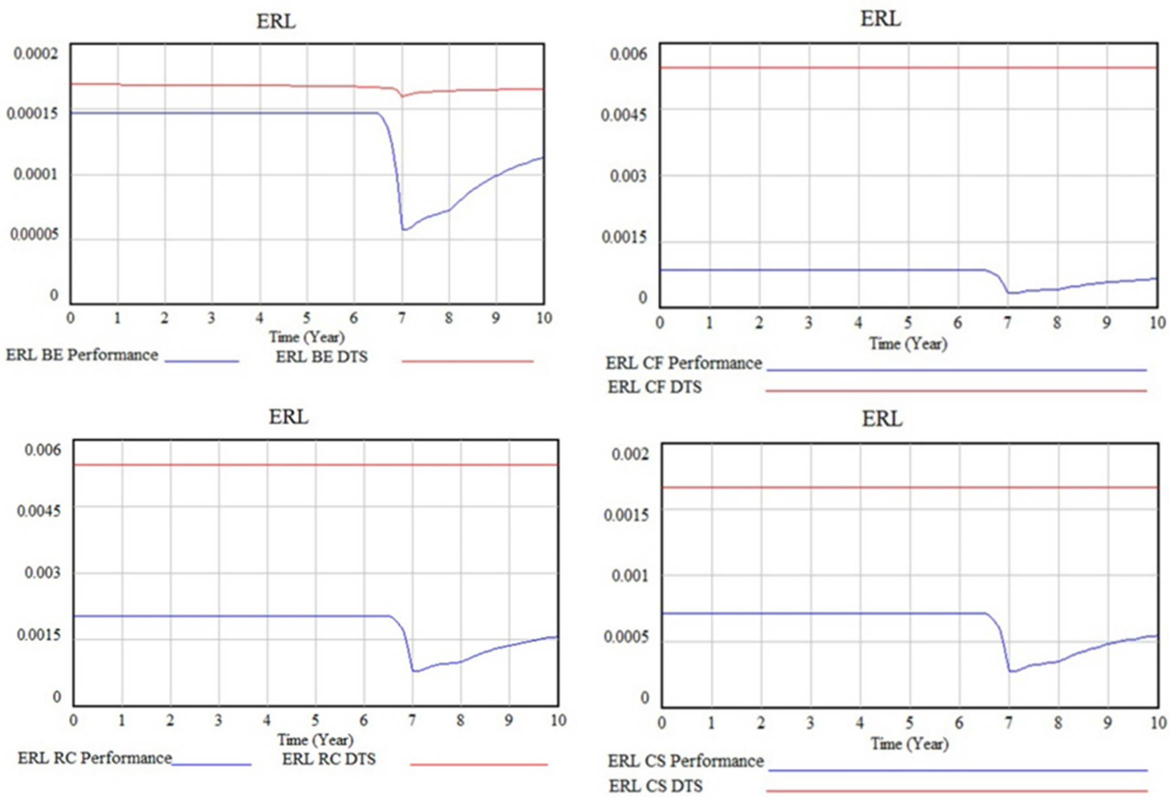

Figure 19. SD result- DTS vs. Performance solution. Risk profile over 10-year period (Case #1).

During the 10-year life span considered, the performance solution shows a lower level of risk than the DTS solution. It can also be noted that there is no variation in risk for the DTS solution over 10 years; this is because the DTS solution has no active fire protection measures (detection or suppression system), hence no HOEs can significantly alter the level of risk. However, outside the active protection system, it is always possible that HOEs reduce the reliability of passive protection systems (for example, obstructions of the exits and refurbishment activities) but they are not modelled in the T-H-O-Risk model. In the risk-over-time curve related to the performance solutions, the level of risk reduces after a seven year-long period of stability, because the building maintenance team has developed a thorough knowledge of the reliability of safety systems. At the same time, the perception of risk is reduced because little or no accidents have occurred during the initial lull period and a lax attitude towards maintenance procedures takes over. Consequently, the operator reliability falls and reduces the effectiveness of the sprinkler system. When the building management realises that the level of organization is not as effective as planned, countermeasures are activated, which in turn improves risk indicators although uncertainty is highest around year seven. Risk again increases with time in the final years of the 10-year period due to the relaxation of measures, as expected.

All the curves exhibit similar behaviour, experiencing a reduction in risk level after seven years and a subsequent increase due to relaxation of the rules (Figure 20). It can be noted that the different curves shift vertically according to the various global risk value as shown in Figure 21.

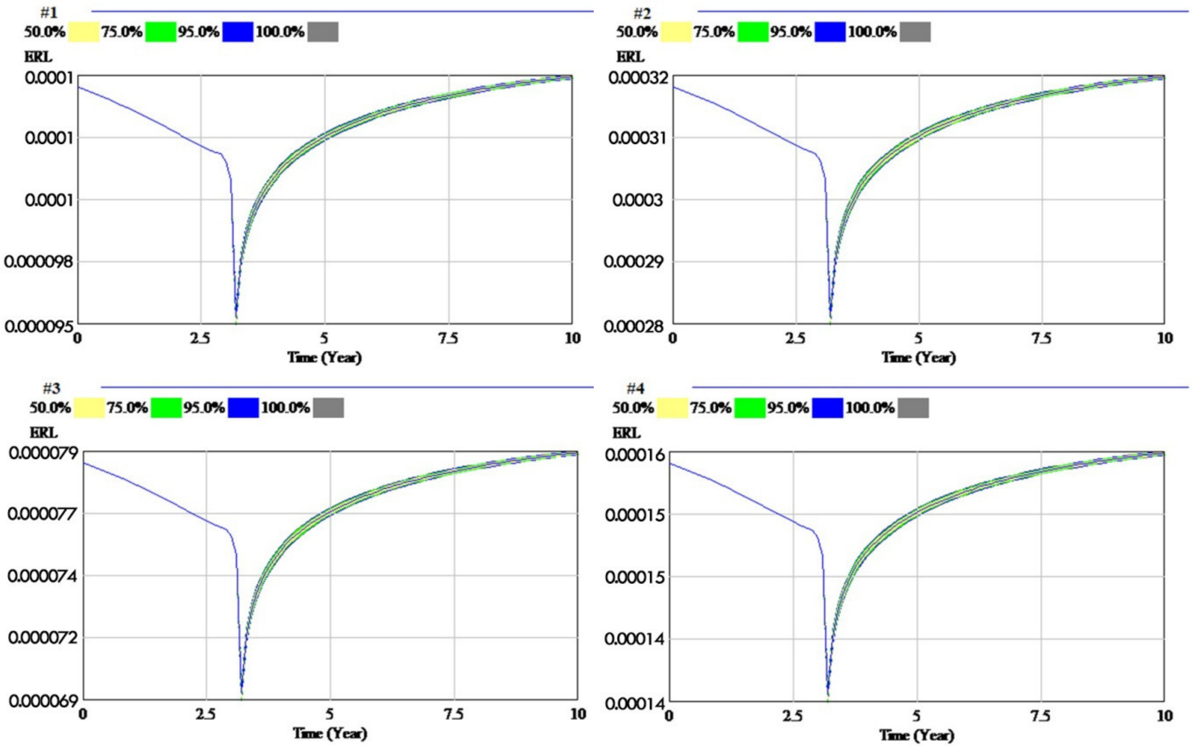

Figure 20. SD sensitivity trace range under multivariate uncertainty—ERL over 10 years for Case #1 to #4.

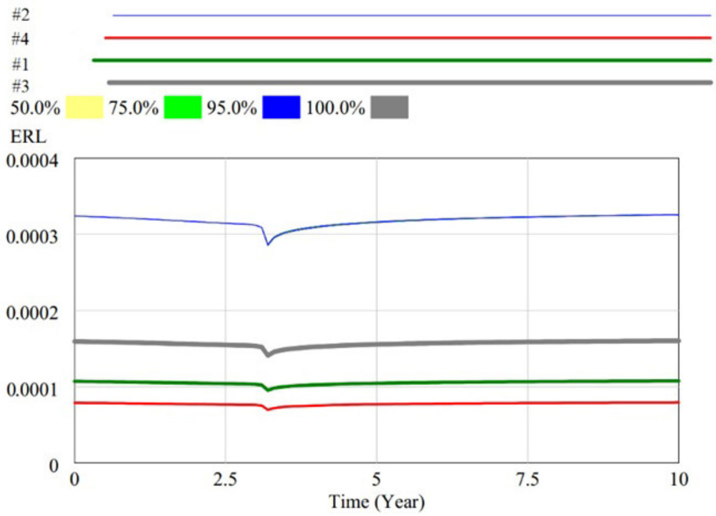

Figure 21. SD sensitivity trace range under multivariate uncertainty—global risk over 10-year period for Case #1 to #4.

It is observed that the sensitivity of the curves to the HOE parameter results in no variations in the scale of the dynamic curve, so the rankings of the four designs are not affected by that parameter.

Sensitivity analysis was further conducted on key variables in the SD model to assess model robustness and to explore how uncertainty influences the analysis of different safety systems and reliability of model outputs. The first step is an investigation of the parameters with the most influence on the HOE variables (target). Most of the model parameters have little influence on the outcome, so that they do not produce noticeable variations in the target variable. The impact of a parameter can be assessed in relationship to every target variable; only if the sensitivity is above a determined value (25%) would the parameter need further analysis. For each HOE variable there are parent nodes that have low influence, such as 'Probability of valve closed', which has a sensitivity of 0.1% related to the target value 'adopt unsuitable equipment'. There is negligible impact of an open valve on the final result, as it provides very small variations.

After identifying the sensitive parameters for the HOE variables, a Monte Carlo simulation (1000 runs) was performed (see Appendix E for description of procedures on SD sensitivity analysis). The Vensim tool for Monte Carlo simulation provides the 50th, 75th, 95th and 100th percentile confidence interval bounds of the simulations and according to [39], these intervals can be approximated as the corresponding confidence bounds for uncertainty. The fire ignition probability variable is associated with a uniform probability distribution, with upper and lower values 0.4 and 0.3 for apartment fire (0.384-point value) and 0.02 and 0.01 for corridor fire (0.0198-point value). This distribution was chosen to characterize uncertainty in non-calibrated uncertain parameters varied in the Monte Carlo simulations. Figure 22 represents the variation of the 'fire yes detection yes node' (FYDY node) with fire ignition frequency. The FYDY node expresses the frequency of fire ignition and subsequent fire detection. As expected, the relationship between the two variables is linear and the SD curve is shifted upward when fire ignition probability increases and downward when fire ignition decreases. Moreover, this relationship remains constant with time.

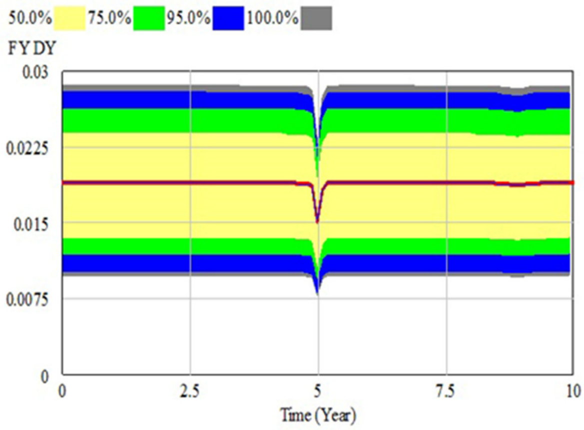

Figure 22. SD sensitivity trace range of fire ignition probability variable.

Another important variable, 'reliability', is not affected by the fire ignition frequency (see Figure 23). Given the fact that after a fire event all safety systems are properly checked, it can be safely assumed that their efficacy is not determined by the number of previous activations. The same observations can be made for the loop variable 'accident rate' as shown in Figure 24. In Figure 25, the ERL varies linearly with the fire ignition frequency. Sensitivity is not affected here by dynamic behaviours.

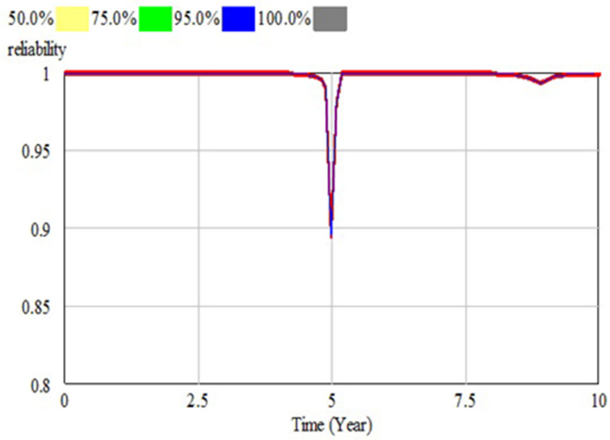

Figure 23. SD sensitivity trace range of 'reliability' variable.

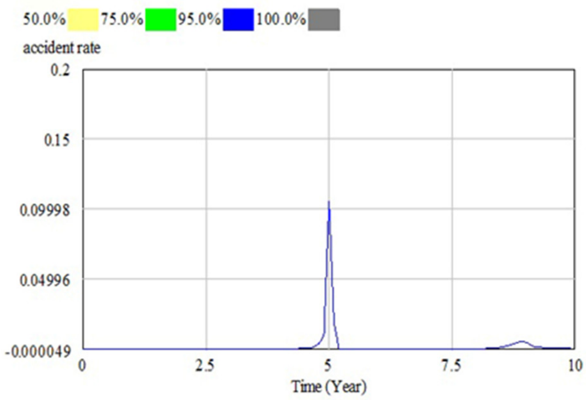

Figure 24. SD sensitivity trace range of 'accident rate' variable.

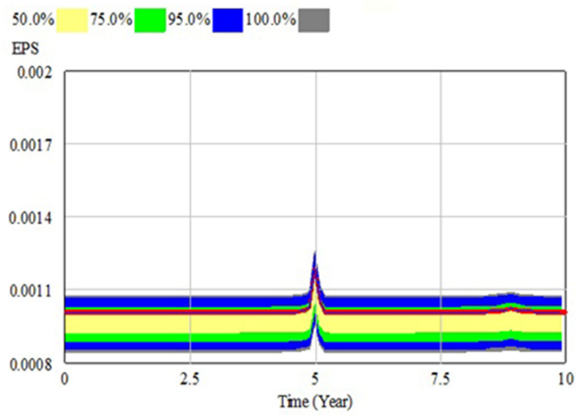

Figure 25. SD sensitivity trace range of ERL variable.

To determine sensitivity of the model to HOE variables, the parameter 'Probability of valve left closed' was analysed. A triangular probability is associated with the variable, with values comprised from 0.01 to 0.015 (min = 0, max = 0.5, start = 0.01, peak = 0.01, stop = 0.015). The resulting curve for the reliability parameter is shown in Figure 26. It can be argued that the reference curve (in red) is smoothened by variations in the HOE variable. The fall in reliability is always below the static values at year five for the 'Probability of left valve closed' ranging from 0.01 to 0.015.

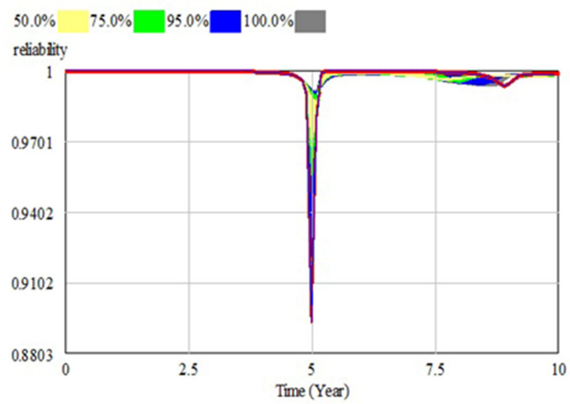

Figure 26. SD sensitivity trace range of 'reliability' variable.

Similar observations can be made from the 'detection' node as shown in Figure 27. From the results it can be observed that the impact of the fire ignition frequency is greater than all other variables and the correlation is not linear as different variations occur at different time steps.

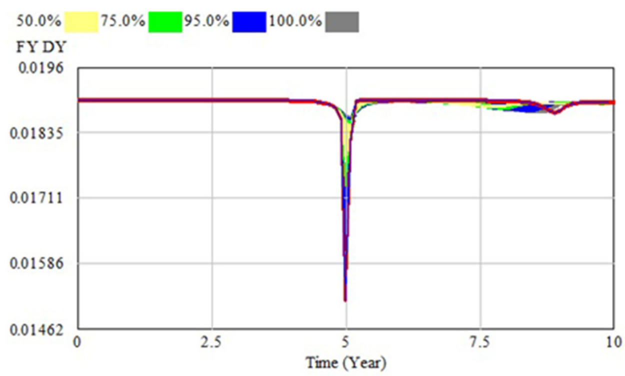

Figure 27. SD sensitivity trace range of 'detection' variable.

4.5. Assessment of Robustness of SD Model Outputs

The outputs of the SD model are tested for robustness by screening the variables to identify and select the most sensitive parameters for each target variable in the model. Monte Carlo simulations were performed (one for each target variable) to establish the confidence intervals (CI) for outputs responding to sensitive variables. The variation coefficient $VC_{i,t}$ of the target variables was calculated for ten years based on the following equation:

$$VC_{i,t} = (\frac{OM95_{i,t} - Om95_{i,t}}{O_i^m}) \times 100 \quad (6)$$

where $VC_{i,t}$ is relative variation of target variable *I* with respect to the mean using 95% CI; $OM95_{i,t}$ and $Om95_{i,t}$ are max. & min. values of the *ith* target variable at time *t*, using the 95% CI; and O_i^m is mean value of target variable *i*. There are 3 categories of response: low where *VCi* is less than 50%, moderate where variation coefficient is between 50–100% and high where variation coefficient is higher than 100%

First, for each of the three responsive parameters (i.e., perception, number of accident and probability valve closed) a univariate analysis is performed to assess the sensitivity of the following target variables: deficient training, inefficient emergency plan, not comply with instruction, no check rules, deficient maintenance, wrong risk assessment, not obey standard and improper safety organization. A uniform distribution was applied. In this way, it is possible to characterize which variables are more sensitive to organizational response.

The analysis shows that the influence of the parameter 'Perception' is high for 'Inefficient timely control' and 'Not comply with instructions' target variables, with values above the 100% sensitivity. 'Improper safety organisation', 'Inefficient emergency plan', 'No check rules' and 'Not obey standards' presents a sensitivity between 50% and 100%, Finally, 'adopt unsuitable equipment' is insensitive to the variation of the 'Perception' parameter, with a sensitivity value of about 1%. The 'Max number of accidents' parameter has little influence on the HOE variables, with values in the range between 0.1% and 23%. Finally, the variable 'Probability Valve Closed' has the lowest impact, in the range from 0.1 to 11. In general, it can be observed that the variable 'Perception' is by far the most impacting factor and the target variables of 'Inefficient timely control' and 'Not comply with instruction' are much more sensitive to variation of the reference parameters than the other variables.

A multivariate analysis is used to assess the robustness of the model and to define the ranges of variations of the target variable. Results are reported in Table 8 and sensitivity of some variables are shown in Figure 28. See Appendix F Table A6 for list of parameters:

Table 8. Results of Monte Carlo Sensitivity analysis of responsive parameters.

Target Model Variables	Responsive Parameters	Sensitivity Results 95% Confidence Interval
Adopt unsuitable equipment:	Perception, Max number of accidents, Probability Valve Closed	0.92 ± 0.004 (dimensionless)
Improper safety organisation	Perception, Max number of accidents, Probability Valve Closed	1.29 ± 0.233 (dimensionless)
Inefficient timely control	Perception, Max number of accidents, Probability Valve Closed	0.25 ± 0.212 (dimensionless)
Inefficient emergency plan	Perception, Max number of accidents, Probability Valve Closed	1.24 ± 0.226 (dimensionless)

No check rules	Perception, Max number of accidents, Probability Valve Closed	0.29 ± 0.211 (dimensionless)
Not comply with instructions	Perception, Max number of accidents, Probability Valve Closed	0.30 ± 0.219 (dimensionless)
Not obey standards	Perception, Max number of accidents, Probability Valve Closed	1.29 ± 0.236 (dimensionless)

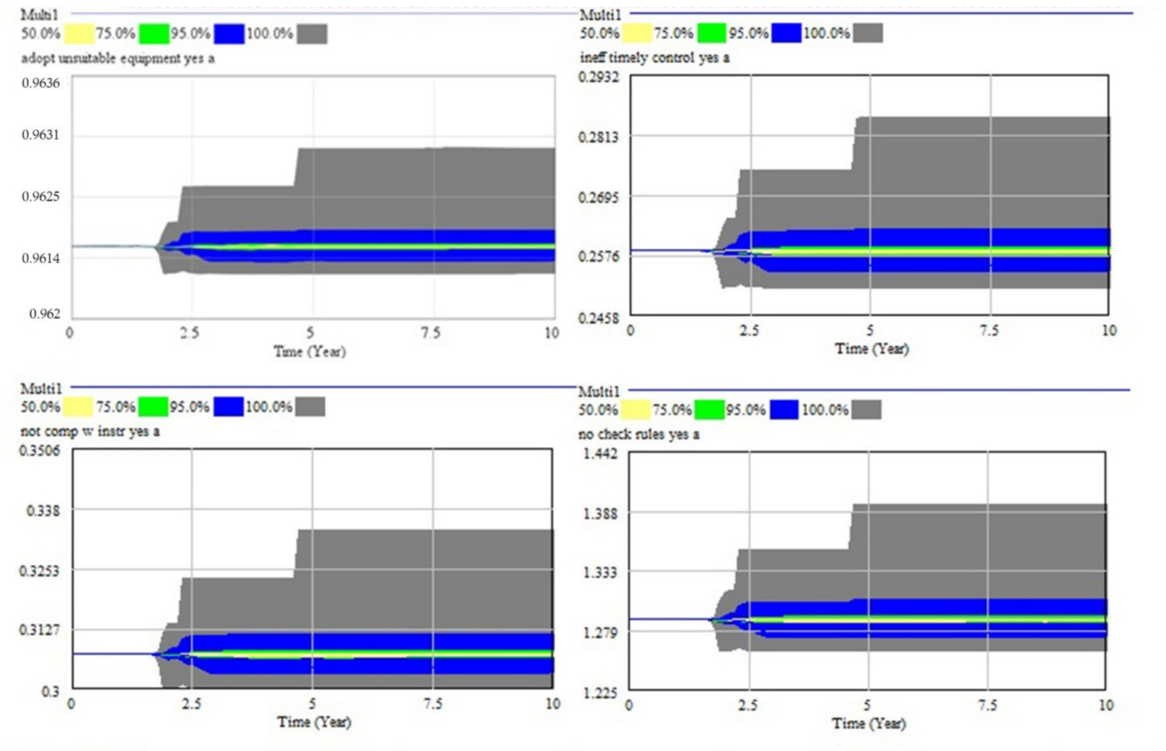

Figure 28. SD sensitivity analysis of 'not comply with instructions' and 'inefficient timely control' variables.

Results from this analysis indicate that all targets show similar ranges of variations around their own average value, except 'Adopt unsuitable equipment' which has a very low variability of 0.04. The results of the MC simulations show that all the target variables exhibit either a low or moderate response to changes in the responsive parameters. This indicates a high degree of robustness in the SD model and hence, the model outcomes can be accepted with confidence.

5. Conclusions

Summary: The current study demonstrates how T-H-O-Risk methodology enhances current FSVMs by incorporating HOEs in a PRA for a more inclusive view of risk in high-rise residential buildings. The limitations of existing deterministic methods and how they are overcome using the T-H-O-Risk methodology is elaborated in this paper. While the T-H-O-Risk approach enables an integrated analysis of HOE factors and their nonlinear interactions and feedbacks, it generally results in a higher level of uncertainty, hence, detailed sensitivity and uncertainty analyses were performed to assess the model robustness and reliability of model outputs.

Influence of HOEs: The study identifies the most important HOE variables and the extent they contribute to the fire risk in high-rise buildings. Uncertainties in point estimate of ERL values are propagated through appropriate probability distributions with Monte Carlo simulations while a family of F-N curves propagate epistemic uncertainty in societal risks of the case studies. Four case studies were used for the study including the reference case from the ABCB FSVM Handbook. For each case, a performance solution, a performance solution incorporating HOEs and a DTS solution were compared using risk values that assess the level of safety. The analysis finds that the level of risk as measured by the ERL of the performance solution is lower than the DTS solution however when HOEs are considered, their influence is significant for all cases.

Sensitivity and uncertainty analyses—A sensitivity analysis using a Monte Carlo approach found that the most influential HOE variables were 'not complying with instructions', 'deficient training' and 'inefficient emergency plan'. An uncertainty analysis of the ERL indicates that the most influencing HOE factors determine important variations in the ERL value of the system by up to 30% of the reference value. The minimum amount of variation associated with these HOEs is approximately 3–5% indicating that HOEs impact global risk levels; the F-N curves for all cases and scenarios with HOEs shift upwards indicating risk is underestimated when HOEs are ignored. Indeed, as system complexity increases, so does the influence of HOEs on risk primarily due to increasing numbers of fire safety measures and maintenance regimes. Sensitivity and uncertainty analyses in SD risk modelling indicate that risk thresholds oscillate or spike at year seven over the 10-year cycle. Risk variation over time analysis indicates that maintenance of an active safety system is required within five to seven years due to the degrading influence of HOEs on the reliability of the system.

Advantages of T-H-O-Risk—The research demonstrates how fire safety verification methods can be improved with the incorporation of human and organizational risks in PRA, where uncertainties in point estimates of individual risk are propagated with probability distributions while uncertainties in societal risks and risk variations over time due to human and organizational risks are propagated with confidence-interval-based societal risk curves. It is important to determine the significance of uncertainty in the PRA process, to produce effective fire safety measures for high-rise residential buildings.

State-of-the-art PRA—Although there are instances of using HOEs for modelling in other applications and industries, this is the first state-of-the-art methodology where HOEs have been incorporated in the fire risk analysis for high-rise buildings in a comprehensive manner, where technical systems such as sprinklers and smoke detection systems are integrated with HOEs. When HOEs are ignored in a PRA, overall risk levels are likely to be underestimated given that some DTS or performance-based designs that were initially assessed as within an ALARP region may fail the tolerability limit when HOEs are included. Hence, HOE variables will need to be considered when performing a Cost–benefit Analysis. The risk is not only quantified with the T-H-O-Risk approach, but the methodology also pinpoints various parameters that need to be controlled to minimize risk. Existing methods do not provide any empirical relations in predicting risks for different HOE parameters, making the T-H-O-Risk methodology even more significant.

Contribution—The T-H-O-Risk model contributes to the existing knowledge base related to risk modelling and the incorporation of HOEs in those models. This effort fills an existing gap in the literature and in existing fire risk models that fail to include and quantify the impact of HOEs. By incorporating BN and SD techniques, the enhanced model addresses HOEs dynamically in an innovative and integrated quantitative risk framework. This integrated modelling approach allows for a broader understanding of technical, human, and organizational risks in high-rise buildings, including a means to estimate the range of impacts that result from including these risks in the model that is lacking in current state-of-the-art models.

Policy implications—As far as policy implications are concerned, the ability to estimate the risk impacts: (a) significantly benefits stakeholders in Australia, including the ABCB, and their efforts to better quantify risk and tolerability levels as quantifying at this level means that health and safety can be clearly represented in terms of individual and societal risk and allows for flexibility in achieving these goals. (b) by incorporating individual and societal risk, fire authorities and building regulations can be proactive in their approach to events with multiple fatalities. Evaluating the frequency of events and the number of fatalities supports a quantitative (c) risk assessment (QRA) and ultimately drives risk as a basis for fire safety; (d) contributes to the development of next-generation building codes and risk assessment methodologies by demonstrating how fire safety verification methods can be improved with the incorporation of HOEs in PRA.

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Appendix A. T-H-O-Risk Methodology

The salient features of the T-H-O-Risk methodology are as follows:

- In the current study, the variation of the risk over time is considered along with technical, human, and organizational risks.
- Hazards and potential risk factors are identified in the first step which can cause damage to buildings or harm to humans.
- With the help of identified factors, risk computation is done in the next step using frequency and consequence analyses [27–29,40].

The overall risk for a system is given as the product of the frequency of occurrence of an accident scenario and its consequence. Risk models are based on the definition of risk as follows [40]:

$$R = \sum_{i=1}^{n} P_i C_i \quad \text{(A1)}$$

- o Frequency analysis: conventional event and fault tree techniques are used to compute risk. In addition to technical errors, HOEs are included in the risk analysis using the BN. BNs are based on the Bayesian statistical decision theory [41] according to which uncertainties originate from real-world situations along with subjective analyses are intended to help aimed engineers in the decision-making process. Some common HOEs are listed later.
- o Consequence analysis: ASET/RSET method is employed to check whether building design is safe or not. In both approaches, if the risk is found to be higher than the acceptable level, risk control is done in the analysis framework. The steps are iterated until the risk is acceptable.

For analysis, Microsoft Excel is used for the ET and FT calculations, Netica from Norsys is employed for BN, and Vensim from Ventana Systems is employed for SD. A detailed description of the calculations is encompassed as Supplemental Data, see later.

Appendix A.1. Step 1—Hazard Identification

Hazard identification is generally done during the design and implementation phase of a new process or installing new machinery. Hazards can also be identified during an inspection or after incidents or when a near miss has occurred. The main cause of fire hazard in buildings could be due to short circuit, electrical appliances, cigarette butts, flammable liquids, or cooking appliances. While identifying hazards, three elements that must be considered are:

- Ignition source;
- Fuel (such as waste products and textiles);
- Oxygen.

Furthermore, the structural aspects such as ducts, open roof spaces, and escape routes are also considered.

Appendix A.2. Step 2—Event Tree

An event tree (ET) is built to perform an overall system analysis (in two steps as follows) through a logical modeling technique for both success and failure through a single initiating event.

- The probabilities are defined for each successive event through fault tree analysis and some typical events.
- Based on the logical structure of the events, the overall risk is then estimated for the building design related to fire safety. The overall risk is presented as ERL.

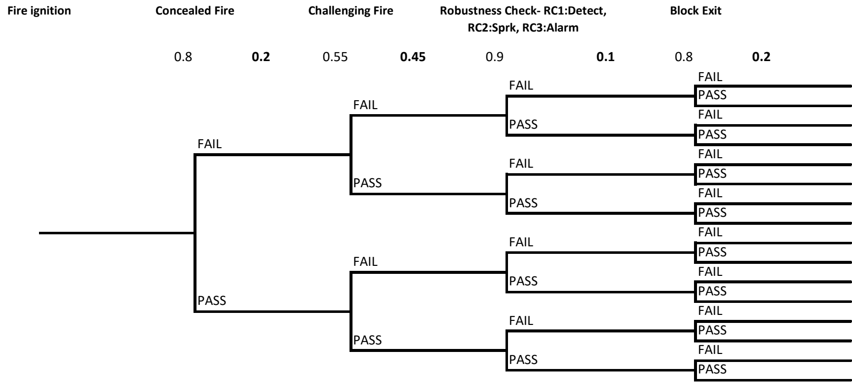
Thus, the goal of the event tree is to compute the probability of a negative outcome that can cause harm, starting from an initiating event. Some key advantages of the event tree analysis are:

- It can identify critical events that result in higher risk;
- It can determine cause and effect relationship;
- It can be automated.

The following events can be found typically in the ET (refer to Figures A1 and A2):

(1) Initiating event;
(2) Location of fire, e.g., apartment or corridor, concealed space or in a room;
(3) Challenging fire or smouldering fire
(4) Detection failure;
(5) Alarm failure;
(6) Sprinklers failure;
(7) Egress protection where an emergency exit is blocked.

The first row in Figure A1 shows the failure probability for each event that results in probabilities for each of the pathways. The ET begins with an initiating event that can cause failure (represented by 'FAIL') cases. In the present example, relevant design scenarios are sequenced. Figure A2 shows a typical event tree encompassing apartment and corridor fire and sub-systems: Fire in a CS—Concealed space or other room, Fire type- CF-Challenging fire or not, e.g., flaming or smouldering fire, Robustness Check includes failure probabilities for RC1: Detection failure RC2: Sprinkler failure RC3: Alarm failure, Egress protection failure BE—Blocked exit.



Scenario	Failed scenarios	Probability
1	CF.CS.RC.BE-FAIL	0.0018
2	CF.CS.RC.-FAIL	0.0072
3	CF.CS.BE-FAIL	0.0162
4	CF.CS.-FAIL	0.0648
5	CF.RC.BE.FAIL	0.0022
6	CF.RC.-FAIL	0.0088
7	CF.BE-FAIL	0.0198
8	CF.-FAIL	0.0792
9	CS.RC.BE.-FAIL	0.0072
10	CS.RC.-FAIL	0.0288
11	CS.BE.-FAIL	0.0648
12	CS.-FAIL	0.2592
13	RC.BE.-FAIL	0.0088
14	RC.-FAIL	0.0352
15	BE.-FAIL	0.0792
16	PASS	0.3168
		1.0000

Figure A1. Example of a typical Event tree incorporating fire scenarios.

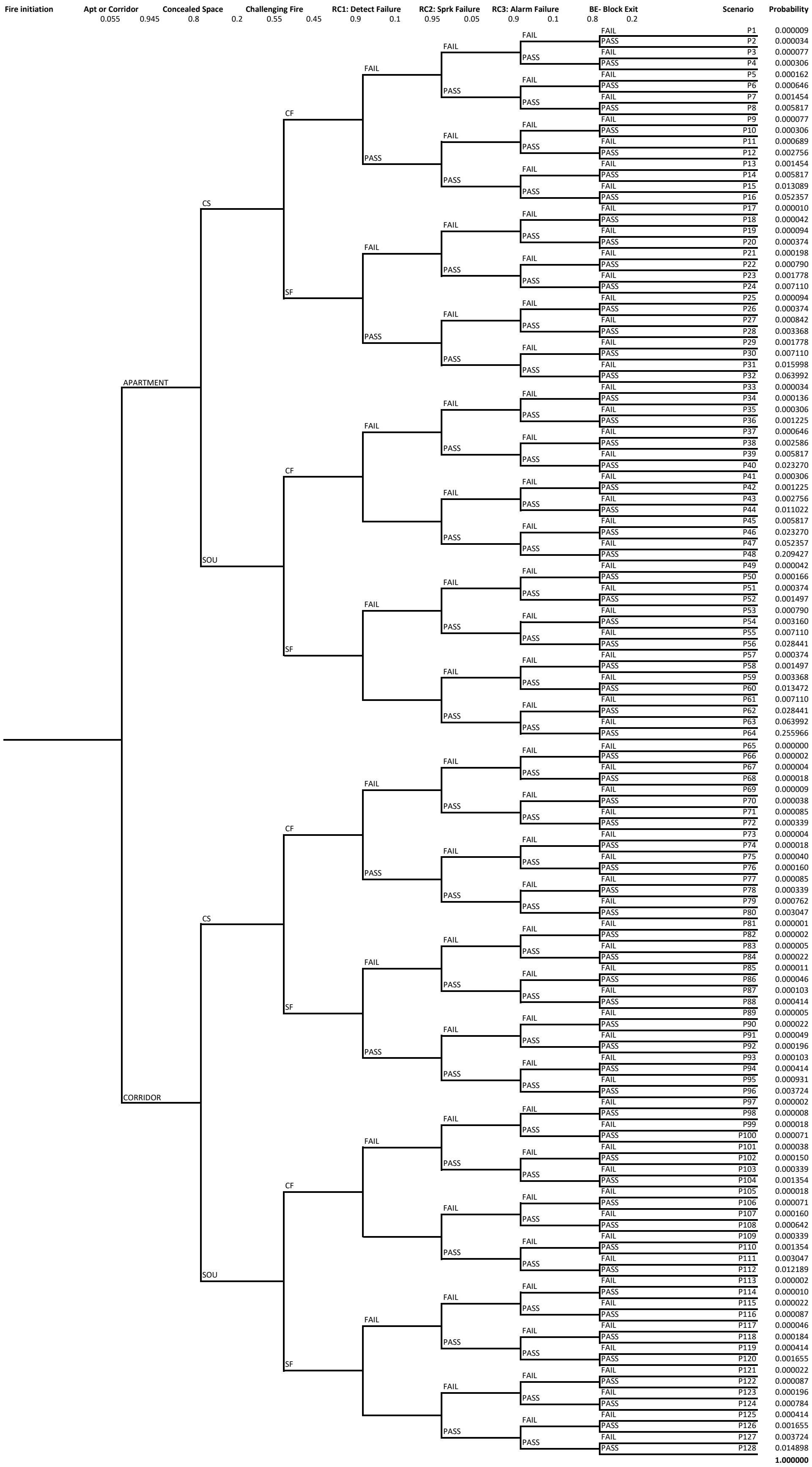


Figure A2. Typical Event Tree for apartment and corridor fire.

Reliable ignition frequency is a prerequisite for the overall risk estimation. The ignition frequency depends on the floor area of a particular building category. The annual ignition frequency is estimated based on the following generalized Barrois model [32]

$$P_1(A) = c_1A^r + c_2A^s \quad \text{(A2)}$$

where $P_1(A)$ is the ignition frequency of a building with floor area A during one year and c_1, c_2, s, and r are constants that are derived empirically, computed through fire statistics available from different countries.

Appendix A.3. Step 3a—Identification of Human and Organizational Errors

One of the main strengths of this method is that it introduces HOEs in addition to the conventional analysis methods. The Fussel-Vesely method is employed in this study to measure the significance of the basic events [33]. The approach can be defined as the ratio of the occurrence probability of the union of the minimum cut sets containing event X to the occurrence probability of the top event. To better understand the method, the following equation is used to consider a basic event:

$$p(e\ S) = \frac{p\ (eS)}{p\ (S)} \quad \text{(A3)}$$

where e is the event where a model element of the hybrid approach is set to a specific probability of a risk state S. For example, a risk state may represent a hardware component failure appearing as a basic event in an event/fault tree analysis, or as a specific state of a Bayesian Network (BN) variable such as maintenance procedures quality set to low rather than a higher value.

The HOE basic events that significantly contribute to the fire accidents' occurrence have been identified and listed in Table A1. Their occurrence probabilities are estimated based on statistical data obtained from the literature [14,42–48] as shown in the following table.

Table A1. Probability of relevant HOE basic events acquired from the literature.

Basic Events	Probability (10^6 h)
Poor safety supervision	4.60×10^{-4}
Deficient training	1.89×10^{-3}
Not following procedures	1.70×10^{-4}
Deficient risk assessment	1.80×10^{-4}
Deficient knowledge	1.89×10^{-3}
Inexperience	1.10×10^{-3}
Insufficient technical handover	6.30×10^{-3}
Insufficient safety check	2.50×10^{-2}
Inadequate periodic inspection	2.50×10^{-2}
Invalid daily record	5.60×10^{-3}
Inadequate emergency plan	5.00×10^{-4}
Failure to read monitoring data correctly	2.50×10^{-3}
Design error of operator	2.20×10^{-3}
Failure to follow technical requirements	1.92×10^{-4}
Not following technical requirements	1.92×10^{-4}

Appendix A.4. Step 3b—Bayesian Network

When unknown elements are given, Bayesian networks are generally used as the decision-making criteria [49] because they help incorporate the following:

- Multi-state variables;
- Dependent failures;
- Expert opinions that cannot be performed using standard FTA.

BNs allow for the combination of previous probability assignments with the newly available statistical data. In this study, Bayes' theorem is applied to derive a scenario probability that depends on uncertain factors. The key features of the method are:

- For the incorporation of HOEs, ET is mapped into a BN.
- In the first instance, the BN inserts observations in the nodes that are observable and then utilizes the rules of probabilistic calculations forward and backward from the nodes that are observable to the target node via an intermediate node, if exists.
- The extended BN model incorporating HOEs, determines a more precise estimate for the probability of occurrence of the top event if a specific configuration of critical HOEs is given.
- The critical parameters are revised based on prior probability, posterior probability, and mutual information (i.e., entropy reduction) computed for each given HOEs.
- The BN scheme is essential when the system state depends on more than one event. Since ETs are only capable of representing single input in a node, multiple inputs are ensured by adopting a Bayesian approach [50]. This is the case when human errors are considered.

By writing a conditional probability table, an ET can transform into a BN that provides the probability of an outcome given the probability of its causative events using the method suggested by Unnikrishnan et al. [51]. Netica which is a BN tool from Norsys was used for the BN modeling due to its ability to:

- To incorporate case files;
- To provide sensitivity analysis;
- To operate in batch mode.

Netica computes standard belief updating which solves the network by finding the marginal posterior probability for each node. The Netica BN scripts are given as supplementary material. In Figure A3, the aforementioned scenarios are depicted in the BN structure. It should be noted that in Figure A3, the symbol 0+ indicates values that are very small and negligible. The exact calculation of those values is computed by Netica and exported to an Excel spreadsheet.

Notations for the BN structure below:

- FY: fire ignition.
- FN: no fire ignition.
- DY: detection ON.
- DN: detection OFF.
- SuY: Suppression ON.
- SuN: Suppression OFF.
- SpY: fire and smoke spreads outside AOF
- SpN: fire and smoke does not spread outside AOF.
- NY: alarm/notification ON.
- NN: alarm/notification OFF.
- EY: egress protection ON.
- EN: egress protection OFF.

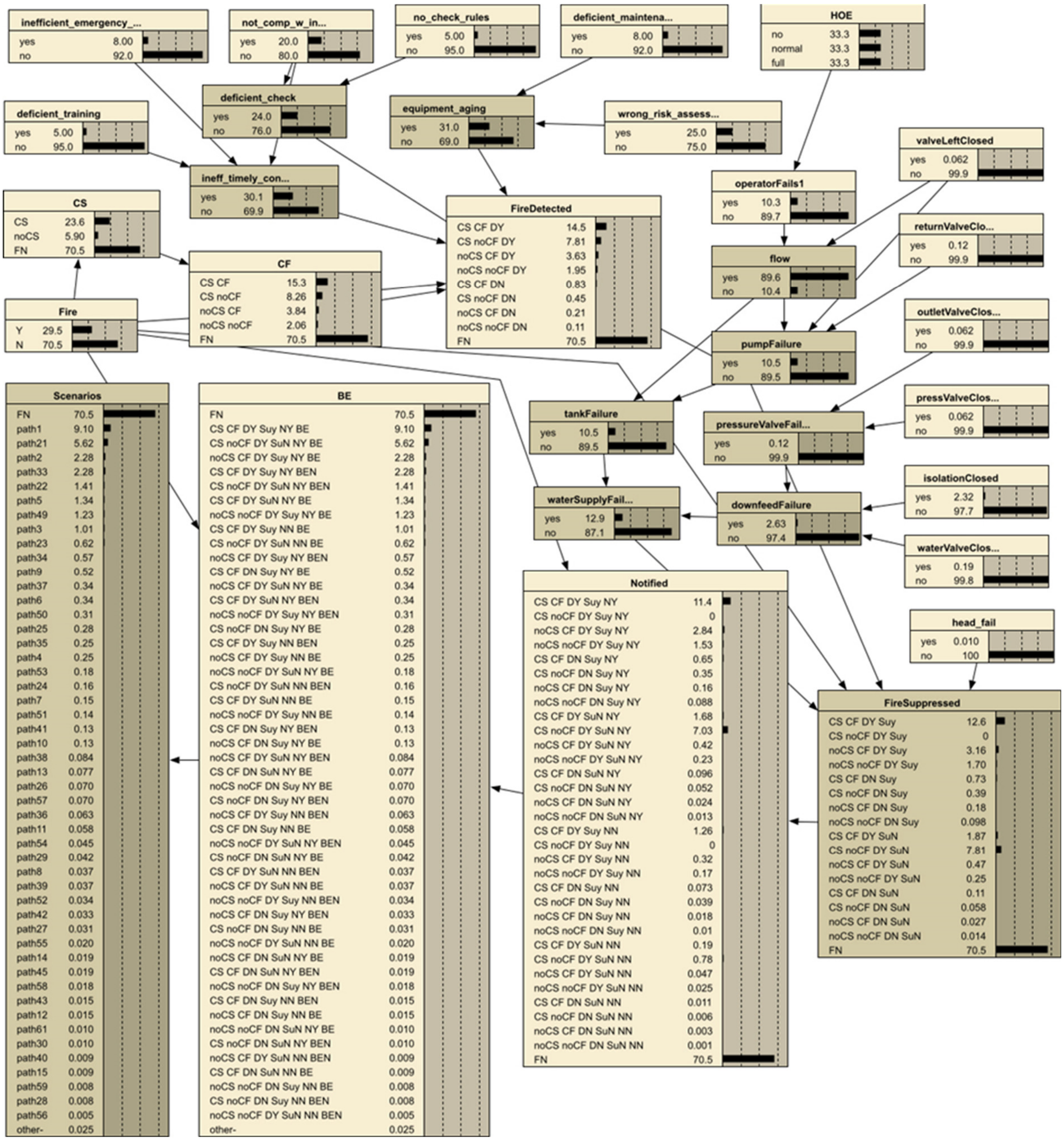


Figure A3. Example of Bayesian Network structure.

Appendix A.5. Step 4—System Dynamics

System Dynamics modeling is used to obtain time-varying probabilities which allow for the illustration of feedback loops and delays. Both [52,53] showed that fire accidents are dynamic processes that are complex and SD can be used to analyse them. BN is the starting point where each node of the BN is mapped into an SD model node. The SD perturbation equation with a random term is as follows:

$$P(fire\ yes) = 0.055 + Random\ Uniform\left(-\frac{defaultChange}{4}, \frac{defaultChange}{4}\right) x\ 0.055 \quad \text{(A4)}$$

As an example, for scenario 16, the SD behavior is shown in Figure A4. This scenario describes the failure of alarm/notification system due to deficient maintenance.

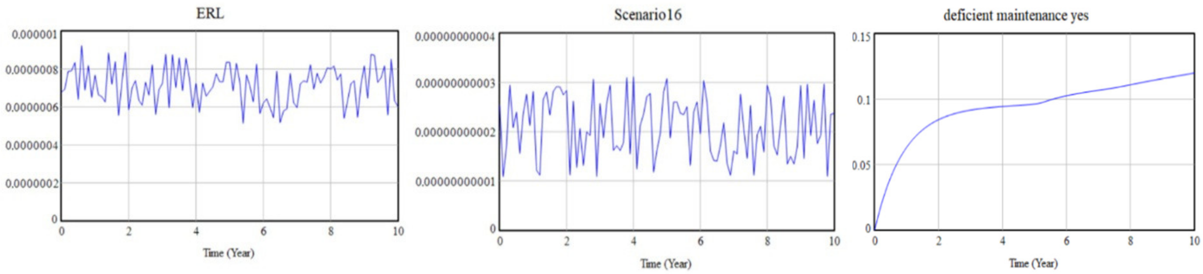


Figure A4. SD behaviour of risk over time.

The equation that governs the loop for the flow is as follows:

$$P(deficient\ training\ yes) = Random\ Uniform\left(-\frac{defaultChange}{4},\frac{defaultChange}{4}\right) P(deficient\ training\ yes) \quad (A5)$$

Using the Boolean logic, the CPT presented in Table A2 is transformed into an equation. Consider the CPT for the BN node, i.e., 'inefficient timely control' which consists of three parent nodes as follows:

- 'Deficient training';
- 'Inefficient emergency plan';
- 'Not comply with the instruction'.

In the SD model, it is characterized by the variables—'inefficient timely control yes' and 'inefficient timely control no' and can be converted into the equation below:

$$P(ineff\ timely\ control\ no) = \big(1 - P(deficeint\ training\ yes)\big)(1 - P(not\ comply\ w\ instr\ yes))(1 - P(ineff\ emerg\ plan\ yes)) \quad (A6)$$

Table A2. CPT for the BN node 'inefficient timely control'.

Deficient Training	Inefficient Emergency Plan	Not comply with the Instruction	Inefficient Timely Control
yes	yes	yes	yes
yes	yes	no	yes
yes	no	yes	yes
yes	no	no	yes
no	yes	yes	yes
no	yes	no	yes
no	no	yes	yes
no	no	no	no

The probability of each state displayed in the left-most column is the product of the probabilities of the terms to the right in the same row. If in the left column, more instances of the same state are found, then the probability is presented as the sum of the probabilities of all instances. The alternative state 'inefficient timely control yes' is given by the following equation:

$$P(ineff\ tim\ contr\ yes) = 1 - P(deficent\ training\ no) \quad (A7)$$

The node has the following four parent nodes:

- Fire;

- Inefficient timely control;
- Deficient check;
- Equipment aging.

The influence of these nodes is quantified through the CPT displayed in Table A3. The node consists of three possible states as follows:

- FY DY (fire yes, detection yes);
- FY DN (fire yes, detection no);
- FN (fire no).

The influence of the parent variables is stated through the listed values in the columns on the left of the CPT. The same reasoning is applied to all other nodes in the BN.

Table A3. CPT for the four parent nodes, i.e., fire, inefficient timely control, deficient check, and equipment aging.

Fire	Inefficient Timely Control	Deficient Check	Equipment Aging	FYDY	FYDN	FN
yes	yes	yes	yes	70	30	0
yes	yes	yes	no	70	30	0
yes	yes	no	yes	70	30	0
yes	yes	no	no	70	30	0
yes	no	yes	yes	80	20	0
yes	no	yes	no	80	20	0
yes	no	no	yes	80	20	0
yes	no	no	no	90	10	0
no	yes	yes	yes	0	0	100
no	yes	yes	no	0	0	100
no	yes	no	yes	0	0	100
no	yes	no	no	0	0	100
no	no	yes	yes	0	0	100
no	no	yes	no	0	0	100
no	no	no	yes	0	0	100
no	no	no	no	0	0	100

The final ERL variable encompasses the risk value for the specific design solution computed as the sum of the ERLs of every single outcome. The consequence of each sub-scenario (determined via ASET/RSET analysis) is multiplied by the associated path node probability. A consequence is the number of fatalities estimated based on ASET/RSET analysis.

The mapped SD model is demonstrated in Figure A5. An extended model has been developed to include human and organisational factors and is primarily based on the concept of reliability associated with maintenance practices (Figure A6). This dynamic model is based on the BN and its HOE variables are as follows:

- Deficient training;
- Inefficient emergency plan;
- Not comply with the instruction;
- No check rules;
- Deficient maintenance;
- Incorrect risk assessment;
- Not following standards;
- Improper safety organization.

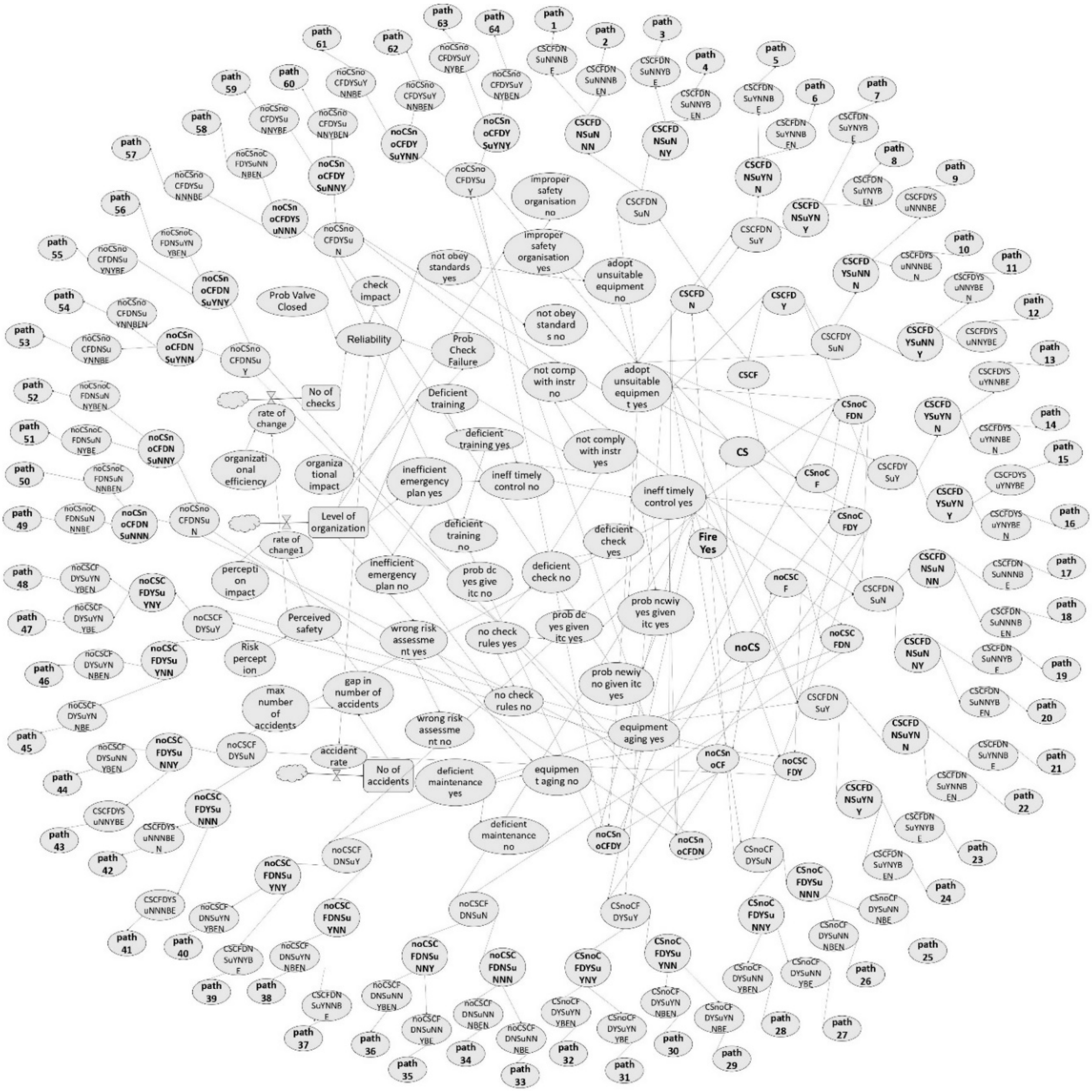


Figure A5. Mapped System Dynamics Model.

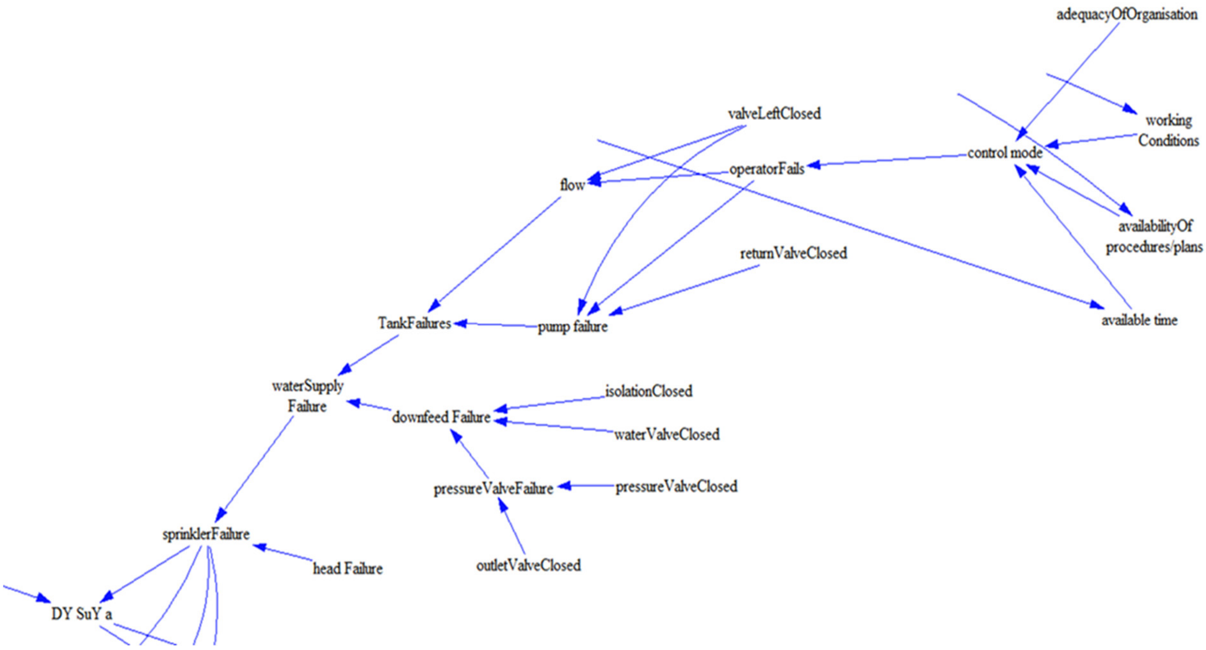


Figure A6. System Dynamics Model extension.

All variables in the cycle are dynamic and their interaction shows an oscillating pattern for the reliability parameter. The dynamic behaviour is simulated by stock and flow variables using Equations (A8) and (A9):

$$NoC = 12 + \int RoC\,(t)dt \tag{A8}$$

$$RoC(t) = 5\,\frac{d}{dt}(ps) \tag{A9}$$

Appendix A.6. Step 5—Probabilities

Step 5 is to estimate the probabilities of each variable. This is done after the structure of the model is fully defined including both static and dynamic modes. These were obtained either from the literature or thorough fault tree analysis. Some of the key features of this step are as follows:

- Different estimates for ignition frequency could be obtained through literature. Ignition frequency is considered one of the most influencing parameters.
- For the reliability of detection and sprinkler, the estimates are similar to the literature, as discussed above in Step 2.
- For HOEs, a review and assessment of selected incident data and maintenance databases were performed to obtain average probabilities/ frequencies of HOEs in industry, which are assigned to initiate events and basic events in the model to further carry out a quantitative analysis of the occurrence frequency.

Appendix A.7. Step 6—Available Safe Egress Time (ASET)

The ASET is determined based on the criteria referred to as tenability limits and derived from the physiological effects of fire on humans. Using B-Risk [35], a fire modelling software capable of characterizing a fire scenario and its consequences, it was made possible to establish the time to reach those limits using the following criteria:

- Temperature;
- Visibility;
- Fractional effective doses.

Appendix A.8. Step 7—Required Safe Egress Time (RSET)

The RSET is the time required for a person to reach a safe place in the event of a fire. The present method assumes a mixed computational approach, based on the equation as follows:

$$RSET = T_d + T_p + T_m \quad \text{(A10)}$$

where:

T_d is detection time;
T_p is pre-movement time;
T_m is movement time.

Detection time is computed from B-Risk simulations, which generates the time to activate a smoke/heat detector in the AOF origin. Evacuation times were computed using the hydraulics methods outlined in SFPE Handbook [8] and Pathfinder software for egress modelling from Thunderhead Engineering.

Appendix A.9. Step 8—ASET-RSET Analysis

The analysis of ASET and RSET is performed to confirm that in the actual scenario, occupants have enough time to safely escape the building. Adverse consequences are assumed if ASET is lower than RSET. Those calculations for each ET scenario complete the consequence analysis for the building solution.

Appendix A.10. Step 9—Risk Evaluation

The risk calculation is performed using the following equation:

$$R = \sum_{i=1}^{n} P_i\, C_i \quad \text{(A11)}$$

where P_i is the probability of each scenario and C_i are the consequences for the same scenario.

The resultant ERL (from ET) for each building solution that does not consider HOEs is compared with the solution (from BN) with HOEs to determine the HOE impacts on the overall risk.

Appendix A.11. Step 10—Risk Reduction

The global ERL has been estimated by static or dynamic analysis. In the static analysis, the resulting value is compared with generally accepted industry criteria or with a DTS solution following the BCA in all scenarios with and without HOEs. If the ERL exceeds those criteria, the building design is modified and undergoes a new iteration.

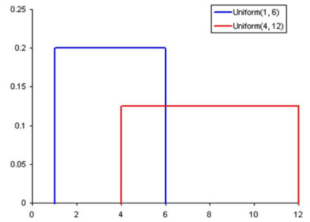
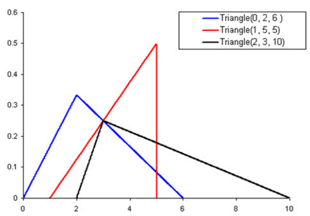
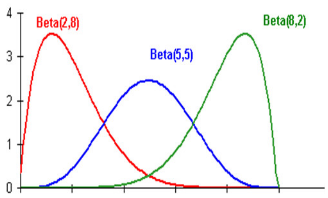
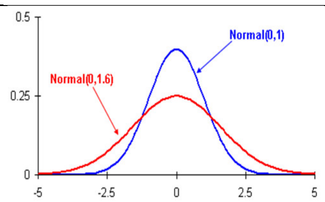
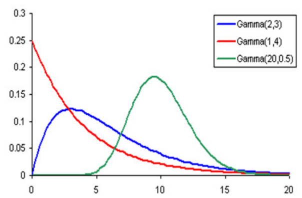
Appendix B

Table A4. Failure probabilities of technical risks implemented in Event Tree analysis.

Safety System Failure	Critical Component	Low	Expected	High	Reference
Challenging Fire		0.25	0.35	0.45	Hall [54]
Emergency Exit is Blocked	Human error	0.15	0.20	0.25	Magnusson et al. [55]
Fire in Concealed Space	Non-combustible partition ceiling/wall	0.15	0.20	0.25	N.A.
Sprinkler system	Main valve shut off, Human errors	0.02	0.05	0.15	Moinuddin & Thomas [43]
Smoke detection	Poor maintenance	0.05	0.10	0.15	Bukowski [56]

Alarm system	Shut-off after maintenance	0.05	0.10	0.15	PD7974–7 [6]
Manual detection	Human errors	0.30	0.48	0.60	Holborn et al. [57]
Smoke Control/Mechanical ventilation	Fire damper failure	0.20	0.30	0.50	Zhao [58]
Smoke barrier	Door seal failure	0.05	0.20	0.50	PD7974–7 [6]
Fire department response	Human and organizational errors	0.02	0.05	0.30	USFA [59]
Management strategy	Human errors	0.05	0.15	0.30	Sabapathy et al. [40]

Table A5. Types of distributions.

Distribution	Graph	Probability Density Function	Properties	Framework
Uniform		$f(x) = \frac{1}{max - min}$	Close-ended with same probability	Same likelihood of either overestimating or underestimating (+/− 10%)
Triangular		$f(x) = \frac{2\,(x-\min)}{(mode-\min)(\max-\min)}$ $if\ min \le x \le mode$ $f(x) = \frac{2\,(max-x)}{(max-\min)(\max-mode)}$ $if\ mode < x \le max$	Close-ended With possible skewness	Possible under-estimation of ML is [−10%; ML: +50%
Beta		$f(x) = \frac{(x)^{\alpha-1}(1-x)^{\beta-1}}{B(\alpha,\beta)}$ $Where\ B(\alpha,\beta)\ is\ a\ Beta\ funtion$	Close-ended with possible skewness	Possible under-estimation of ML is [−10%; ML: +50%
Normal		$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$	Close-ended With no skewness	The most likely value is set to first-year impact, std. dev. is set to 15%
Gamma		$f(x) = \frac{\beta^{-\alpha}x^{\alpha-1}exp\left(-\frac{x}{\beta}\right)}{\Gamma(\alpha)}$	Semi-close-ended Possible right skewness	k-value setting is 5, calculated based on mean from Lichtenberg [−25%; ML: +100%]

Appendix C. Sensitivity Calculations of HOE Variables

The calculation procedure of sensitivity for the three main HOE variables are described below.

Note:

D = difference in absolute terms between values at 95%and at 5% cumulative probability

dr = difference in relative terms between values at 95%and at 5% cumulative probability

Challenging fire scenario

'not comply with the instruction'

$$D_{95-5} = 0.70 - 0.21 = 0.49 \text{ in absolute terms}$$

$$d_{95-5} = \frac{0.49}{0.46} = 1.07 \text{ relative to the mean value}$$

'deficient training'

$$D_{95-5} = 0.41 - 0.10 = 0.31 \text{ in absolute terms}$$

$$d_{95-5} = \frac{0.31}{0.25} = 1.24 \text{ relative to the mean value}$$

'inefficient emergency plan'

$$D_{95-5} = 0.21 - 0.03 = 0.18 \text{ in absolute terms}$$

$$d_{95-5} = \frac{0.18}{0.11} = 1.64 \text{ relative to the mean value}$$

'ERL'

$$D_{95-5} = 5.88 * 10^{-6} - 5.59 * 10^{-6} = 2.90 * 10^{-7} \text{ in absolute terms}$$

$$d_{95-5} = \frac{2.90*10^{-7}}{5.77*10^{-6}} = 0.05 \text{ relative to the mean value}$$

Sensitivity

$$S(not\_comply\_with\_instr) = \frac{0.05}{1.07} = 0.05$$

$$S(deficient\_training) = \frac{0.05}{1.24} = 0.04$$

$$S(ineffective\_emergency\_plan) = \frac{0.05}{1.64} = 0.03$$

As expected, the HOE variable 'not complying with the instructions' has the greatest influence on the outcome with a sensitivity of 5% followed by 'deficient training at 4% and 'inefficient emergency plan' at 3%

Robustness Check scenario

'operator fails'

$$D_{95-5} = 0.037839 - 0.0257955 = 0.012 \text{ in absolute terms}$$

$$d_{95-5} = \frac{0.012}{0.03157} = 0.38 \text{ in relationships to the average value}$$

ERL

$$D_{95-5} = 7.11 * 10^{-4} - 6.36 * 10^{-4} = 0.75 * 10^{-4} \text{ in absolute terms}$$

$$d_{95-5} = \frac{0.75 * 10^{-4}}{6.68 * 10^{-4}} = 0.1123$$

in relationship to the average value

Sensitivity

$$S(operator\_fails) = \frac{0.1123}{0.38} = 0.29$$

Appendix D. Uncertainty—Confidence-Level Based Societal Risk in F-N Curves

Societal risks for the case studies are presented as F-N curves and constructed using the following equation:

$$F = k \times N^{-a} \tag{A12}$$

where F is the cumulative frequency of N or more fatalities, k is a constant, N is the number of fatalities, a is the aversion factor.

Sun et al. [38] propose a confidence-level-based SR characterize the uncertainty of SR in two dimensions by defining the confidence bounds of the SR given by the F-N diagram. In this method, it is assumed that the events' occurrence in the ET model of PRA follows Poisson distribution. Based on this assumption, the confidence interval of the number of times an event occurs can be determined by:

$$\varphi_U = \frac{X^2_{1-\omega/2}(2n+2)}{2}$$
$$\varphi_L = \frac{X^2_{\omega/2}(2n)}{2} \tag{A13}$$

where φ_U and φ_L are the upper and lower boundaries of the CI for the mean value of a Poisson distribution, respectively; n is the number of times an event occurs in an interval (e.g., number of fatalities; ω is defined as the significance level of the statistics. $X^2_{1-\omega/2}(2n+2)$ is the $(1-\omega/2)$ th quantile of the chi-squared distribution with $(2n + 2)$ degrees of freedom; $X^2_{\omega/2}(2n)$ is the $(w/2)$th quantile of the chi-squared distribution with $(2n)$ degrees of freedom; and $X^2_{1-\omega/2}(2n+2)$ and $X^2_{\omega/2}(2n)$ can be found in the table of chi-squared distribution. Then, the mean value of event frequencies and the corresponding confidence interval can be determined by:

$$\theta = n.\frac{1}{S}$$
$$\theta_U = \varphi_U.\frac{1}{S} \tag{A14}$$
$$\theta_L = \varphi_L.\frac{1}{S}$$

where θ is defined as the mean value of event frequencies; θ_U and θ_L are the upper and lower boundaries of the confidence interval of θ, respectively; and S is the product of the number of experiments and an interval of time.

The reliability of the F-N curve evaluation is examined by the confidence-level-based SR uncertainty in two dimensions in the F-N diagram. Specifically, a-cuts of F(N) and N are taken as the CI to quantify the SR uncertainty according to the possibility theory by:

$$\prod(A) = \max_{c \in A}\{\pi(c)\}$$
$$N(A) = 1 - \prod(\bar{A}) \tag{A15}$$

where $N(A)$ is the necessary measure from the possibilistic distribution $\pi(c)$ of C, for set A.

Appendix E. Sensitivity Analysis for System Dynamics

Sensitivity analysis for the SD model is then performed for the dynamic response of the system over 10 years. Sensitivity analysis is used to determine how the model behaves and responds to a change in a parameter. Each simulation with changed parameters and slope of the nonlinear relationship was compared with the base run simulation to determine whether the parameters and nonlinear relationships exhibited sensitive behavior. If the model behavior only changes numerically with the values of parameters, it indicates that the underlying behavior is not sensitive to changes in parameters. In fact, most of the input parameters will not have a great influence on the model behavior, except for critical variables in the model. The sensitivity of a parameter is given by the equation below:

$$S(t) \left| \frac{(Y(t+1) - Y(t))/Y(t)}{(X(t+1) - X(t))/X(t)} \right. \tag{A16}$$

where *S* is the sensitivity function, *Y* is the output behavior variable, *X* is the model parameter and *t* is time.

The Monte Carlo simulation is suitable when models are capable of generating interactions between factors or have non-linear outputs. The sensitivity analysis tests are carried out in Vensim software V7.4.5 from Ventana Systems. A Latin Hypercube search was used as a mechanism to ensure that the full reasonable range of each parameter was studied using 1000 simulations. The Latin Hypercube is designed to reduce the required number of simulations required to obtain adequate information about the distribution. The sensitivity runs provide a comparative graph of final results, which cause the simulation results to be displayed as confidence bounds ranging from 0 to 100 percent. Confidence bounds [39] are used to represent the sensitivity of the variable. The analysis is computed at each point in time by ordering and sampling all the 1000 Monte Carlo simulation runs. The color area in the sensitivity graph indicates whether the specified variable may affect the simulation results to a great extent. For the confidence bounds color in the output graph, yellow represents 50%, green represents 75%, blue represents 95% and grey represents 100%.

Appendix F

Table A6. List of parameters in System Dynamics model.

Parameters	Model Value (Units)	Definition/Equation	Range of Variation (Multi)
adopt unsuitable equipment	dimensionless	1 − (improper safety organisation yes) × (1 − dump1 × not obey standards)	0.0028–0.0048
fire probability	dimensionless	ignition frequency + RANDOM UNIFORM(−default Change/4, default Change/4, 1) × ignition frequency	0.0023–0.0038
inefficient emergency control plan	dimensionless	1 − (1 − deficient training yes) × (1 − dump2 × not comp w instr yes) × (1 − control2 × inefficient emergency plan yes)	0.0053–0088
not obey standards	dimensionless	1.05 − Level of organisation/4	0.16–0.28
wrong risk assessment	dimensionless	1.3 − Level of organisation/4	0.48–0.58
deficient check	dimensionless	1 − deficient check no	0.23–0.45
deficient maintenance	dimensionless	deficient maintenance = RANDOM UNIFORM(−default Change, default Change, 1) × deficient maintenance yes	0.06–0.10
deficient training	dimensionless	1 − Level of organization	0.0645–0.1075
electrical failure	dimensionless	1 − (1 − component faulty connection) × (1 − no battery)	0.0375–0.0625
equipment aging	dimensionless	1 − (deficient maintenance yes a)*(1 − wrong risk assessment)	0.2325–0.3875
improper safety organisation	dimensionless	1.3 − control4 × Level of organisation/4	0.075–0.125
inefficient timely control	dimensionless	1 − (deficient training yes) × (1 − dump2 × not comp w instr yes) × (1 − control3 × inefficient emergency plan)	0.315–0.525
inefficient emergency plan	dimensionless	1.25 − Level of organisation*dump5/4	0.092–0.154
Level of organisation	dimensionless	rate of change	1 to 4
n° of accidents	dimensionless	INTEG(accident rate)	15–25
no check rules	dimensionless	1.3 − Level of organisation*dump6/4	0.1065–0.1775
not comply with instructions	dimensionless	0.3 + deficient training	0.3045–0.5075

Number of checks	number per year	INTEG(rate of change)	23.25–38.75
perceived safety	dimensionless	gap in no of accidents × perception	2.175–3.625
ProbCheckFailure	dimensionless	0.4 × deficient training + 0.1	0.0825–0.1375
ProbValveClosed	dimensionless	ProbValveClosed = 0.01 + RAMP(0.05,1,20)	0.0075–0125
reliability	days/year	1 − (((ProbCheckFailure × 19) + 1)/20) + ProbValveClosed a + (1/N° of checks)	9 to 15
smoke alarm failure	dimensionless	1 − (1 − panel failure) × 1 − zone isolated)	0.675–0.925
notification failure	dimensionless	1 − (1 − bell failure) × (1 − bulb failure)	0.75–0.95
panel failure	dimensionless	1 − (1 − electronic failure)*(1 − notification failure)	0.011175–0.018625
sprinkler failure	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.85–0.95
sprinkler head failure	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.00225–0.0375
water supply failure	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.099–0.165
downfeed failure	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.019725–0.032875
pressure valve failure	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.00093–0.00155
outlet valve failure	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.000465–0.000775
isolation closed	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.0174–0.029
water valve closed	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.001425–0.002375
pressure valve closed	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.000472–000788
tank failure	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.08175–0.13625
pump failure	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.0423–0.0705
return valve closed	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.0009–0.0015
operator fails	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.0009–0.0015
flow probability	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.70–0.90
valve left closed	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.0009–0015
alarm valve	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.00141–00235
ordinary stop valve	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.000465–000775
non-return valve	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.0008925–001488
alarm bell	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.02175–0.03625
storage tank	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.0054225–0.009038
mains power	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.0002745–0.000458
pressure switch	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.0059175–0.009863
diesel pump	dimensionless	Probability of Failure on Demand (PFD) [43,48]	0.069–0.115

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5.6 Synopsis of Chapter 5

The application of the methodology shows that for all design scenarios, the level of risk of the performance solution is lower than the DTS solution. The confidence-level uncertainty bounds in the F-N curves identifying the uncertain risk areas indicate that two out of four cases marginally exceed the tolerance limit when HOEs are considered. Sensitivity and uncertainty analyses of HOEs in SD risk modelling indicate that risk thresholds oscillate or spike at year seven over the 10-year cycle, even given stable parameters. An analysis of risk variation over time indicates that maintenance of an active safety system is required within five to seven years due to the influence of HOEs on the degradation of reliability in the system. A multivariate analysis is used to assess the robustness of the SD model and to define the ranges of variations of the target variable. The results indicate that all targets show a similar range of variations around their average value, except 'Adopt unsuitable equipment' which has a very low variability of 0.04 Results of the validation process of the T-H-O-Risk model compare reasonably well with available statistical and historical data. Further, reliability obtained for different configuration's using T-H-O-Risk methodology falls between the upper and lower bounds obtained from the international data.

Chapter 6 is the concluding chapter and summarizes the main findings in this research, outlines limitations and suggest directions for future research.

Chapter 6

Conclusions and Future Research

Overview

Chapter 6 closes out this thesis by presenting a summary of the research with the main findings of each chapter discussed. Contribution, significance and recommendations for future work are also included. Overall, the T-H-O-Risk approach demonstrates how technical, human, and organizational risks can be quantified in a comprehensive probabilistic framework which represents an important step in the development of next generation building codes and risk assessment methods. The results demonstrate that HOEs have a significant impact on overall fire risks in high-rise residential buildings.

6.1 Conclusion

Modelling of fire safety risks in high-rise residential buildings typically has included technical risks and errors, while ignoring the impacts of HOEs resulting in significant underestimation of overall risks. Additionally, the reliability of fire safety systems are taken as constants whereas in reality it varies over time. The significant contribution of this study is to develop probabilistic risk analysis (PRA) that includes HOEs and risk variation over time. This model is applied to seven buildings located in different geographical positions. This model is named as technical, human and organizational risk (T-H-O-Risk) methodology and it will provide more accurate PRAs of high-rise building fire safety designs. The T-H-O-Risk methodology incorporates the HOEs through Bayesian Network (BN) and dynamic risk variations through system dynamics (SD) modelling techniques.

At first through a systematic literature review, important HOEs for fire safety in high-rise buildings were identified. This is done based on the HOEs identified for other industries. The relevant HOEs are:

- deficient training,
- inefficient emergency plans,
- personnel not complying with instructions,
- not checking the rules,
- deficient maintenance,
- incorrect risk assessments,
- not following standards
- an improper safety organization
- deficient checks
- inefficient timely control
- adopt unsuitable equipment

For the scope of this thesis, our model is focused on Level 3 & 4 human and organizational factors that organizations have influence over, while Level 2 factors are macro intranational factors [1] that are difficult to quantify with unavailable or access to such government data and hence, were not modelled. The T-H-O-Risk methodology integrates analyses of building and occupant characteristics, fire safety systems, evacuation, and statistical data. The methodology is flexible and can be applied to a variety of structures, allowing for both relative and absolute risk evaluation. It further addresses the issue of potential underestimation of the risk resulting from the adoption of less demanding maintenance and operational practices along with the lifecycle of the system. In addition to providing a tool for quantifying HOEs with multiple levels of analysis and supporting analyses over time, the model accounts for refurbishment activity and interactions with other safety systems that can result in a global loss of safety when these relationships are overlooked. The method is an incremental risk approach allowing for the quantification of the impact of HOEs on different fire safety systems including the active systems of sprinklers, building occupant warning systems, smoke detectors, and smoke control systems. The methodology enables technical, human and organizational risks to be assessed in multiple FN curves to determine if risk levels meet the tolerability criteria, if risk levels are situated within the expanded ALARP zone, and whether CBA will need to be carried out.

Case studies included prescriptive, DtS solutions and performance-based solutions with variations of apartment, retail tenancy and office fire scenarios. The buildings were located across five countries and the Building Code of Australia (BCA) was considered as the reference for all seven designs. Both active (sprinklers, building occupant warning systems, smoke detectors and smoke control systems) and passive (egress protection systems and fire and smoke spread compartmentation systems) fire safety measures were considered. Assumptions were made regarding the systems' operability, characteristics of the occupants, and the level of organization. The impact of other parameters such as building area and occupancy use on risk levels were incorporated in the ignition frequencies for the case studies which were computed based on the generalized Barrois model [2] in the risk framework. The acceptance criterion was that the calculated value of risk be less than the defined expected risk to life (ERL) benchmark and societal risk curves are not to exceed the allowable tolerability limits in the F-N curves

The results from the case studies show that while HOEs have a limited impact on passive protection systems, SD modelling identified large variations in the reliability of active systems due to HOEs over time. This outcome emerged because of the introduction of time-varying probabilities that allowed for feedback and delays. The model utilized the ALARP principle in comparing risk acceptance for different cases and societal risks were represented in F-N curves. Generally, HOEs resulted in an increase in risk levels for all seven case studies. It was estimated in general terms that the fire safety designs that do not consider HOEs underestimate overall risks in the range of 6% to 42%. SD modelling indicated that risks over time due to HOEs varied by as much as 30% over a 10-year period. The reliability of safety systems such as detection or suppression systems varied with time as well as the effect of perceived safety impacted the actions of safety personnel. The analysis demonstrated that there is an initial period, from zero to five years in which the reliability declines slowly, thus causing an increase in accidents. In response, the excessive number of accidents compel the safety personnel team to implement new safety measures that improve the reliability from years five to seven, capturing the human response to safety conditions over time.

It is important to note that societal risks remain high in the absence of active safety systems and generally risk is lower where stairwells and active safety systems are present. The simulation results further demonstrate that the dynamic effects of human, organizational, and social factors alter component reliability and that the influence of these factors develops over time. Small behavioural changes in risk perception of a building management team can lead to large ERL variations over time.

While the T-H-O-risk approach enables an integral analysis of HOE factors and their nonlinear interactions and feedbacks, it generally results in a higher level of uncertainty, hence, detailed sensitivity and uncertainty analyses were performed to assess the model robustness and reliability of model outputs. The study identifies the most important HOE variables and the extent they contribute to the fire risk in high-rise buildings. A sensitivity analysis using a Monte Carlo approach found that the most influential HOE variables were ‘not complying with instructions', 'deficient training' and 'inefficient emergency plan'. Uncertainties in point estimate of ERL values are propagated through appropriate probability distributions with Monte Carlo simulations while a family of F-N curves propagate epistemic uncertainty in societal risks of the case studies. An uncertainty analysis of the ERL indicates that the most influencing HOE factors determine important variations in the ERL value of the system by up to 30% of the reference value. The minimum amount of variation associated with these HOEs is approximately 3-5% indicating that HOEs impact global risk levels; the F-N curves for all cases and scenarios with HOEs shift upwards indicating risk is underestimated when HOEs are ignored. Indeed, as system complexity increases, so does the influence of HOEs on risk primarily due to increasing numbers of fire safety measures and maintenance regimes. Sensitivity and uncertainty analyses in SD risk modelling indicate that risk thresholds oscillate or spike at year seven over the 10-year cycle. Risk variation over time analysis indicates that maintenance of an active safety system is required within five to seven years due to the degrading influence of HOEs on the reliability of the system.

Although there are instances of using HOEs for modelling in other applications and industries, this is the first comprehensive methodology where HOEs have been incorporated in the fire risk analysis for high-rise buildings in a comprehensive manner, where technical systems such as sprinklers and smoke detection systems are integrated with HOEs. When HOEs are ignored in a PRA, overall risk levels are likely to be underestimated given that DtS or performance-based designs that were initially assessed as within an ALARP region may fail the tolerability limit when HOEs are included. Hence, HOE variables will need to be considered when performing a cost benefit analysis (CBA). The risk is not only quantified with the T-H-O-Risk approach, but the methodology also identifies various parameters that need to be controlled to minimize risk. Existing methods do not provide any empirical relations in predicting risks for different HOE parameters, making the T-H-O-Risk methodology even more significant and represents an important step in the development of the next generation building codes and risk assessment methods. This is the significant contribution to the knowledge in this study.

6.2 Research questions

This section discusses how the primary research question has been addressed in this thesis as follows:

Research Question – *What human and organizational errors are relevant to probabilistic fire risk analysis of high-rise residential buildings?*

This research work addressed and explored the primary research question regarding what probabilistic scenarios involving HOEs can be quantified and what their impacts on risk are. A systematic review was conducted that identified important HOEs and drew from recent fire events such as Grenfell Tower and Lacrosse building fires where common HOEs include safety culture of an organization, occupant errors and errors committed by building staff. PRA in other industries such as offshore platforms, aviation and nuclear plants have included some quantification of HOEs such as HRA and Socio-Technical Risk Analysis. The review identified a knowledge gap in PRA/HOE models for high-rise residential buildings and this research proposed a new T-H-O-Risk methodology using BN analysis of HOEs and SD modelling for dynamic characterization of risk variations over time.

The primary question has led to two sub-research questions:

Sub-research question I – *What are the quantitative impacts of human and organizational errors on probabilistic risk analysis of high-rise residential buildings?*

The new T-H-O-Risk methodology was applied to various case studies of high-rise residential buildings to determine the quantitative impacts of HOEs on overall fire risk. The methodology enabled the analysis of the decision-making process in the presence of multi-state variables, dependent failures, and expert opinions that cannot be performed using standard event/fault tree analyses. It enabled computations of the effect of the probability variations and uncertainty of outputs of the model. It is evident from the results that T-H-O-Risk model obtains a better estimate for the occurrence probability of an event given a specific configuration of critical HOEs. The inclusion of SD enabled time-varying parameters that can cause risk oscillation during the life cycle of a building.

These observations helped to define corrective measures to contain excessive variations in the risk level over the life cycle of the building.

Sub-research question II – *How is risk modelling improved when incorporating BN and SD methodologies into existing probabilistic fire risk analysis of high-rise residential buildings?*

It is clear the application of T-H-O-Risk methodology highlights the usefulness of specific modelling techniques and quantitative solutions that integrate HOEs into probabilistic risk models. The advantage of integrating BN and SD methods in the early design phases to model human and organizational risks allows for compensating measures and quantification of societal risks to compare different buildings. This information can be used to supplement data used for high-level decisions to determine effective policies and regulations. The T-H-O-Risk methodology provides robust results in comparison with conventional quantitative risk analyses and the dynamic risk analyses improves existing PRA. Probability update and uncertainty reduction are two inherent specifications incorporated in the dynamic T-H-O-Risk methodology.

6.3 Limitations

The inclusion of human and organizational factors in the probabilistic T-H-O-Risk model has proved to be very beneficial and the approach contributes to the development of the next generation building codes and risk assessment methodologies. However, there are some limitations on the application of the model which are summarized below:

1) The risk model requires a lot of statistical data, and the available data in the high-rise residential building domain are inadequate as compared with other industries such as nuclear power plants, offshore oil and gas platforms.

2) Three of the five parameters with high sensitivity were determined by an automatic calibration process, since no other information was available. More information is needed to provide better calibration accuracy.

3) There is a lack of knowledge about the acceptable range of change for several of the parameters. Such knowledge would provide greater certainty in the model outputs.

4) The model verification is mainly focused on the prevention of failure in the maintenance regime, but such failures can also arise also from other HOEs. For example, occupants covering the smoke alarms, refurbishment mismanagement, and organizational issues during evacuation have caused unexpected failures of the planned fire protection countermeasures. These HOEs are not fully studied which causes some limitations.

5) The human and organizational error sub-model is not applied to the reliability of other safety systems such as smoke management during evacuation, as well as the reliability of prevention measures that could impact the probability of fire ignition.

6) The rational human behaviour pattern in the pre-movement process due to the insufficient existing data is not fully obtained. In the current study, only a number of factors affecting human behaviour has been studied. Other factors such as the complexity of building, intensity of warning system, the occupant familiarity with the building, etc., should be further studied in the future. More real data must be collected so that we can calibrate the model to a finer level of granularity.

7) Another limitation is the simplified simulation model. For the sake of the convenience in the focus on the major behaviour of the system some assumptions were made to simplify the model. The panic behaviour was left out of our consideration which may occur in real situations. Some emergency activities at the recognition stage and response stage were not involved in the model, such as taking refuge in place, fighting the fire.

8) The simulations that incorporate all the above-mentioned factors requires modern modelling techniques and computational power to enable techniques that can facilitate HOE analysis in PRA. A toolkit of techniques to assess risk across technical, human, and organizational systems would be an appropriate approach to the scarcity of a systems approach.

6.4 Recommendations for Future Research

This study shows that incorporating HOEs into a PRA model for high-rise buildings is feasible and is a research area that needs to be explored and understood. Future work should focus on simplifying the model characteristics for wider applications to broader building occupancies as well as expanding the sensitivity and uncertainty analyses. More research is needed on HOEs and how they interact in prediction of fire events, especially in high-rise buildings. Currently, there are scarce sources in the literature specific to high-rise buildings, HOE scenarios and their impact on risk. Further, research is needed to identify the controllable characteristics of individuals and organizations for inclusion in probabilistic risk models to better estimate risk levels of fire incidents. This will require a systematic and comprehensive methodology for causal modelling with a view to relating the risk scenarios to their human and organizational performance roots, and to the regulatory and oversight functions.

The findings reveal a need for more computational modelling studies that are specific to risk in high-rise buildings. New mathematical models will need to be developed that include occupant behaviour, building staff errors and safety culture in the risk analysis. The process of validating these models includes comparisons with statistical data in high-rise residential buildings where there is more available data and existing models relevant to fire hazards in high-rise buildings. The advent of modern modelling techniques and computational power allows for rapid simulation techniques that can facilitate HOE analysis in PRA. A toolkit of techniques to assess risk across technical, human, and organizational systems would be an appropriate approach to the scarcity of a systems approach.

Future research should consider the development of dynamic probabilistic risk models that address risk variations over time. Such models can account for changing risk profiles during the life cycle of a complex system as safety components age and/or fail over time requiring repairs, refurbishment, or replacement. Updates of risk profiles can be performed dynamically to reflect the safety state of the overall system. These changes may be physical such as equipment modifications, operational such as procedural enhancements or human and organizational such as knowledge-driven, operational experience and data. A dynamic PRA will enable continual risk estimations of a deteriorating system depending on the states of its components and systems knowledge acquired over time.

6.5 References

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