BALANCING STAKEHOLDER GOALS IN STRUCTURAL FIRE DESIGN OF STEEL-FRAMED BUILDINGS

by

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Abstract

When designing a steel-framed building, there are many design options available in terms of meeting the structural fire resistance objectives. Different stakeholders have different opinions about which approach is the most appropriate. A tool or procedure is needed that allows the integration of these diverse stakeholder desires to achieve the most appropriate option. Hence, this research aims to develop this tool.

Firstly, extraction and understanding of stakeholder views, along with the capacity to rank them, are needed. However, the challenge is that there are many stakeholder views, so there is also the need to manage these views without ignoring any of them. Towards that some tools are identified in this work to manage different and sometimes divergent stakeholder views to rank them for appropriate decision making.

Secondly, to achieve consensus on multiple stakeholder views, the Weighted/Geometric Mean Method (W/GMM) is investigated. Decision analysis techniques including Analytic Hierarchy/Network Processes (AHP/ANP) and Technique of Order of Preference and Similarity to Ideal Solution (TOPSIS) are also studied to understand the influences of stakeholder views on competing design options and to rank the options in the decision-making process.

Thirdly, to critically assess the ranking of the design options, a parametric study is needed to predict the suitability and cost-benefit of the various available options. This is carried out by probabilistic analysis of typical structural steel members considering varying parameters and limit state criteria. A probabilistic cost evaluation is also included. Hence, a hybrid design decision analysis tool is developed for the integration of the assessment outcomes to enable the identification of the most cost-effective design option.

The final part of this work takes a case study of a realistic building and demonstrates how the process can be applied to structural fire design. This is carried out by integrating and synthesising views from chartered stakeholders and outcomes of the parametric study on representative steel members of the building using the developed hybrid decision analysis tool. The case study follows a risk-based structural fire design decision-making procedure.

Acknowledgement

I am grateful to God for granting me life, the opportunity and strength to achieve this research project.

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To my dear and lovely daughter, Charissa Uzoamaka Aroha Akaa, your birth at the time of writing this thesis brought great joy and more energy toward its successful completion.

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List of Abbreviations

AHP – Analytic Hierarchy Process

AMM – Arithmetic Mean method

ANP – Analytic Network Process

ARC – Architects

AS/NZS – Australian and New Zealand Standard

ASI – All Stakeholder Involvement in Design

BA – Building Aesthetics

BC – Business Continuity

BCA – Building Consent Authorities

BCT – Building Contractors

BDO – Building Owners

BI – Building Insurers

BOCR – Benefits Opportunities Costs and Risks

BRA – Building Regulation Approval

BST – Board Systems

BUF – Building Use and Features

CA - Constructability

CBD – Central Business District

CDD – Clarity in Design Details and Specifications

CES – Concrete Encasement of Steel

CFD – Computational Fluid Dynamics

CI – Consistency Index

COV – Coefficient of Variation

CPT – Compartmentation

CR – Consistency Ratio

DM – Decision-Maker

EAC – Environmental Act Compliance

EGP – Extended Goal Programming

ELECTRE - Elimination et choix traduisant la realité

ES – Environmental Sustainability

EVP – Environmental Professionals

EU – End Users

FE – Fire Engineer

FFO – Fire Fighting Operations

FPFP – Fire Protection Failure Probability

FPOC – Fire Protection Costs

FPP – Fire Protection Products

FRA – Fire Risk Assessment

FRM – Financial Risk Management and Loss Prevention

FRR – Fire Resistance Rating

FSC – Fire Spread beyond Compartment

FSB – Fire Spread beyond Building

FSP – Fire Service Personnel

GAT – Geometric mean method + Analytic Hierarchy Process + Technique for order of preference and similarity to ideal solution

GMM – Geometric Mean Method

HC – Human Comfort

HS – Health and Safety

HSNO – Hazardous Substances and New Organisms

ITC – Intumescent Coating

MA - Maintainability

M&S – Manufacturers and Suppliers

MMU – Minimum Material Use

MSC – Maintaining Supply Chain

MBIE – Ministry of Business Innovation and Employment

MCDA – Multi-Criteria Decision Analysis

MCS - Monte-Carlo Simulation

MLV – Most Likely Value

NZFS – New Zealand Fire Service

OTR – Others

PCA – Principal Components Analysis

PDF – Probability Distribution Function

PF1 – Pre-Fire Building Resilience

PF2 – Post-Fire Building Resilience

PM – Profit-Making

PROMETHEE-1&2 – The Preference Ranking Organisation Method for Enrichment Evaluations Version 1 & 2

RCI – Random Consistency Index

SCM – Sprayed on Cement-based Material

SE – Structural Engineers

SFR – Structural Fire Resistance

TOPSIS – Technique for Order of Preference and Similarity to Ideal Solution

UPS – Unprotected Steel

VIKOR – VIseKriterijumska Optimizacija I Kompromisno Resenje (*Multi-criteria Optimisation and Compromise Solution*)

WAMM – Weighted Average Mean Method

WGMM – Weighted Geometric Mean Method

WSM – Weighted Sum Model

WPM – Weighted Product Model

Notations

a	the number of decision makers in geometric mean judgement aggregation;
B_i	the benefit preference score of the competing options;
c_a	the specific heat of steel (J/kg.K);
c_i	the specific heat of fire protection or insulation material (J/kg.K);
C_i	the cost preference score of the competing options;
CI	the consistency index of pairwise compared judgements;
C_i*	the relative closeness to the ideal solution in the hybrid decision analysis;
CR	the consistency ratio of pairwise compared judgements;
e_f	the fuel load density (MJ/m^2 of floor area);
f_y	the yield strength of steel at 20 °C (MPa or N/mm^2);
Hp/A	the steel section factor (m^{-1});
k_b	the factor for compartment linings;
k_i	the thermal conductivity of fire protection or insulation material (W/m.K);
k_i*	the effective/apparent thermal conductivity of intumescent coating (W/m.K);
k_m	the structural material factor;
L	the steel column length;
L_{fi}	the steel column buckling length in fire;
$M_{fi,ED}$	the beam moment demand in fire condition;
N	the number of probabilistic analysis iterations in a simulation;
$N_{b,fi,t,RD}$	the design buckling resistance at time t of a compression member;
$N_{fi,D}$	the axial load on steel column;
O	the competing decision options;
p	the p^{th} decision-maker with weight represented as α_p;
P_f	the probability of failure;
$q_{fi,ED}$	the total action (load) on beam (kN/m);
r_{ij}	the normalised element in a decision matrix of option i with respect to criterion j;
R_c	the structural fire resistance capacity from reliability theory;
RCI	the random consistency indices corresponding to number of decision-makers;
R_d	the demand fire resistance from reliability theory;
R_m	the structural fire resistance safety margin from reliability theory;
S	the plastic section modulus of steel section;
S^*	the hypothesised ideal solution in the hybrid decision analysis;

S'	the hypothesised negative ideal solution in the hybrid decision analysis;
t	the time (min);
T_s	the steel temperature
w_j	the importance weights of the j^{th} decision attribute
w_f	the ventilation factor;
$z_{ij}^{[G]}$	the aggregated judgements for the compared criteria or options i and j;
$Z^{[G]}$	the geometric mean of the group;
θ	the gas temperature (°C);
ρ_a	the density of steel (kg/m^3);
ρ_i	the density of fire protection or insulation material (kg/m^3);
x_{ij}	the score of competing option i with respect to criterion j;
λ_{max}	the mean of normalised new performance scores decision attributes.

1. INTRODUCTION

1.1. Decision-Making in Structural Fire Design of Steel-Framed Buildings

Decision-making is a constant activity in our everyday lives which include simple and complex decisions. Simple decisions (e.g. deciding on a time to sleep, eat, etc.) involve few variables for consideration while complex decisions (e.g. deciding on whether to build or buy a house) may consist of a combination of many influencing factors, interests/preferences and uncertainties. For every problem, human beings must analyse different solutions or options before a decision is made. Saaty (1994a) opines that given conflicting factors (e.g. socio-political, environmental and others), human beings make judgements based on their know-how, experience or outcomes of costs-benefits/risk analysis. These bases of human judgements are also instrumental in deciding among solutions to a problem that has multi-attributes, whereby a decision-maker is expected to compare these attributes to assess the advantages and disadvantages of the various solutions. However, some conflictual multi-attributes in decision-making processes may defy simple solutions and would need some form of a robust balancing act.

For instance, a company wants to buy a mobile phone out of these options, Samsung S8, iPhone-X and HTC-U11 for each of its executive directors. Each executive director may have their respective preference. However, they may qualitatively assess each mobile phone by weighting them against their conflicting interests, which may include durability, cost, memory capacity, etc., as well as the company's goals to achieve a balanced decision. Here, buying a suitable mobile phone for the business is the goal. Durability, cost and memory capacity are the decision attributes, while, the Samsung, iPhone and HTC phone brands are the competing options. Decision-making techniques can suitably combine the decision attributes with respect to the goal to rank the competing options and support the company's decision.

In another instance, to choose a ten-year central business district (CBD) road management strategy, given two distinct strategies: maintenance *(i.e. keeping the road functioning above its minimum required service level*) or renewal (*i.e. refurbishing the road to restore it to a specific service level*). The relevant city council stakeholders (decision-makers) may have varying views and preferences with respect to safety, socio-economic factors, etc. Also, condition assessments of the CBD road may produce variable quantitative data on deterioration levels, e.g. roughness, cracking, failure probabilities, etc. The varying stakeholder views and road assessment outcomes give room to uncertainties which may influence decision-making. Hence, the stakeholders may need to balance or optimise their road management strategy/investment decision through the combination of their qualitative views and quantitative road assessment outcomes. Here, choosing the right strategy is the goal, the options are maintenance and renewal; safety, socio-economic factors and failure probabilities from the road assessments are decision attributes that may be aggregated for optimal decision-making. The decision-making techniques that help in solving this type of problem can be applied to structural fire design decision-making problems.

The fire design of buildings will typically need to consider the ability of the structure to resist the effects of fire. This requires critical decision-making on suitable structural system design and/or selection of appropriate passive fire protection. For instance, in steel building designs, the use of moment resisting frames provides significant redistribution of forces to enhance fire resistance. The design of the structure may then include plastic analysis of the frame to predict its failure (formation of plastic hinges) in fire conditions. Notably, an unprotected structure may be considered inadequate in fire conditions compared to protected steel and reinforced concrete structures. However, several studies on steel structural behaviour in fires have shown that unprotected steel members can resist severe fires without collapse if the structural system is optimally designed; hence such a system may be considered as a structural fire design option. Applied passive fire protection options are also available to designers to achieve fire resistance. These include intumescent coatings, board systems (gypsum plasterboard, etc.), concrete encasement of steel (full or partial), sprayed on cement-based insulation. These options are considered to achieve the same fire response objectives given specific fire resistance requirements. However, design decision-makers may have varying opinions on how long each option may stay in place throughout the life of the building. Hence, their ability to stay in place in fires among other design decision attributes, e.g. cost-effectiveness, maintainability etc., may need to be assessed and established.

Furthermore, stakeholder decision-making on selecting the most suitable fire protection for steel buildings are critical to addressing design and construction uncertainties. There are multidisciplinary stakeholders involved in various stages of the structural fire design decision-making processes among conflictual decision criteria. The stakeholders are faced with the challenge of managing their divergent opinions, varying interests and preferences to make design decisions. In many practical scenarios, some stakeholders may lean toward a design decision criterion, e.g. economy or one stakeholder among others may have a dominant influence in the decision-making process. The stakeholders may collaborate as a group needing suitable consensus and optimisation of their decision toward accounting for design decision uncertainties. The combination of their qualitative views and quantitative analysis of ‘competing’ design options through decision synthesis can help approach a balanced design decision.

This research project investigates the stakeholder decision-making process around the selection of applied passive fire protection measures for the design of steel-framed buildings exposed to post-flashover fires. This is achieved by extracting qualitative stakeholder views on fire protection of steel-framed buildings, along with analysing these views and inherent structural fire design uncertainties to rank them for suitable decision-making. Importantly, the design of steel-framed buildings exposed to post-flashover fires is mainly used in this research to test the decision-making process/techniques in general and in a virtual case study.

1.2. Research Motivation

As mentioned earlier, there are many stakeholders involved in the fire design of a building, e.g. building owners, architects, structural engineers, fire engineers, building contractors, end users, etc. These stakeholders often have divergent opinions with respect to design decision criteria such as safety, economy, environmental and societal considerations toward the selection of the most suitable option. For instance, architects are keen on building aesthetics and prefer the use of intumescent coated or unprotected steelwork due to their aesthetic appeal (Meacham, 2000). In contrast, the structural engineer could recommend partial or full concrete encasement of steel which eliminates the disadvantages of intumescent coatings such as adhesiveness and non-uniform thickness but may increase the weight of the structure (Buchanan and Abu, 2017). Each of these options will likely have different costs regarding design, installation and maintenance. The divergent views of fire engineers and other practitioners in the fire industry during the 2014 New Zealand Ministry of Business, Innovation and Employment (MBIE) open stakeholders’ forum (MBIE, 2014a) give further credence that steps need to be taken towards an agreed decision-making process within the fire engineering design context.

The varying interests of multiple fire design stakeholders, the use of different fire protection options and design codes may lead to design uncertainties in achieving steel structural fire design adequacy. Given the different stakeholder categories and inherent multiple attributes of design decision problems, there is the need to develop a quality decision analysis technique which can extract and manage divergent stakeholder opinions without overlooking anyone. This will help manage fire design stakeholder desires, reduce design uncertainties and achieve balanced or optimised design decision-making.

1.3. Research Objectives

The key objectives of this research project are:

(1) To identify and balance the views of stakeholders to select the most appropriate applied passive fire protection for steel buildings exposed to post-flashover fires.

The sub-goals under this objective are:

- i. To investigate the effect of aggregating individual stakeholder views extracted at different times and places against getting stakeholders in one room to rank decision options in a structural fire design decision-making process.
- ii. To obtain suitable stakeholder weights to account for the stakeholders' influences on design decisions for steel-framed buildings.
- iii. To demonstrate the viability of using decision analysis techniques to integrate qualitative stakeholder views and quantitative structural fire design analysis toward selecting cost-effective design options.

(2) To develop a suitable stakeholder decision-making procedure and tool to reduce design decision uncertainties given unbalanced stakeholder goals.

Stakeholders involved in fire engineering and structural fire designs that make up the consulting and building industries shall be the primary beneficiaries of this research. Other associated organisations such as insurance companies and regulatory authorities are also potential beneficiaries, as their goals and preferences are considered in this work.

1.4. Scope of this Research

Given the key research objectives, this research project is divided into four stages as shown in Figure 1.1.

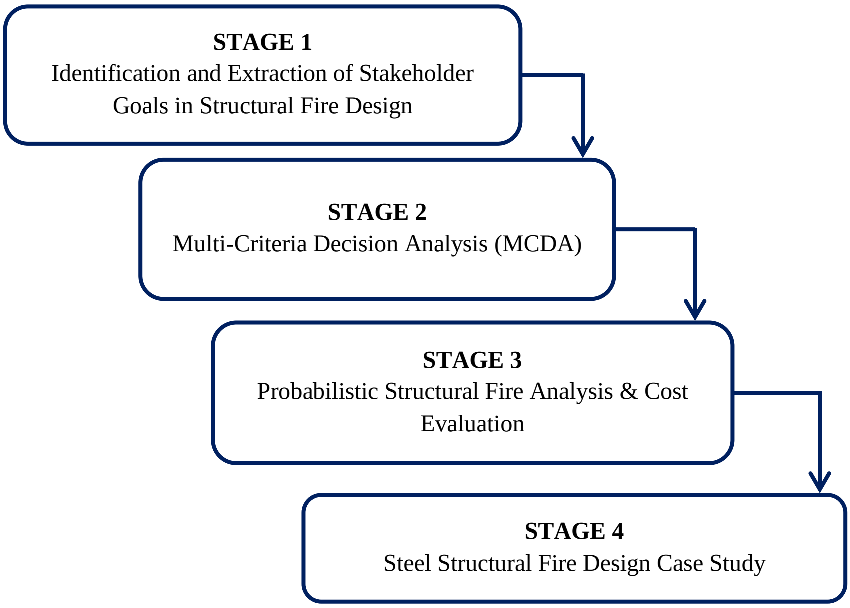

Figure 1.1. Research flowchart.

The first and second stages of this work will extract stakeholders' views through structured interviews and use decision analysis techniques to manage the different stakeholder desires and to rank them. Probabilistic structural fire analysis and cost evaluation of the ranked options are carried out to predict their suitability and cost-benefit. The structural fire analysis is conducted according to Eurocode 3 Part 1.2 (BSI, 2005a). The final stage of this work takes a case study of a realistic steel-framed building and demonstrates how the decision-making process can be applied to the design of the building.

The following stages and tasks are carried out to achieve the objectives of this research:

Stage 1: Identification and extraction of stakeholder goals in structural fire design

Tasks:

i. A literature search is conducted to identify fire design stakeholder categories, structural fire design decision attributes and potential decision analysis tools.
ii. A stakeholder management framework consisting of a stakeholder engagement plan and decision analysis processes is developed according to risk management guidelines of AS/NZS ISO 31000:2009.
iii. A 'goal rating document' using the design decision attributes and tools extracted from the literature is also developed.
iv. The developed framework in conjunction with the goal rating document is applied to extract fire design stakeholder views through interviews. Initially, the process is tested

on quasi-stakeholders (i.e. non-chartered/inexperienced stakeholders) and then implemented on chartered/experienced stakeholders.

Stage 2: Multi-criteria decision analysis (MCDA)

Tasks:

i. The stakeholder decision analysis tools are set up. This entails developing decision matrices using the structural fire decision attributes extracted in Stage (1).
ii. The extracted stakeholder judgements from the interviews are entered into the set-up decision analysis tools, and multi-criteria decision analysis (MCDA) is performed using the appropriate MCDA techniques to obtain ranked fire protection options.
iii. The viability of the various MCDA tools applied to the extracted stakeholder judgements is also investigated to develop a suitable MCDA technique.

Stage 3: Probabilistic structural fire analysis and cost evaluation

Tasks:

i. Deterministic structural fire analysis of a representative simple steel member is conducted using the ranked options in Stage (2).
ii. The input parameters of the deterministic analysis are defined as probabilistic distributions to evaluate failure probabilities of the ranked fire protection options.
iii. The deterministic and probabilistic analyses on actual costs of the competing fire protection options are also conducted.
iv. The failure probabilities and actual costs of the competing options are then integrated into an enhanced MCDA technique.

Stage 4: Steel structural fire design case study

Task:

i. A realistic steel-framed building is considered in the application of the stakeholder management framework in Stage (1) on selected experienced fire design stakeholders.
ii. The stakeholder judgements on the fire protection of the case study building are analysed using the researched MCDA tools.
iii. The stakeholder judgments and probabilistic study on representative steel members of the building are synthesised to support suitable design decision-making using the enhanced MCDA technique.

iv. A risk-based steel structural fire design decision-making procedure that follows the guidelines of AS/NZS ISO 31000:2009 is proposed.

1.5. Organisation of the Thesis

This thesis has nine chapters. The chapters are organised to firstly provide overviews and reviews of relevant concepts considered in the research as well as outcomes from the various investigations carried out in this research. Parts of several chapters have been published as conference or journal papers. A full list of publications this research has produced is given at the end of this chapter.

Chapter 1 briefly introduces this study by presenting its background, motivation and scope.

Chapter 2 presents an overview of stakeholder decision-making and steel structural fire design. The literature review examines processes in structural fire design by contrasting New Zealand design with the Eurocodes. Furthermore, this chapter summarises preceding research on fire design stakeholders and goals in a fire engineering decision-making process.

Chapter 3 presents discussions on decision theory and decision analysis. It also provides relevant multi-criteria decision analysis techniques adopted for this research project.

Chapter 4 presents the first stakeholder management framework developed in this study and a test of the framework as well as stakeholder decision-making process through a pilot study. Importantly, the effectiveness of one MCDA technique, the Analytic Hierarchy Process (AHP) is tested on judgements of stakeholders having few years of fire engineering experience. This chapter has been reported in Publication No.1 (see Section 1.6).

Chapter 5 builds on the success achieved in Chapter 4 and reports preliminary fire protection ranking achieved by applying the framework and AHP on large judgements of chartered and experienced fire design stakeholders. Parts of this chapter have been reported in Publication No. 2.

Chapter 6 presents the application of a generalised technique to the AHP known as Analytic Network Process (ANP). ANP is thoroughly investigated using the proposed framework from Chapter 4. The results of applying ANP to an expanded sample set of fire design stakeholder judgements are discussed. Notably, parts of this chapter have been reported in Publication Nos. 3 and 4.

Chapter 7 presents a hybrid-MCDA technique, "GAT", which is a joint implementation of Geometric Mean Method (GMM) + AHP + Technique for Order of Preference and Similarity to Ideal Solution (TOPSIS). This chapter demonstrates the viability of the tool in integrating qualitative stakeholder judgements, quantitative probabilistic structural fire analysis outcomes and fire protection costs toward appropriate ranking of fire protection options. Parts of this chapter have been reported in Publication No. 5.

Chapter 8 reports on the application of the stakeholder decision-making framework and decision analysis techniques on a case study steel portal-framed building. Importantly, the application of GAT in the decision-making process for the case study building is demonstrated.

Chapter 9 presents a summary of the research findings, limitations, recommendations, areas for future research and conclusion.

1.6. Publications Associated with this Research

1. Akaa, O.U., Abu, A., Spearpoint, M. & Giovinazzi, S. (2015). Balancing stakeholder views for decision-making in steel structural fire design. In *Proceedings of 2nd International Conference on Performance-Based and Life-Cycle Structural Engineering*, 983-992. https://doi.org/10.14264/uql.2016.535
2. Akaa, O.U., Abu, A., Spearpoint, M. & Giovinazzi, S. (2016). A group-AHP decision analysis for the selection of applied fire protection to steel structures. *Fire Safety Journal*, *86*, 95 – 105. https://doi.org/10.1016/j.firesaf.2016.10.005
3. Akaa, O.U., Abu, A., Spearpoint, M. & Giovinazzi, S. (2016). Decision analysis of stakeholder views in the design of steel structures in fire, Proceeding *of ISPE International Conference on Transdisciplinary Engineering: crossing boundaries*, Curitiba, Brazil, 4: 523 - 532. IOS Press Ebook Online http://ebooks.iospress.nl/volumearticle/45435
4. Akaa, O.U., Abu, A., Spearpoint, M. & Giovinazzi, S. (2017). Group-analytic network process for balancing stakeholder views on fire protection of steel-framed buildings. *J Multi-Crit Decis Anal. 24: 162 – 176.* https://doi.org/10.1002/mcda.1607
5. Akaa, O., Abu, A., Spearpoint, M. & Giovinazzi, S. (2017). Optimising design decision-making for steel structures in fire using a hybrid analysis technique, *Fire Safety Journal*, 91, 532-541. https://doi.org/10.1016/j.firesaf.2017.03.018

2. STAKEHOLDER DECISION-MAKING IN STRUCTURAL FIRE DESIGN

2.1. Structural Fire Safety of Steel Buildings

Fire can induce catastrophic impact on the built environment and society. This is exemplified by the devastating effects of past major fires such as the construction fire of Broadgate phase 8 London in 1990 (which had a duration of 4.5 hours and caused severe structural deformations, but no collapse of the building), February 1991 One Meridian Plaza fire in Philadelphia, USA (which went on for 18 hours and caused structural damage to 9 floors) and Windsor fire, Madrid, Spain in 2005 (which went on for 18-20 hours and caused partial collapse of the building). Notably, the Broadgate fire led to studies looking at how much steelwork needs protection against fires; the Windsor fire led to a better understanding of the partial collapse of reinforced concrete buildings in fire conditions (Fletcher *et al*. 2006). Evidently, these accidental and incidental structural fires in modern history exemplified the need for fire safety. Lessons learned from these events formed the basis of early strategies employed in fire risk mitigation for buildings (Wang *et al*. 2013).

Fire safety is one of the fundamental necessities in the design and construction of steel-framed buildings and other infrastructural facilities with the aim to reduce to an acceptable risk level the loss of life, property and environmental damage. This entails the determination of fire risk levels (i.e. likelihood and impact of fire) at the initial design stage followed by the selection of appropriate measures to sufficiently meet the design objectives. Figure 2.1 shows a typical fire development process represented as a temperature-time curve. Over a period, fire can grow from a small ignition to full-room involvement and then decay when sufficient combustible material has been consumed.

In designing buildings for life safety, the knowledge of fires is highly essential. Fire development starts with single item ignition and terminates with complete burnout of items or an entire room. Pre-flashover fires refer to fires that generally start with burning an item, spreading to other items which then grow in size and intensity. The transition from a small growing fire to full-room involvement is known as flashover. Flashover can also be defined as the near-concurrent ignition of directly exposed combustible materials in an enclosed space. In building compartments, fire growth can increase to the fully developed stage, at which point all combustible materials in the compartment are involved in burning. The fully developed fire could be (a) a fuel-limited fire (b) a ventilation-limited fire or sometimes called post-flashover fire (c) a travelling fire. Of primary interest to structural fire design of buildings is the post-flashover phase of fires. This is regarding property protection and safety of fire-fighters. Post-flashover fires are known to constitute radiant heat fluxes and highly elevated temperatures that affect structures. Importantly, post-flashover is not a characteristic of all fully-developed fires as some fires can extinguish naturally without reaching flashover due to insufficient fuel or inadequate ventilation to support continued burning. In addition, some fires may not reach flashover because the compartment may be too large to support near simultaneous ignition of all items.

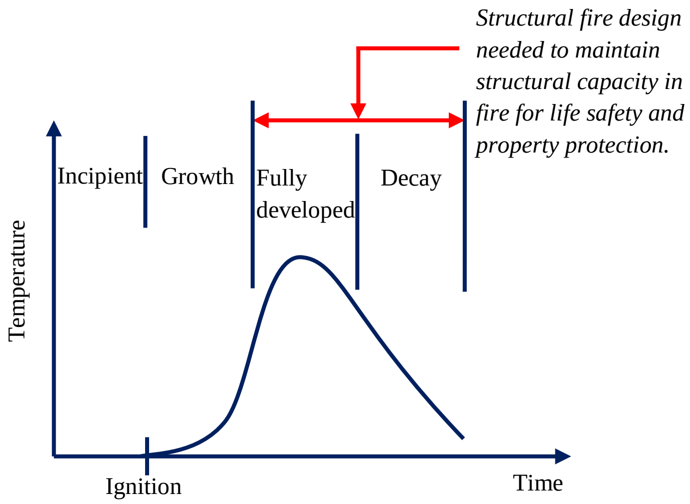

Figure 2.1. A typical fire development process adapted from (Buchanan and Abu, 2017).

In characterising post-flashover fires for structural fire analysis, conventional design fires including the standard fire curve (ISO 834) and parametric fires (BSI, 2002a) have been used for many years. The conventional fires have been criticised in the literature as not representing the worst-case scenario of fires due to the assumption of uniform burning and homogenous gas phase temperatures (Stern-Gottfried, 2011). Gales (2014) mentioned that structural fire designs are overtly simplified with the use of conventional fires without considering more destructive ones, such as travelling fires. Notably, Stern-Gottfried (2011) investigated the use of travelling fires to develop real fire scenarios for structural fire analysis and highlighted the effects of ‘far-field’ temperatures on structures of larger compartments. Nevertheless, the knowledge and application of travelling fires currently remain evolving in the structural fire design environment.

Modern facets of fire safety in buildings include: preventing fire ignition through fire risk management, fire detection, and provision of warning to building occupants, provision of adequate escape routes, fire growth and spread management, enhancing fire-fighting operations as well as averting building collapse (Yung, 2008). In some cases, these fire safety goals can be achieved through timely detection and suppression with automatic sprinklers. However, during a severe/fast-growing fire, the control of fire spread, protection of adjacent buildings and prevention of building collapse will necessitate fire resistance of structures and fire barriers (Buchanan and Abu, 2017). In this case, the fire is resisted with passive protection measures which are applied systems/products in the structure and fabric of buildings.

2.2. Overview of Structural Fire Design

Structural fire design entails the analyses and detailing of structures such that they can resist the effects of severe or destructive fires. It requires the prediction of realistic temperatures and structural response in fire conditions (Abu, 2014). A key measure of satisfying this design is to establish that the fire resistance of structural elements is higher than the equivalent fire severity to which the elements are exposed.

According to CIB (1986), building structures should be suitably designed to fulfil the following: load bearing capacity, separating function, maintainability and rectifiability (i.e. capable of being repaired). The load-bearing capacity of a building will entail the potential to withstand all loadings ranging from imposed to accidental loads (fire or temperature loads). In this case, the structural system of the building should adequately resist fires thereby reducing the possibility of partial or total building collapse significantly. The separating function implies that the different partitions of each fire compartment must meet adequate thermal insulation and integrity in the event of a fire (MBIE, 2014b). Given that incidental fires may damage parts of a building, the design for structural capacity must consider the need to reduce possible business interruption and cost of rectification and maintenance. Notably, the design for structural fire resistance may largely depend on a building owner’s personal goals and the required level of structural fire resistance set by the design jurisdiction. Hence, some buildings may be designed to have nominal fire resistance. In this case, it is acceptable that there is complete collapse during a fire.

Generally, in structural fire design, a fire model is used to determine the temperatures in the building compartment. The temperatures that develop in the building structure are analysed with a thermal model, and the mechanical response of the structure is determined through structural analysis. The outcomes of these analyses are expected to meet established design standards and/or performance criteria as well as provide sufficient information for appropriate structural detailing for the building.

2.2.1. Prescriptive and performance-based structural fire design

Building designs for fire safety can be achieved by adopting either a prescriptive or a performance-based approach. The prescriptive approach refers to established rules by regulatory agencies for design compliance to life safety, property, and environmental protection. However, the rules are often deficient in clear objectives (Hadjisophocleous and Benichou, 1999). In contrast, the performance-based approach clarifies the objectives and allows freedom in the choice of rational solutions for meeting the fire safety objectives. Currently, the performance-based approach is widely adopted in several jurisdictions around the world (Bukowski, 1997) due to its flexibility in demonstrating fire safety performance of buildings irrespective of the building's structural material, e.g. concrete, steel or timber. It is noteworthy that there are a number of possible disadvantages of the performance-based design codes. These might include: the need for new techniques and methods; increase in design time and cost; the need for better expertise and expense in retraining designers and design approval uncertainties experienced in some jurisdictions. However, Ramsay (1988) opines that the prescriptive approach may be used alongside a performance-based code to achieve optimal fire safety design, considering a positive benefit-cost outcome in designing a building.

2.2.1.1. New Zealand (NZ) building code and its compliance document

In the New Zealand building code (DBH, 2012), the requirements for protection from fire are stated in clauses C1, C2, C3, C4, C5, and C6. Clause C1 summarises the key objectives of clauses C2-C6 for fire safety designs in New Zealand. These are: to protect human life from unsuitable risks in the event of a fire, to protect neighbouring buildings from fire damage, and to ensure safe fire-fighting operations. Notably, a building owner's property protection and environmental considerations are not mentioned in the code. Clause C6 contains the functional and performance requirements for structural fire stability. The functional requirement section states the requirements for life protection (building occupants, fire-fighters and anyone near the building). While the performance section mainly states the requirements for the stability of structural systems in buildings regarding safe access during fire-fighting operations, collapse onto neighbouring properties and prevent the consequential collapse of building elements expected to have a higher level of fire resistance.

The compliance document for clauses C1 – C6 (MBIE, 2014b) provides more information and is considered as one of the different means of achieving fire safety. For instance, fire resistance rating (FRR) is described by three numbers that account for the nominal performance of a building element on exposure to the standard fire. These are *structural adequacy*, *integrity* and *insulation* (e.g. 60/30/30 respectively). This is in line with other countries having building codes based on fire testing. The three FRR indicators are applied in structural fire design depending on the purpose of the building elements. The *structural adequacy* criterion refers to the supporting ability of the building elements in any loading condition, which applies to primary elements, i.e. load bearing elements such as beams, columns and slabs. The *integrity* criterion refers to the ability of the building element to prevent transmission of flames or hot gases through it. Such transmission can occur due to the existence of cracks, gaps or holes on the element. This criterion applies mostly to secondary elements (i.e. non-load bearing elements), e.g. some fire separation walls but also applies to slabs and load-bearing walls. The primary and secondary elements are to satisfy the *insulation* requirement, which refers to the building elements' ability to provide sufficient barrier between adjacent fire compartments ensuring limited heat transmission. Notably, Part 4.3.1 of the acceptable solution C/AS4 (MBIE, 2014b) which provides a means of compliance to the building code requires primary building elements to retain their FRR throughout fire duration to prevent early failure. This also includes primary elements within a firecell and those providing support to fire separations.

The term 'fire resistance' is a measure of the ability of a building element/component to withstand a specified fire severity without collapse as well as prevent fire spread. Fire resistance is assessed in relation to standard fire exposure conditions. This does not equate to real fire performance which refers to the expected behaviour of a building component or assembly in a wide range of fire conditions. Importantly, fire resistance needs to be maintained for a reasonable period of exposure to fires; however, it may not be feasible throughout real fires given the dynamic nature and variabilities in real fires. Notably, the terms (*i.e. fire resistance and fire performance*) have been used interchangeably among fire design stakeholders in New Zealand to mean the resistance of an element exposed to the standard fire for a given duration.

2.2.1.2. NZS 3404 steel structures standard

The behaviour of steel structures in fire conditions is known to depend on: the increase in steel temperatures, steel strength and stiffness, applied loads and support conditions of the steel structure (Buchanan and Abu, 2017; Franssen and Real, 2012). In steel structural fire design, steel temperature increase is dependent on fire severity, the size of the cross-section and the amount of applied fire protection on the steel. The design requirements for steel building elements are laid out in the steel structures standard of New Zealand, NZS 3404:1997. The fire part of the New Zealand steel structures standard NZS 3404:1997 assumes the exposure to the standard fire. As such realistic fire scenarios are treated with the time-equivalence concept by most fire engineers, whereby severity of real fires is related to standard fire tests as shown in Figure 2.2. However, the time-equivalence method has been known to produce different results occasionally. This review highlights one type of time-equivalence concept developed by Law (1971); Pettersson *et al*. (1976), given its relevance to the New Zealand standard.

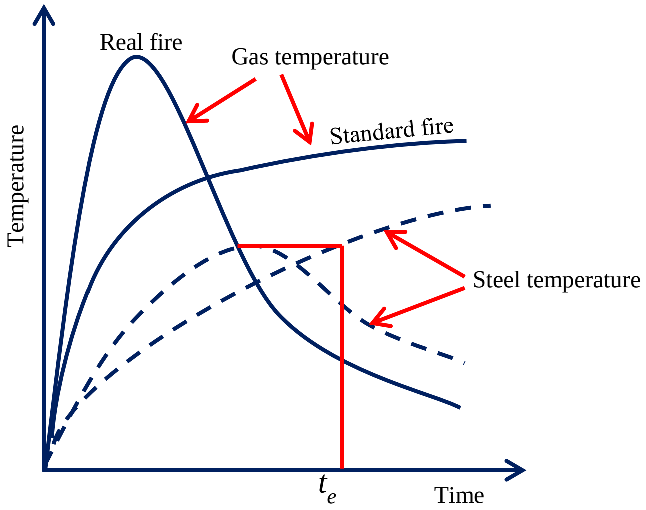

Figure 2.2. Representation of time equivalence based on temperature (Buchanan and Abu, 2017).

In the illustration (Figure 2.2), the equivalent time of exposure to the standard fire is the time at which the protected steel member exposed to the standard fire reaches the maximum temperature of that same protected steel member exposed to a real fire. The standard fire curve (ISO 834) is expressed as:

$$\theta = 20 + 345\log(8t + 1) \tag{2.1}$$

Where: θ represents the gas temperature (°C), and t represents time (minutes).
Hence, time equivalence is determined by the following expression:

$$t_e = e_f k_b k_m w_f \tag{2.2}$$

Where: e_f represents fuel load density (MJ/m^2 of floor area); k_b represents the factor for compartment linings; k_m represents structural material factor, and w_f represents ventilation factor (CIB, 1986).

Wong (1999) reported that structural analysis of building elements could be carried out in the time domain if the FRR needed for structural steel member is known. In this domain, the time to reach limiting temperature is compared to the time equivalence of fire severity given in Equation 2.2.

Importantly, the New Zealand fire design philosophy entails that the fire engineer will firstly carry out an early fire hazard check given conceptual pre-flashover fire consideration. The fire engineer then defines a compartment to determine FRR by idealising a parametric fire and converting it to the standard fire using the time equivalence equation (Equation 2.2). Afterwards, the fire engineer recommends to the structural engineer the desired FRR for the structural member/s. The structural engineer then determines the structural fire capacity based on limiting temperature and loading actions on the member/s. The conceptual steel structural fire design effectively considers post-flashover fires whereby the time equivalence approach is used to calculate FRR following the standard fire. The structural engineer ensures that fire protection is provided for the steel members to meet the specified FRR.

The structural fire design philosophy of the New Zealand steel structure standard has been criticised in the literature. Graham and Willard (2013) reported that the New Zealand standard have some issues which include the reliance on the standard fire curve. The standard fire curve was adjudged as a curve achieved from a thoroughly controlled furnace, which has limitations in modelling a real fire. The illustration of a real and parametric fire is shown in Figure 2.3. Real fires are understood to transit from growth to decay stage as shown in Figure 2.1, but a parametric fire is an idealised real fire without a growth stage and considered as a post-flashover fire. Although the use of standard fires has been criticised, Eurocodes consider that in some scenarios of determining thermal actions on steel structures, the use of standard fire curve is appropriate for engineering solution, e.g. structural fire design of single-storey buildings in fully developed fires (Manuals, 2008). Also, there are simple design processes in the Eurocode that have been developed from standard fire test results. The approach in using the standard fire curve for steel structural fire design is detailed in Eurocode 1 Part 1.2 (BSI, 2002a) and Eurocode 3 Part 1.2 (BSI, 2005a).

Graham and Willard (2013) also mentioned the restrictive nature of applying the factors k_b and k_m in the time-equivalent formulae (Equation 2.2) and structural fire design of columns without consideration of buckling effects due to loss of stiffness and strength in fires. Their study suggested a shift from standard fire time-temperature structural fire analysis to capacity-based design (i.e. capacity-time analysis) and a change in the design approach of the New Zealand standard to account for the rapid reduction in stiffness of columns at elevated temperatures.

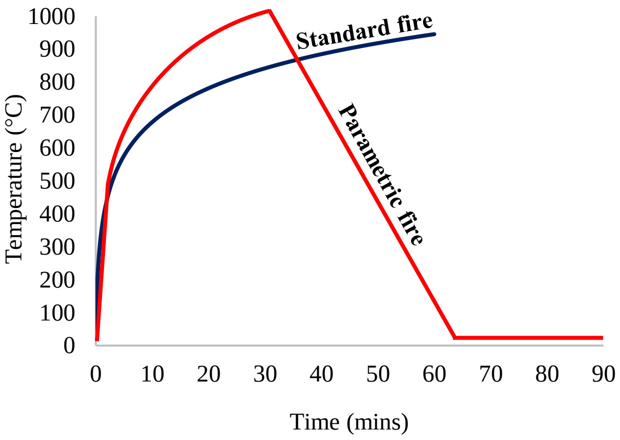

Figure 2.3. Parametric and standard fire curves (SCI, 2016).

2.2.1.3. Eurocodes

In Europe, Eurocodes 0, 1, 3 and accompanying annexes are used for structural fire design of steel structures. Eurocodes 0 and 1 are used for the derivation of characteristic loads (actions) and loading combinations on structures. Eurocode 0 (BSI, 2002b) presents the basis of structural design, including the consideration of different levels of reliability (conversely, failure probability) among other things for structural resistance and serviceability. This includes design measures regarding structural analysis using values of loading actions and partial factors to account for design uncertainties. Notably, Annex B of Eurocode 0 mentions that values of partial factors can be determined from calibrations based on historic/longstanding building experience and/or statistical evaluation of empirical data within a probabilistic framework. Eurocode 1: Part 1.1 (BSI, 2002c); Part 1.2 (BSI, 2002a); Part 1.3 (BSI, 2003); and Part 1.4 (BSI, 2005c) deal with general actions on structures regarding self-weight, imposed loads; structures exposed to fire; snow loads and wind loads respectively. Eurocode 3 (part 1), (BSI, 2005b) deals with general rules for structural or mechanical analysis of steel structures; while, Part 1.2 of Eurocode 3, (BSI, 2005a) specifically presents the general rules used in steel structural fire design. Notably, Eurocodes are performance-based codes; the performance-based approach using Eurocodes can be achieved for both standard and parametric fires. Thermo-mechanical responses of steel structures in fire conditions can also be investigated in different domains using the Eurocodes. The Eurocodes will be used in the structural fire analysis (deterministic analysis) part of this work; the details of the relevant steel properties, design parameters and formulas used in this work are presented in Appendices 3 and 4.

2.2.2. Structural fire analysis

Three successive steps are involved in determining the structural fire response of a building; they are fire analysis, thermal analysis, and structural analysis (Abu, 2014).

Fire analysis

The principal objective of the fire analysis is to assess the fire development and thermal exposure (heat flux, gas temperature) on building structures. Natural fire models (e.g. parametric fires) or the standard fire curve is commonly used depending on the design scenario. Other types of fire models exist; they are dependent on the significance of the fire development (i.e. either localised or fully developed fire) in the compartment and they can be used for fire modelling, e.g. zone and field models [e.g. computational fluid dynamics (CFD)] as shown in Table 2.1.

The simple models are based on experimental evidence; they can be used to predict gas temperatures given localised and fully developed fires. The zone and field models are used for the calculation of the effects of temperature, smoke and fire spread, etc., in a building compartment.

The 1-zone model allows for the assumption of homogenous conditions in modelling a compartment fire. It also uses simplified assumptions, and its application is restricted to fire compartments of simple geometry (e.g. small compartments with small ventilation openings) Manuals, 2008). In using the 2-zone model, the compartment fire conditions follow the smoke separation theory whereby two different layers, upper and lower layers are modelled. The upper layer contains more heat and smoke; while the lower layer is smokeless. The layers are then calculated by simulation to predict gas temperature evolution over time (Tavelli *et al*. 2014).

Table 2.1. Model levels for different fires (Manuals, 2008)

Model levels	**Localised fire**	**Fully developed fire**
Simple model	Hasemi model; Heskestad model	Parametric fires
Zone models	2 zone model	1-zone model
Field models	CFD	CFD

Field models (computational fluid dynamics (CFD) models) are used to model compartment fires based on 3-dimensional configurations, application of conservation laws (e.g. energy, mass etc.) and time-dependence. The fire compartment, in this case, is split into several thousand and often millions of cells depending on its geometry, the needed accuracy and computer speed. Typically, the outcomes of CFD simulations include heat and smoke spread, time of sprinkler and smoke detector activation, flashover time and temperatures in the cells (Manuals, 2008). Importantly, the sophistication and simulation time needed for CFDs are best utilised for complex compartment geometries and are rarely used to predict structural fire performance. However, CFD models can be used to predict fire resistance if the CFD model represents that of a furnace. As mentioned earlier in Section 2.1, a set of travelling fires can also be used to model realistic fire scenarios idealised as two regions of flames and smoke beyond flames (i.e. ‘far-fields’) for large compartments (Stern-Gottfried, 2011). Importantly, it was demonstrated that travelling fires have more severe effects on structural resistance than conventional fully-developed fires. Hence, travelling fires have been proposed as realistic design fires for structural fire analysis.

Thermal analysis

The temperature development or heat transfer to structural members is assessed after a suitable fire model has been selected. Established theory of heat transfer is employed in thermal analysis, given appropriate assumptions and design needs. In the structural fire analysis of steel elements, prediction of uniform temperature across the steel cross-section is allowed (Purkiss and Li, 2013). For standard fire exposure, a hand calculation best-fit-method may be used, or an iterative (incremental) procedure which treats the entire steel cross-section as a lumped mass at a uniform temperature may also be used (Buchanan and Abu, 2017). The lumped mass method can be used with any design fire curve. Advanced computational models based on the finite element or finite difference techniques can also be used to estimate temperatures within cross-sections of 2D and 3D structural steel assemblies. In localised and post-flashover fire conditions, non-uniform temperature distributions may exist along steel structures needing accurate prediction which can be achieved with 2D or 3D thermal analysis. Notably, an understanding of the thermal properties of the steel structure and insulation materials is essential; these properties include density, specific heat, and thermal conductivity. The thermal properties of some insulation materials can be found in the literature (Wang *et al*. 2013; Kodur, 2014; Buchanan and Abu, 2017).

Structural analysis

In fire conditions, the mechanical response of steel structures is determined by structural analysis; this is similar to structural analysis at ambient conditions except that thermal actions, fire limit state gravity loading and reduced material properties of steel at elevated temperatures are considered. Structural analysis may proceed by either the analysis of each structural member or structural component (i.e. part of the building structure) or whole (global) structure.

Eurocode 3, Part 1.2 (BSI, 2005a) provides three methods for assessing the mechanical response of steel members in fire conditions; they are *tabulated method; simple calculation method and advanced calculation method*. The *tabulated method* is based on sets of data, which can be used only for specific members on exposure to the standard fire. The *simple calculation method* applies to steel and composite member analysis and is sub-divided into two calculation methods namely, critical temperature (i.e. calculation in temperature domain) and resistance methods (calculation in strength domain). The advanced calculation method applies to the structural or mechanical assessment of parts or the global structure based on finite element methods, using sophisticated computer software. In the analysis of parts or global structure, several steel members are considered, which provides more clarity on steel structural behaviour, e.g. effects of load redistribution or structural deformations. The designer's decision on the appropriate fire protection material may follow the satisfactory determination of the mechanical response of steel structures in fire conditions.

2.2.3. Steel structural fire protection

Steel is a non-combustible material that has high thermal conductivity, and therefore allows rapid temperature increase in fires. The increase in steel temperature reduces its strength and stiffness, which may cause structural deformations and collapse. At about 500°C, the yield stress and modulus of elasticity which are vital material properties of steel are considerably reduced to 50% – 60%. This implies that the strength of unprotected steel is unlikely to be sufficient to resist applied loads in fully developed or post-flashover fires. There are many options available to steel structural fire designers to achieve fire resistance; one way is to apply passive fire protection materials or products on the steel member. The following passive fire protection measures are discussed by Buchanan and Abu (2017) and Purkiss and Li (2013) as typical options applied to steel structures:

i. Board systems;
ii. Spray-on protection;
iii. Intumescent coatings;
iv. Concrete filling;
v. Brick or blockwork;
vi. Concrete encasement;
vii. Water filling;
viii. Flame shields; and
ix. Use of timber.

Blanket systems have also been described in the steel construction information document, (SCI, 2016) as a fire protection method. Another option is to optimise the structural design and leave the steel structure unprotected. In this review, the summarised descriptions of some applied fire protection options are presented. It is noteworthy that, the applied passive fire protection options and alternative structural fire design of unprotecting steel structures are herein referred to as *Fire Protection Options (FPO)* for the ease of writing this thesis.

Board systems

Most board protection systems are made of gypsum plasterboards, rock fibre bonded by resins, calcium silicate, etc. Calcium silicate boards are made of inert materials and designed to protect the steel member without damage during fire exposure; while the insulation performance of gypsum plasterboards is heightened by the water of crystallisation existing in the material which dries up at elevated temperatures. Boards can be screwed or glued to framing to encase the steel. The key advantages of board systems are: there is no surface preparation needed for its application implying that dry fixing and quick ‘housekeeping’ is guaranteed; thickness is also guaranteed, and board systems can have good visual appeal. The disadvantages of board protection are: high-costs; may need highly skilled labour given the difficulty in fixing it around complex details, e.g. steel brackets; boards are rarely used for cellular steel sections, and as such, they have limited external applications.

Spray-on protection

Cement-based, vermiculite and mineral wool are common spray materials. They are low-cost passive fire protection products which are wet sprayed on steel structures as shown in Figure 2.4. They are easy to cover complex details, unlike board systems. Some of the spray products can be used externally and are often applied on non-primed steel. However, sprays can produce much mess due to their wet application as well as restrict other trades on building construction sites. The poor appearance of sprays on steel buildings is also a demerit which is not suitable for aesthetic purposes. Sprays are soft and may need further protection if used on unsecured building sites.

Intumescent coatings

Intumescent coatings are thin film paints developed specially to swell up when heated and produce protection foam to shield the steel structure as shown in Figure 2.5. Several amounts of coats may be needed to achieve the desired thickness. They can provide a nice visual appeal after their application and can simply cover complex details, e.g. bolted connections. The application of intumescent paints can be fast, does not increase the weight of the structure or take up space and can be applied externally.

Figure 2.4. Cementitious spray application (SCI, 2016).

Figure 2.5. Finished application of intumescent coatings and the result of intumescence (SCI, 2016).

However, the demerits of using intumescent paints include the high-cost implication of aesthetic demands or high thicknesses, wet application on site which may restrict other trades, the ageing effect due to adverse climatic conditions and it may be difficult to use where very high FRRs are required. The unavailability of information on thermal conductivity property of intumescent coatings has been discussed by Wang *et al*. (2013) and Zhang *et al*. (2014), given that most intumescent paints are proprietary products. Hence, its suitability may not be accurately modelled in a structural fire design. Notably, from the stakeholder interviews carried-out in this research, some fire design stakeholders opine that given unpublished thermal conductivities of intumescent paints, their use may depend on the confidence built over time on using a particular proprietary product. Further to this, the stakeholders considered this as a limitation of intumescent coatings given the risk that the 'deemed-reliable product' can be compromised in a pre-fire event e.g. earthquake (i.e. stickability throughout fire duration due to possible professional/production errors).

Concrete encasement of steel

Concrete encasement is one of the oldest and traditional methods of fire protecting steel structures. The key advantages of encasing steel in concrete are: the availability of materials, concrete is weather and impact resistant and may not require special skills in its application. The fire resistance requirement regarding insulation thickness of concrete is available in prescriptive codes. Concrete can also be subtly reinforced or designed as a composite structure in its application on steel structures for fires. Nevertheless, concrete encasement cost is high, its application can be slow on site, and encasing steel columns can take up much floor space and increase the weight of the steel building.

Blanket systems

This type of applied passive fire protection on steel structures is designed to meet the needs of fire protecting complex shapes and details. Given that blanket systems (shown in Figure 2.6) do not require any surface preparation, quick application can be guaranteed.

Figure 2.6. Application of blanket fire protection on structural steel members (SCI, 2016).

The use of the blanket system is also advantageous in scenarios where dry fixing is needed and can also guarantee that the recommended thickness is applied. However, blanket products are mostly limited to internal building environment; blankets do not add to the visual appeal of the building as shown in Figure 2.6 and are rarely used, given the limited number of manufacturers of the product.

Unprotected steel

As mentioned earlier, structural fire designs can be optimised to accommodate unprotected steel structures. This design philosophy became more prominent after the Cardington structural fire tests on a multi-storey steel-framed building. Armer and O'Dell (1997) mentioned that the results from the Cardington tests showed that there was no structural collapse of unprotected steel members even at elevated temperatures up to 1000°C. The attributes of the complex interrelationship of floor/beam systems (*having survived the very high temperatures applied in the Cardington test*) are presented by Buchanan and Abu (2017). In the structural fire analysis of a single steel element, Wong (1999) reported that a steel column of very high mass could absorb a considerable amount of heat and may not attain its limiting temperature in post-flashover fires of around 40 min. The prospects of achieving structural fire resistance without applying fire protection materials on steel would imply a reduction in cost and construction duration, and ensuring aesthetic appeal of the steel building. However, the risk perception and confidence of some stakeholders (e.g. building owners, insurers etc.) to accept the design option of unprotecting a building's structural members are highly tested given inherent structural fire design uncertainties.

2.2.4. Uncertainties in structural fire design

Decisions made at different phases of a design process are affected by uncertainties. This is due to the impossibility of gaining complete and accurate analytic or design information needed at each stage. Undoubtedly, the presence of uncertainties is acknowledged in various design standards with the provision of safety factors for many design conditions as code drafters/writers are aware of design uncertainties and risks either by intuition or perception. Therefore, structural fire design entails guaranteeing that in post-flashover fires there is a very low probability of failure of the building structure (Wong, 1999). Notably, the assessment of reliability (which is the converse of risk or probability of failure) in a limit state design is mostly a method for assessing and mitigating design uncertainties (Lemaire, 2013). Reliability-based design has also influenced the ultimate limit state design principle in many design codes including the Eurocode, whereby failure probability is measured from the difference between structural resistance R_c and load demand R_d as shown in Figure 2.7. The shaded area in Figure 2.7 is considered as the failure region in which the probability of failure, P_f in a normal distribution is less than or equal to zero, i.e. $P\ (R_c - R_d \leq 0)$. Figure 2.7 also shows that reliability index β is another way of expressing the failure of a system based on the failure distance. Importantly, the prediction of P_f and β does not inevitably imply actual rate of structural failure given that real failure rate is significantly dependent on human error (BSI, 2002b). The basic theory including the mathematical assumptions and derivations for reliability analysis can be found in Zhang *et al*. (2013) and Guo *et al*. (2014). In the management of design uncertainties, Eurocode 0 (BSI, 2002b) mentions that historic and probabilistic calibrations may be combined to determine limit state partial factors for loadings and materials. And such that structural reliability levels should be as close as possible to a target reliability index. Reliability index takes into account stochastic uncertainties in the effects of loading actions, resistances and model uncertainties, thereby allowing for comparison of reliability levels of representative structures of buildings. This also entails that a reliability analysis can be carried out to investigate the suitability of a structural system given expected loading actions and uncertainties.

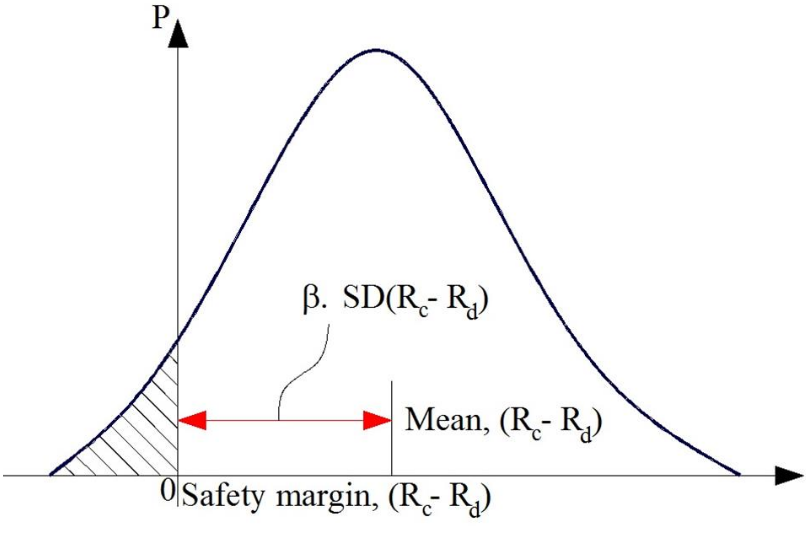

Figure 2.7. Reliability design concept adapted from Lemaire (2013).

Many types of uncertainties exist in different engineering designs; in the design of steel structures in fire conditions, the uncertainties can range from variable parameters (including basic variables, e.g. unit weight, steel density, yield strength etc.) to structural fire model uncertainties (e.g. assumed/adapted calculation values etc.). Melchers (1987) discussed key uncertainties considered in the evaluation of reliability and their interdependencies. In this review, a summary of the relevant uncertainties and brief explanations are given in Table 2.2.

Table 2.2. Summary of relevant steel structural fire design uncertainties (Melchers, 1987; Wong, 1999)

Type of uncertainty	Explanation
Design fire	Refers to the remarkable dynamics of fire phenomenon, which give room for many assumptions and possibilities in structural fire design.
Model	Steel structural models are developed for expected outcomes and are mainly deterministic. Hence, models are susceptible to produce inaccurate results especially in scenarios of different assumptions.
Stochastic	This refers to the uncertainty in the form of the statistical distributions of the considered variables.
Loading action	The variation of loading conditions in fires is inherent uncertainties that may affect structural fire design adequacy. Examples of loading actions, in this case include variance of gravity, live and fire loading actions on steel.
Parameter/property	Material properties of steel are extracted from empirical data which may not represent the exact statistical distributions due to experimental limitations and lack of accurate information, e.g. yield stress and elastic modulus of steel in fires, thicknesses and thermal properties of insulation materials.
Completeness	Inability to fully describe the complexities of the given design problem, or the deliberate omission of some branches of a given design problem.
Estimation	Estimation of structural steel response in fires does not depend only on steel material properties; it also involves designers' knowledge, which may be improved in time or not.
Human error	This is adjudged in the literature as the greatest source of design uncertainty and is divided into gross error (e.g. oversight) and error due to human variability (e.g. human incapability, poor skill, and performance).
Decision	Suitable design decisions largely depend on the mitigation of other design uncertainties. Other kinds of decision uncertainty are within the appropriate use of engineering judgement and cost-benefit analysis outcomes.

In evaluating design uncertainties, different approaches can be considered. An ideal uncertainty measure in engineering design would typically combine, model, statistical, and parameter uncertainties in one system. Ang and Tang (1975) opine that the probability distribution function (PDF) adjudged as the best combination of uncertainty may be insufficient in solving practical problems. Random variables are currently used in the evaluation of uncertainty whereby statistical moments are employed to measure the dispersion of random variables. In this case, normalised calculations using standard deviation and mean of various distributions of random variables give the coefficient of variation (COV) suitable for uncertainty combinations.

The different methods of analysing uncertainties include, among others: Rosenblueth's method (point estimate method); estimation of the first-order variance; and Monte Carlo simulation. Of relevance to this research is the Monte Carlo simulation. This is because Monte Carlo simulation is more preferable to the other methods in terms of the generation of a large number of random variables and the production of model and statistical outputs by iteration. In other words, a typical Monte Carlo simulation simply generates lots of data, computes the uncertainty model a thousand or ten thousand times using randomly selected values from probabilistic functions. In using Monte Carlo simulation, multiple probabilistic outcomes can be compared and the model is customised/combined with respect to different uncertain scenarios. The application of Monte Carlo simulation is also more desirable than other methods due to its ease of sensitivity analysis (i.e. ease of observing the inputs having the most effect on key results) and input correlation (i.e. possibility of modelling interdependent input variables). Notably, the Rosenblueth's method has been shown to have a weaker computational capability albeit it is also adjudged as a method that suitably accounts for skewness of uncertain parameters (Chang *et al*. 1995).

Monte Carlo methods are referred to as stochastic simulations. Halton (1970) defined a Monte Carlo approach as *"representing the solution of a problem as a parameter of a hypothetical population, and using a random sequence of numbers to construct a sample of the population, from which statistical estimates of the parameter can be obtained".* Historically, the Monte-Carlo approach was an expensive uncertainty evaluation technique and therefore a "difficult" method in terms of practical implementation (Rubinstein, 1981). However, the advent of digital computers mainly increased its usage in quantitative risk analysis. Another challenge with Monte Carlo simulation is with its sampling method for the propagation of uncertainty, which typically requires millions of simulations. There are other sampling methods used for uncertainty propagation including random, stratified and Latin hypercube sampling. Latin hypercube sampling has been studied and compared to others. In recent times, the method is most preferred due to its efficiency in stratifying and reducing the number of samples required to perform Monte-Carlo simulations (Helton and Davis, 2003).

The other sampling methods are considerably challenging to implement as they will require the development of empirical and/or alternate models and derivatives which is beyond the scope of this research. In structural fire design, it is possible to use Monte Carlo simulation with reference to a pair of random variables. The random variables represent steel structural demand and capacity used to obtain an output regarding a probability estimation of the structural failure, i.e. when and to what extent demand exceeds the structural member's capacity. Elms (2004) highlighted this capability of Monte Carlo by estimating the probability of failure (p_f) from failure ratios in an iterative process based on randomly chosen samples. The study suggested that this approach could be implemented in limit state structural analysis if probability distributions are defined for chosen variables.

There have been several applications of Monte Carlo techniques in evaluating uncertainties in structural fire design. Wong (1999) studied the reliability of structural fire design through deterministic and probabilistic analyses of case study building structures, which included the evaluation of parameter uncertainties using Monte Carlo simulation. Guo *et al*. (2013) investigated the probabilistic structural fire resistance of a steel beam by combining Monte Carlo and finite element simulation. Recently, Zhang *et al*. (2014) carried out probabilistic structural fire analysis of protected steel columns. In their study, various parameters were defined as stochastic distributions to understand the reliability of intumescent coatings.

The commonest feature in these studies is the characterisation of uncertain parameters as stochastic variables for the probabilistic structural fire analysis, albeit Zhang *et al*. (2014) considered 'professional factor' as a model uncertainty for maximum steel temperature and steel buckling temperature in a parametric fire. The studies also relied on characterisations of parameter uncertainties in the literature. For instance, the statistical characterisation of variable load, fire load density, thermal absorptivity and material properties of applied fire protection on steel can be found in Iqbal and Harichandran (2010). Thermal conductivity, k_i of sprays and gypsum materials are characterised as lognormal distributions; while thermal absorptivity for normal and light-weight concrete is characterised as normal distributions. These associated statistical distributions were obtained from the analysis of raw experimental data. Iqbal and Harichandran (2010) also mentioned that the reported distributions for live, dead and fire loads were taken from the literature. The availability of statistical data has remained a challenge in evaluating uncertainties in structural fire design as exemplified by the many unknown distributions presented in the uncertainty parameter table in Guo *et al*. (2013). This will mean that some relevant parameters remain deterministic while others are defined as statistical variables in the probabilistic analysis. This may be adjudged as the case in the statistic characteristics table presented in Zhang *et al*. (2014). In other cases, statistical characteristics of uncertain variables are assumed if rational reasons for the assumptions are provided (e.g. Wong, 1999). Nevertheless, statistical approaches in structural fire design can provide rational outcomes; hence, the unavailability of statistical data may not be a reasonable excuse to avoid probabilistic evaluations. In scenarios of assumed uncertainty characterisation, sensitivities can also be tested for informed decision-making.

There are different software programs used for defining statistical distributions of uncertain variables and evaluating them in a probabilistic analysis. The @Risk add-on macro to Microsoft Excel (Palisade, 2012) and B-RISK fire risk simulation model (Wade *et al*., 2013) are potential software as they include the Monte Carlo function, which can be used for uncertainty evaluation given a deterministic structural fire design. With any of these tools, the uncertain parameters or input values, and deterministic model outputs will be specified as probability distributions.

Following a structural fire analysis based on the calculation method set out on a spreadsheet, @Risk can be used for the propagation of uncertainties in the input parameters to predict failure probabilities. In the @Risk software, probabilistic distributions must be defined for the parameters and model outputs from any of 30 probability distributions ranging from Beta to Weibull distributions on the @Risk menu. Also, recent versions of the @Risk software include the Latin hypercube sampling option in Monte Carlo simulation. The laudable prospects of evaluating several design uncertainties are ideal for design scenarios involving multi-disciplinary stakeholders having different/conflicting inputs in the design decision-making process.

2.3. Stakeholders in Fire Design Decision-Making Process

There are three design phases of a building namely: concept, formulated and expert design phases. There are also multiple stakeholders involved in fire design decision-making processes within the mentioned design phases. The stakeholders include: *architects (ARC), structural engineers (SE), fire engineers (FE), building owners (BDO), building contractors (BCT), building insurers (BI), environmental professionals (EVP), building consent authorities (BCA), fire service personnel (FSP), manufacturers/suppliers (M&S), end users (EU) and others (OTR)*. Figure 2.8 shows the fire design stakeholders involved in the concept, formulated and expert design phases of a building and the factors that influence their decisions in the design process.

For structural fire design, the concept design phase involves outlining design proposals, fire protection and building services specifications as well as cost implications (RIBA, 2013). At the formulated design phase, the activities and outcomes from the conceptual phase are developed and updated with respect to possible alterations by the stakeholders. Therefore, during both phases, all of the stakeholders may be involved in the fire design decision-making. For instance, BDO participates in these design phases to understand or be advised on feasibility and cost implications of the fire protection option/s conceptualised and developed for the building by the FE.

At the conceptual and formulated phases, ARC may advise the FE and the SE on their aesthetic plan to assess the impact of the proposed fire design option on the visual appeal of the building. On another hand, BCT becomes aware of the proposed fire protection strategies and then advises on salient constructability issues for the building. BCA may participate to ensure that the design meets the minimum requirements of building regulations in the given jurisdiction; while EVP, FSP, EU and OTR add valuable opinions in the considerations of environmental impacts, effect on fire-fighting, occupancy and services respectively.

Stakeholder involvement in the expert phase is limited to few professionals, as this phase requires more specialist and technical input, given the outcome of the formulated design to produce a final fire design output for the building. In the case of the design of steel-framed buildings, this phase is an expert/technical process, which entails among other activities the determination of the capacity of the structural elements (e.g. beams, columns, floors, load-bearing walls) to resist fires. It also relies on the concept and formulated design phases and by implication the contributions of the multiple stakeholders to achieve a suitable design decision. However, in many design scenarios, these stakeholders may be influenced by their various goals, preferences and backgrounds as illustrated in Figure 2.8.

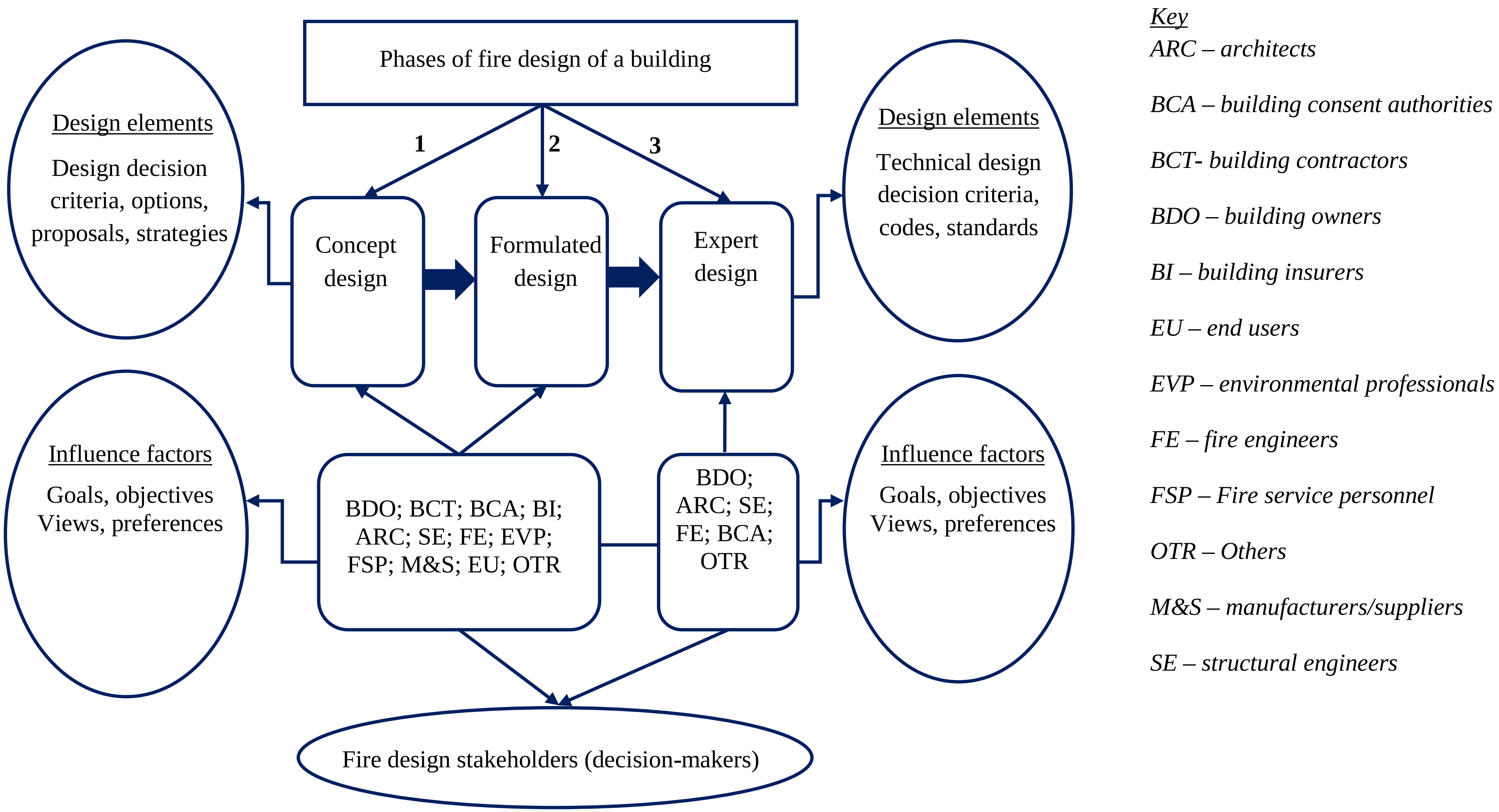

Figure 2.8. Elements in the fire design decision-making process adapted from RIBA (2013).

These influencing factors are in addition to different and interdependent design elements, which are made up of the competing options and design decision criteria within economic, safety, environmental and societal considerations. At the same time, most fire design stakeholders have an unequal influence in the design decision-making process. For example, the BDO or ARC may be the 'super' stakeholder controlling the entire design process, while BCT, EU or EVP may have less influence in the process.

2.3.1. Stakeholder divergent goals in steel structural fire design

Given that the fire design stakeholders in the decision-making process may have diverse design philosophy (stemming from their diverse professional backgrounds); their opinions may be divergent in the midst of different and interdependent design decision criteria. On the other hand, the pros and cons of using passive fire protection options also influence the design decisions of the stakeholders. From the perspective of architects, the visual appeal of steel buildings is a key objective; hence they prefer the use of intumescent coatings or unprotected steel as passive fire protection options (Meacham, 2000). Contrastingly, concrete encasement of steel (either full or partial encasement) could be recommended by the structural engineer with the view of eliminating the weaknesses of intumescent coatings, such as non–uniform thickness and adhesive strength. Concrete encasement also ensures that there is minimal heat transfer (if any) to the steel element, but may increase the weight of the structure (Buchanan and Abu, 2017). Sprays are adjudged as low-cost fire protection materials (Goode, 2004) as they can be quickly applied on site and easily cover complex construction details. Hence, a building owner may prefer the spray option as opposed to the more expensive mineral-fibre or cement-based intumescent paint and plasterboard products.

Some decades ago, concrete encasement of steel was common in the fire protection market of several countries. Nowadays intumescent coatings and the use of unprotected steel have become more popular, recommended by engineers owing to costs and services considerations, building aesthetics demands, etc. In some circumstances, other traditional concrete-based fire protection methods, e.g. blockwork filling, may also be used (Goode, 2004; Corus, 2006). The architect may not support the use of spray due to its poor visual appeal, and the building contractor may also oppose the spray option due to its wet application on site which may restrict other trades or building construction activities. The architect and building contractor in the concept design phase may recommend the use of intumescent paint or plasterboard which enhances building aesthetics and ensures dry on-site fixing respectively.

However, the building owner may be constrained by their financial budget. The use of unprotected steel, given an optimised design, may be suggested to the building owner by the fire and structural engineers to eliminate the use of the passive fire protection. However, the building insurer and end user's confidence may be tested in accepting this option having 'financial risk management' and 'safe occupancy' as their key structural fire design decision goals respectively. Concrete encasement of steel may be appealing to the building insurer, given its suitability in ensuring minimal heat transfer to the steel elements, but may not be easy to construct and can increase the weight of the building (as mentioned earlier) and construction timeframe, in addition to the expense of the additional concrete.

Given these varying stakeholder views on fire protection options, the design decision criteria considered in evaluating the options may be interdependent which can influence steel structural fire protection decision-making. For example, if the stakeholders desire to *maintain supply chain with manufacturers/suppliers* of a fire protection product as a decision criterion, this may be dependent on *constructability* (i.e. cost and ease of applying the fire protection material) and general *profit-making* in using the product. Another example of a dependency is when stakeholders consider *building regulation approval* of structural fire design of a building project as a critical decision criterion to select any of the fire protection options. The stakeholder judgments and decision can be influenced or may depend on fire risk levels from *fire risk assessment*, the effect of the fire protection options on *fire-fighting operations*, and the *maintainability* of the fire protection option. These kinds of influences also need to be accounted for or balanced to achieve suitable structural fire design decision-making.

2.3.2. Balanced stakeholder goals for suitable decision-making

Balancing stakeholder goals in a typical design decision-making process must consider all diverse views, conflicting decision attributes and competing design options without ignoring anyone. In this way, there is a potential that most design and construction uncertainties can be addressed. In steel structural fire design decision-making, attempts to balance fire design stakeholder goals can answer the following questions:

- Can all stakeholder views be incorporated into a structural fire design?
- Can the stakeholder views be ranked for appropriate decision-making?

- Are the stakeholder ranked decision options suitable and cost-effective?
- Are there other goals that fire design stakeholders look for?
- How robust is the decision-making procedure?

However, the challenge in achieving a balanced and appropriate structural fire design decision is that there are multiple stakeholders and their varying views/interests are many, so these views need to be managed with transparent decision-making or support techniques.

2.4. Risk and Decision Management Processes

‘Risk’ has been defined globally to mean different things in different contexts. It is a fact that what may pose a risk to a person may not be to another. In highlighting human exposure to risk as a fundamental continuum, Chapman and Cooper (1983) defined risk as ‘being vulnerable to financial loss or profit, delay or damage due to the impact of uncertainties related to carrying out activities’. Professional institutions’ views on ‘risk’ focus on the balance between managing threats and utilising opportunities. For example, the US Project Management Institute (PMI) in 2000 defined risk as *“An uncertain event or condition that if it occurs, has a positive or negative effect on a project objective”* (PMI, 2000). Ellinwood (2001) considers ‘risk’ in a structural design context as the inherent natural consequence of uncertainty, which represents the probability of negative events and their impacts in human and economic terms. In these definitions, the key word is ‘uncertainty’ which must be acknowledged and managed in every facet of human activities including decision-making. Generally, ‘risk’ is represented as:

$$Risk\ (R) = Probability\ (P) \times Impact\ (I) \qquad 2.3$$

Risks include financial and economic risks, fire risks, design risks, political and environmental risks, and an act of God (e.g. earthquake, tsunami, storm etc.). In relation to fire risk and applicability of Equation 2.3 in structural fire safety, this implies that there must be an ignition then a probability of fire induced structural failure at elevated temperatures leading to consequential property loss, environmental damage etc. Designing for fire resistance of structures is an example of fire risk management applicable to mitigating severe fires. In another hand, making a design decision (given conflicting factors and competing options) is also a risk which can be managed through risk management. Risk management is the harmonised actions to control and direct an event concerning risk. The essence of risk management is to establish an acceptable premise for decision-making, planning, increase the chances of meeting set goals and enhancing stakeholder consensus.

Fundamentally, risk and decision analysis are part of risk management given that they help stakeholders to prioritise their goals and make informed choices among competing options. An example is the use of event and fault trees for probabilistic risk assessment. In the context of structural fire design decision-making, the early involvement of fire design stakeholders in risk management ensures that their views are accounted for in determining criteria for risk evaluation and their views toward suitable design decisions.

Risk management process systematically uses management procedures and techniques to identify, analyse, evaluate and respond to risk events to achieve an optimised level of risk control. In some literature (Dey, 2001; Hallikas *et al*. 2004), risk management process is divided into 3 or 4 stages which include, risk identification, risk analysis and risk response. These stages do not reflect the complete stages of an ideal risk management process especially with respect to planning, risk reviews, consultation and risk communication at all levels of the process. A more established risk management process can be found in the International Risk Management Standard, AS/NZ ISO 31000:2009. Figure 2.9 shows the framework of a risk management process from the International Standard, AS/NZ ISO 31000:2009.

The framework indicates that a context must be established followed by risk assessment which consists of risk identification, analysis and evaluation; risk treatment is then employed based on the outcomes of the risk evaluation. Importantly, outcomes from each stage are communicated to the risk owners and stakeholders for appropriate monitoring and reviews as required. It is noteworthy that methods of stakeholder engagement (e.g. brainstorming, interviews, surveys etc.), decision analysis (decision matrices, trade-offs, Monte Carlo simulation etc.) and decision-making which are relevant to this research are elements of the risk management process. Therefore, Figure 2.9 is fundamental to the fire design stakeholder decision management procedure which this research project intends to achieve.

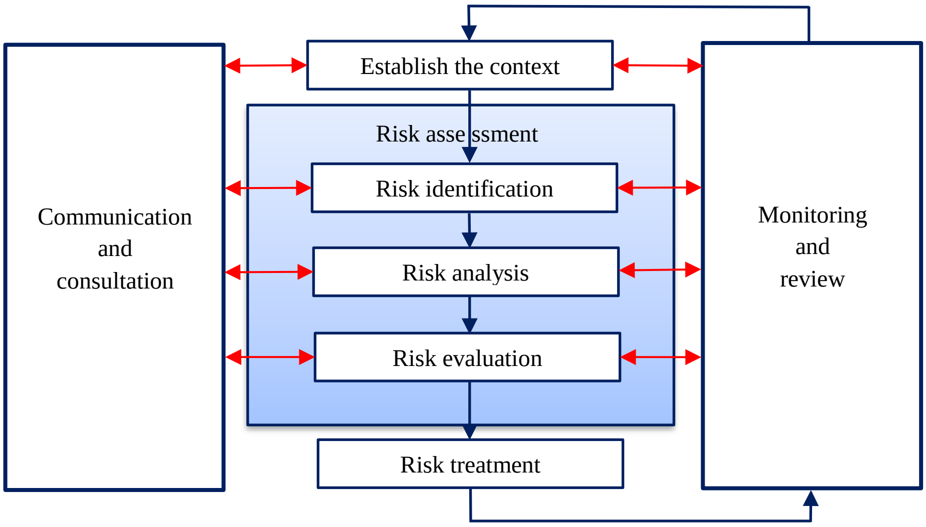

Figure 2.9. Risk management process (AS/NZS ISO 31000:2009).

2.5. Assumptions in Solving the Research Problem

This research project is on 'decision-making' and developing a procedure/tool that can potentially optimise stakeholder goals in design decision-making processes. The structural fire design of steel-framed buildings is used as a general and realistic case study to develop and test the decision-making technique. Having reviewed the relevant literature in structural fire design and stakeholder decision-making, this research firstly appreciates the variability of fires and complexities in structural fire design problems. However, the objective is to develop a process that balances the stakeholders' goals following a conventional structural fire design approach so as not to overcomplicate the decision analysis given the effects of different fires.

The research also appreciates the heights to which performance-based structural fire engineering has attained globally, especially in the use of real and parametric fires in achieving engineered solutions that meet performance requirements. Although, the use of real and parametric fires is the state-of-the-art, the aim of this research is to produce a tool that helps in decision-making; hence using real fires complicates the analysis as the research has to come up with distributions for each real fire and assess them in the structural fire analysis of the decision-making/analysis process. The choice of the standard fire reduces the complexity of the problem, i.e. to not overcomplicate the analyses thereby missing the main objective of developing a process for decision-making. In addition, this research appreciates that a post-flashover fire is one out of many potential stages that a real fire goes through, i.e. a special case of a fully developed fire especially for small enclosures. However, in this thesis, the term *'fully developed fires'* is used to also mean '*post-flashover fires'* in keeping with the assumption of the fire design stakeholders that were engaged in the research interviews.

To predict the suitability and cost-effectiveness of the ranked steel structural fire protection options, deterministic and probabilistic analyses are conducted for unprotected and protected steel structural design scenarios in which some parameters are varied. For the deterministic structural fire analysis, the Eurocodes are used to critically assess the thermo-mechanical response of representative simply supported steel members that are fire protected using the ranked options. The Eurocodes are used based on the arguments in the literature supporting their flexibility in guiding designers to achieve rational deterministic solutions in comparison to the New Zealand steel structure standard (NZS3404) especially in steel column design under fire conditions.

For loading action, parameter/property uncertainties as well as estimation uncertainties (Table 2.2) are considered. Monte Carlo simulation is considered relevant to this work and will be used through @Risk to evaluate the mentioned uncertainties toward achieving failure probabilities. The @Risk tool is used in this project due to its availability as an add-on macro to spreadsheets. Notably, Microsoft Excel (spreadsheet) is also considered as a suitable application in writing/developing decision-making tools and the steel structural fire deterministic analysis.

Given that risk and decision analysis has been established as part of risk management, the development and implementation of the stakeholder design decision-making process in this research project follow the risk management process from AS/NZ ISO 31000:2009.

3. DECISION THEORY AND STAKEHOLDER DECISION ANALYSIS

Decision theory refers to the study of choices (Hansson, 2005). It entails mathematical strategies used to balance several options and their inherent attributes. This study is deeply rooted in management science (Donegan, 2008), but is widely applied in other disciplines including engineering. A decision theory can be normative (i.e. proposing or supporting suitable decision-making in uncertain conditions) or descriptive (i.e. analysing how decisions are made by irrational risk takers). In normative decision theory, which is relevant to this research, the judgement of a decision-maker on competing attributes is critical to the outcome of the decision-making process. The quality of decision analysis can assist the decision-maker to approach a suitable decision (Donegan, 2008). The divergent stakeholder goals in structural fire design decision-making discussed in Section 2.3.1 present a typical multiple-attributes or multi-criteria decision problem. Hence, technique/s are needed to address the problem.

3.1. Multi-Criteria Decision Analysis (MCDA) Techniques

Multi-criteria decision analysis (MCDA) is an advanced technique in operation research that solves complex decision-making problems characterised by divergent views, varying interests and uncertainties (Mateo, 2012). It breaks down a decision problem into components such as a goal, criteria and options. Then it examines and synthesises these components to produce a reasonable solution. The technique can be applied to evaluate qualitative/quantitative decision criteria in a participatory group process transparently and acceptable to decision-makers (Nordstrom *et al*. 2012). MCDA has been applied in diverse fields such as sustainable energy (Doukas *et al*. 2007), healthcare (Saaty, 1994a), environmental management (Ananda, 2007), etc. The successful application of any MCDA technique is dependent on the decision scenario (Caterino *et al*. 2009). There are many MCDA techniques currently employed in decision-making processes such as multi-attribute value theory, analytic hierarchy and network processes (AHP and ANP), utility theory, fuzzy sets, etc. Table 3.1 presents a brief summary of different MCDA techniques including some of their strengths, applicability and limitations.

Table 3.1. Brief Summary of MCDA Techniques

Technique	Description	Key strengths	Limitations
AHP	Hierarchically structured technique for analysing decision problems based on a relative comparison judgement scale.	Easy to apply, derives decision criteria weights, checks judgement consistency, scalable, suitable for hybrid application.	Considers independent criteria only, large criteria (e.g. 7 or more in a judgement matrix) may affect judgement consistency.
ANP	Extension of the AHP technique which accounts for dependency/interaction among decision criteria through network structures.	Considers interdependent criteria, solves complex decision networks, suitable for hybrid application.	May require experts to determine the relevant dependencies, may need a computer software given large criteria and interdependencies.
ELECTRE I, II & III	MCDA techniques used to outrank a set of decision options by establishing their concordance and discordance indexes.	Suitable for assessing few decision criteria and options, suitable for heterogeneous criteria & hybrid application.	Requires the decision-maker to derive two fixed parameters in the process which may be difficult to understand & implement in practice.
PROMETHEE 1 & 2	Group of outranking techniques based on choosing a preference function for each criterion forming a decision problem.	Suitable for criteria of same dimension i.e. homogenous criteria & hybrid application, permits outranking of non-performing options.	Does not derive criteria weights for its decision matrix, may require the decision-maker to derive a fixed parameter in the analysis process.
TOPSIS	MCDA technique based on the best decision option is the one having the closest geometric distance to the ideal solution.	Considers qualitative and quantitative decision attributes, addresses normalisation of multi-dimension attributes, suitable for hybrid tools.	Does not derive criteria weights; hence, may not consider interdependent decision attributes or priorities on its own.
VIKOR	Technique for establishing the compromise ranking-list of decision options based on closeness to the ideal solution.	Same strengths as TOPSIS & considers the satisfaction level of each criterion with respect to the performance of all criteria. .	Does not derive criteria weights, requires the decision-maker to derive a fixed parameter in the decision-making process.
WPM/WSM	Measures decision options by weighting decision attributes & selects the option having the top weighted score as the best option.	Easy to apply, intuitive, suitable for criteria of same dimension i.e. homogenous criteria (e.g. costs or benefits) & hybrid application.	Not suitable for large decision criteria problems; not applicable in assessing/normalising criteria having different dimensions e.g. cost & benefits.

AHP – Analytic Hierarchy Process; ANP – Analytic Network Process; ELECTRE - Elimination et choix traduisant la realité; PROMETHEE - Preference ranking organization method for enrichment of evaluations; TOPSIS - Technique for order of preference by similarity to ideal solution; VIKOR - Visekriterijumska Optimizacija I kompromisno resenje; WPM/WSM – Weighted Product/Sum Models.

A detailed review of MCDA techniques and their application in several decision-making problems can be found in Ho *et al*. (2010) and Huang *et al*. (2011), including hybrid-MCDA technique applications. A summary of some relevant MCDA techniques considered in this research work is presented in the following sections.

3.1.1. Analytic hierarchy process (AHP)

Saaty in the early 1980s developed a decision-making process known as analytic hierarchy process (AHP), in which a problem is broken down, and the solutions of the subproblems are combined to aid the decision-makers to approach a decision. This technique entails the decomposition of a problem into a hierarchy of goal, decision criteria and options as shown in Figure 3.1. The decision criteria are weighted based on pairwise comparisons or judgements to determine the performance/dominance of the criteria to the decision makers. The performance scores are then aggregated to rank the options (Saaty, 1980; 1994a).

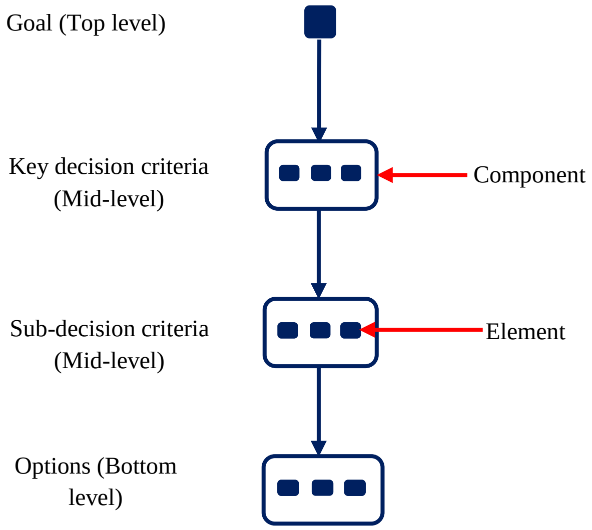

Figure 3.1. AHP hierarchical structure (Saaty, 1994a)

AHP allows for a consistency check of all pairwise comparisons, given that human beings are inconsistent in such judgements (Coyle, 2004). This MCDA solution has been widely applied in over 20 countries in solving decision-making problems ranging from policy making, product marketing strategy, military analysis to cost-benefit assessment in construction (Jato-Espino *et al*. 2014).

3.1.1.1. General AHP method

There are many ways to carry out MCDA using AHP, but in this study, a summary of the procedure by Saaty (1980, 1994a) and Coyle (2004) is presented. There are six steps in the AHP, which are: *Defining the decision goal, criteria, and options (decision model); pairwise comparisons of criteria and options; generate judgement matrices; AHP-prioritisation or weighting; AHP-synthesis; ranking and decision-making as shown in* Figure 3.2.

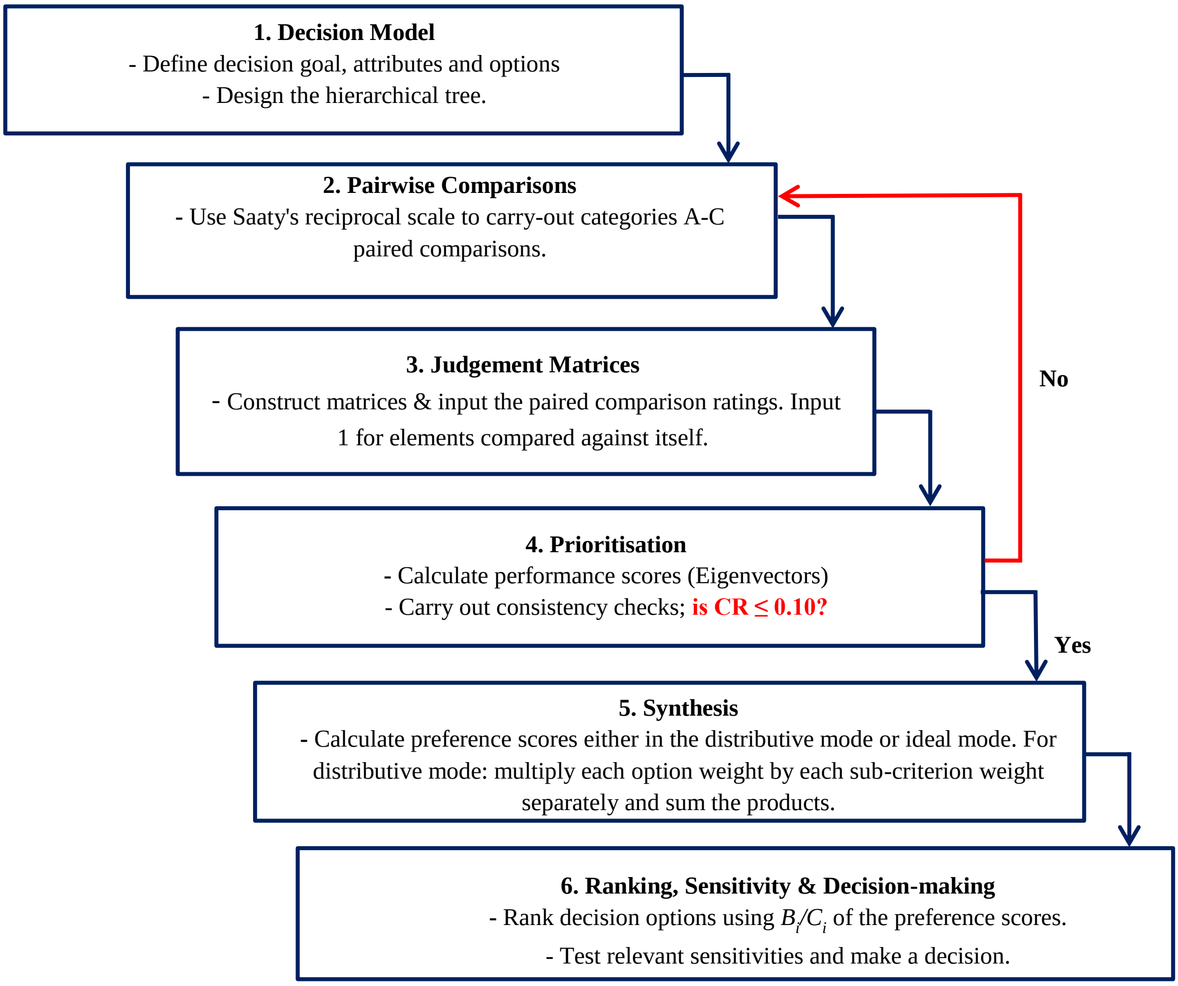

Figure 3.2. The steps for AHP application (Saaty, 1994a).

Step 1

Firstly, in developing the decision model, a goal must be stated, and associated key decision criteria that help to meet the goal are defined. Each key decision criterion is decomposed into sub-decision criteria. In some scenarios, decision-makers may work as a group and agree on common decision criteria and sub-criteria. The competing options are identified at this stage as well. It is ideal to construct hierarchical trees for costs and benefits to represent a breakdown of the decision problem into levels (Figure 3.1). The decision goal is placed at the top level; the key decision criteria are placed at the mid-level and linked to the goal at the top, followed by the sub-decision criteria placed and linked to their respective parent-key decision criteria at the mid-level. The competing options are placed at the bottom to complete the hierarchical tree and decision model (Figure 3.1).

Step 2

The second phase involves pairwise comparisons based on the level of importance in different categories using the Saaty's reciprocal pairwise comparison scale shown in Table 3.2. The values from Table 3.2 are assigned to each compared pair of criteria or options according to the intensity of the opinion of the decision-maker.

Table 3.2. Saaty's rating scale (Coyle, 2004)

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective.
3	Somewhat more important	Experience and judgement slightly favour one over the other.
5	Much more important	Experience and judgement strongly favour one over the other.
7	Very much more important	Experience and judgement strongly favour one over the other. Its importance is demonstrated in practice.
9	Absolutely more highest important	The evidence favouring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed.

The criterion or option with greater importance for every compared pair is assigned a whole number, while the other criterion or option in that same paired comparison is assigned the reciprocal of the whole number. The categories of pairwise comparisons in the AHP are thus classified as:

- ***Category A*** *is the pairwise comparison of the key decision criteria against each other with respect to the stated goal; and the pairwise comparison of the competing options against each other with respect to the stated goal.*

- ***Category B** is the pairwise comparison of the sub-criteria against each other with respect to their parent-key decision criteria as classified.*
- ***Category C** is the pairwise comparison of the options against each other with respect to every sub-decision criterion in the decision problem*.

Step 3

In the third phase (*i.e. judgement matrices phase*), the pairwise comparison ratings are presented in the form of matrices. For every matrix, each element compares the intensity of importance of a criterion or option against each other, where one is retained for a criterion or option compared against itself. This completes the pairwise comparison matrices, which are then ready for further assessment. In scenarios where decision-makers carried out the pairwise comparisons individually, there will be a need to aggregate the individual ratings for each category to form a single or collective group judgement of the criteria or options. The aggregation methods used in the AHP are discussed in Section 3.2.

Step 4

The fourth phase (*i.e. prioritisation or weighting phase*) is to weight the key decision criteria, sub-criteria and options to determine their performance scores for each aggregated category. The dominance of a criterion or option is also deduced from this evaluation. In AHP, the performance scores of the key decision criteria and options are evaluated using either the Eigenvalue method, geometric mean method or mean of normalised values method (Saaty, 1980; Coyle, 2004; Ishizaka and Lusti, 2006). In using the Eigenvalue method, the performance scores are determined by firstly calculating the product of the entries in each row of the matrix. The n^{th} root of the product of each row is then calculated, where n is the number of decision attributes or options in the judgement matrix. The calculated n^{th} root for each row is summed up which give good approximations to that calculated below using the mean of normalised values method. This sum is used to normalise the elements of the performance scores to add up to 1.00. The consistency ratio (CR) of the aggregated pairwise ratings are checked by further normalisation of the performance scores with the matrix row entries to achieve a consistency index (CI), given as;

$$CI = \lambda_{max} - n / (n - 1) \qquad 3.1$$

where λ_{max} is the mean of the normalised new performance scores and n is the total number of weighted criteria or options.

CI is then divided by the corresponding value for *n* from Saaty's random consistency index (*RCI*) judgement table of large matrix samples (Table 3.3) to calculate *CR*, i.e.

$$CR = CI / RCI \tag{3.2}$$

Table 3.3. Saaty's random consistency index (*RCI*) values for different values of *n* (Saaty, 1980).

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

For example, consider judgement matrix, *X* for three decision criteria, x_1, x_3 *and* x_3:

$$\boldsymbol{X} = \begin{pmatrix} 1.00 & 0.20 & 0.33 \\ 5.00 & 1.00 & 3.00 \\ 3.00 & 0.33 & 1.00 \end{pmatrix}$$

For simplicity, the performance scores or weights can be calculated using the 'mean of the normalised row values' approach thus:

$$x_1 = \frac{1.00 + 0.20 + 0.33}{1.00 + 0.20 + 0.33 + 5.00 + 1.00 + 3.00 + 3.00 + 0.33 + 1.00} = 0.10$$

$$x_2 = \frac{5.00 + 1.00 + 3.00}{1.00 + 0.20 + 0.20 + 5.00 + 1.00 + 3.00 + 3.00 + 0.33 + 1.00} = 0.61$$

$$x_3 = \frac{3.00 + 0.33 + 1.00}{1.00 + 0.20 + 0.33 + 5.00 + 1.00 + 3.00 + 3.00 + 0.33 + 1.00} = 0.29$$

The summation of the weights must be equal to unity (i.e. 0.10 + 0.61 + 0.29 = 1.00)

To check the consistency ratio of judgement matrix, *X*, the performance scores are normalised thus:

$x_1 = (1.00 \times 0.10) + (0.20 \times 0.61) + (0.33 \times 0.29) = 0.32$;

$x_2 = (5.00 \times 0.10) + (1.00 \times 0.61) + (3.00 \times 0.29) = 1.98$;

$x_3 = (3.00 \times 0.10) + (0.33 \times 0.61) + (1.00 \times 0.29) = 0.79$.

The normalised weights for each criterion are

$x_1 = 0.32/0.10 = 3.20$;

$x_2 = 1.98/0.61 = 3.25$;

$x_3 = 0.79/0.29 = 2.72$

so that the mean (λ_{max}) is

$\lambda_{max} = (3.20 + 3.25 + 2.72) / 3 = 3.07$

The consistency index (*CI*) is found using Equation 3.1,

$CI = (3.07 – 3) / (3 - 1) = 0.04$

and thus, the consistency ratio (*CR*), using Equation 3.2 and Table 3.3, is

$CR = 0.04 / 0.58 = 0.07$.

Saaty (1980) and Coyle (2004) mention that a $CR > 0.10$ means that the pairwise judgements of the decision makers are at the consistency limit and in practice, it is unacceptable if it increases toward unity. In the case of determining the actual performance scores or weights of the sub-criteria under their parent-key decision criteria, the Eigenvalue process is applied. But each resultant Eigenvector is multiplied by the performance score of their parent-key decision criterion. Hence, the summation of the performance scores of the sub-criteria must equal the exact value of their respective parent-key decision criterion performance score, and the summation of performance scores of all key decision criteria must equal 1.00.

Step 5

The fifth phase of the AHP involves the synthesis of performance scores of the options with respect to the sub-criteria under each key decision criterion. This is aimed at determining the preference scores of the competing options, which can be carried out either in the distributive or ideal synthesis mode. In the distributive (dominance) synthesis mode, the options' preference scores are determined by distributive multiplication of the performance scores or weights of each option by the actual performance scores of the sub-criteria. It entails multiplying each option weight by each sub-criterion weight separately and summing the products. The performance score of each option is derived from the Category C paired judgement earlier presented as '*the pairwise comparison of the options against each other with respect to every sub-decision criterion in the decision problem'*, then followed by the Eigenvalue process. The derivation of the actual sub-criteria weights has been explained in the fourth phase. Notably, the preference scores sum up to 1.00 and the dominance of an option can be deduced. In the ideal (performance) mode, the best option under each sub-criterion is normalised to 1.00 as a benchmark; then the other performance scores are divided by the score of the best option, multiplied by the respective sub-criteria performance scores and summed as well. This implies that the preference scores of any option do not depend on the performance scores of others except for the chosen benchmark option (Saaty 1994a). The total value from the addition of the summed-up column is used to normalise them to add up to unity. As part of the AHP guideline, Millet and Saaty (1999) suggest that the distributive synthesis mode should be used when the decision-makers wish to assess the amount of dominance of one of the options and the dependence among these options. They also suggest that the ideal synthesis mode should be used to evaluate the performance of each option relative to a chosen benchmark.

Step 6

The final phase of the AHP decision analysis is to rank the assessed options to aid decision-making. However, where benefits and costs are considered, the key decision can go in three directions: whether the benefits justify their costs, whether the costs outweigh the benefits or both variables are too close to call. Saaty (1994a) suggests that in complex decision-making problems, cost criteria with respect to the options should be separated and synthesised when all the benefits of the competing options have been assessed. Therefore, when these two variables are separated, they produce a scenario to determine benefit-cost ratios given as:

$$B_i/C_i \qquad 3.3$$

where B_i is the benefit preference score of the options and C_i is the cost preference score of the options.

The result from this calculation ranks the competing options and presents the option with the highest benefits and least costs as the top-ranked option.

For all its strengths, some difficulties in the application of AHP have been mentioned in the literature. These include:

i. The problem of group consensus;
ii. The problem of rank reversal.

Ramanathan and Ganesh (1994), and Donegan (2008) in their AHP studies highlighted the issue of achieving group consensus, where there are multi-decision makers and large decision criteria and options to be considered within the AHP-framework. In fire risk indexing by Watts (2008), the issue of rank reversal (i.e. change of the final ranking of decision options due to the change of some options in the set or method of choosing) was mentioned. Despite these criticisms, AHP has a transparent procedure of relative weighting of expert judgements that are acceptable to stakeholders (Nordström *et al.*, 2012). The consistency checks of decision criteria weights and a clear demonstration of the performance/dominance of compared decision criteria or attributes among stakeholders contribute toward decision-making. It is also noteworthy that these AHP-issues and arguments have been explicitly discussed and addressed by Saaty (2005). Recently, Tomashevskii (2015) proposed ways of eliminating rank reversal when using the AHP technique and opined that errors in the AHP-calculation are dependent on using the wrong judgement scale (e.g. using ordinal number scales in place of Saaty's pairwise comparison rating scale) and inconsistent pairwise comparison judgements of decision makers.

3.1.1.2. Application of AHP in Fire Safety Research

AHP has been discussed as a technique that can assist decision-making, after the completion of fire risk analysis (Wolski, 2008). Several different applications of AHP to solve fire safety related decision-making problems are described in the literature. Some examples are provided below to demonstrate the applicability and adaptability strengths of the AHP technique for supporting fire-related research, risk-based structural fire design and fire-safety decision making.

One of the early applications of AHP in fire safety research was by Shields and Silcock (1986). They illustrated how the AHP technique could be used to build a simple fire safety system and analyse the relative effectiveness of three fire safety "tactics". Having deployed the traditional AHP procedure, they were able to demonstrate the capability of the technique to manage fire safety uncertainties and proposed to use the AHP for fire safety modelling of public buildings. Since then Hansen (1999) carried out fire risk analysis to establish an area of frequent maritime fire and explosion occurrences in a case study of shipboard fires. Eight maritime safety experts were engaged as decision-makers to solve the maritime fire safety and regulatory problem, given the data obtained from the risk analysis. Through brainstorming, the expert panel came up with 18 fire safety options and 19 decision criteria. The relative comparisons of the criteria were carried-out by the same expert panel. The problem breakdown was modelled in a hierarchical structure, and the AHP was applied to rank the fire safety options. More recently, Yan *et al*. (2015) applied AHP to formulate an index criterion score system for the fire risk assessment of a large central business district (CBD). In their work, the AHP pairwise comparison scale (Saaty's pairwise comparison rating scale) was used to compare the primary fire risk indicators for the CBD, which included fire load, danger and hazard indicators. The weights of these indicators were calculated from the pairwise ratings as well as the consistency of the judgements; these showed the priority levels of the indicators for completing the fire risk assessment and coming up with proposals for the CBD planning.

The applications of AHP in fire safety and fire risk assessment adhered to the fundamental principles of the technique, which break a decision problem to decision elements (decision criteria and options), pairwise or relative comparison of the elements to prioritize them and checking the consistency of the decision-maker(s) judgement. However, the strengths of AHP were not fully accessed and demonstrated. Shields and Silcock (1986) presented mathematical details of the decision criteria pairwise comparisons, criteria weightings and consistency checks but there is the need to understand further the ways of balancing views of multiple decision-makers and the effects of the type of AHP-final synthesis on the decision analysis. Hansen (1999) engaged the same panel to derive decision criteria and to rate the derived criteria. Critical consideration of possible expert bias in the pairwise comparison judgement of the derived decision criteria as well as the method of aggregating the individual judgments of panel members will further demonstrate the strength and transparency of the AHP. Solving the issue of expert bias and multiple decision-makers having conflicting views with the AHP accounts for decision-making uncertainties, e.g., balancing outright dominance of a decision criterion due to vested interest on the criterion and prevailing opinion of a decision-maker in a group, which could affect decisions that are subsequently taken.

An example of possible bias and dominance of decision criteria scenario; an architect may highly prioritise building aesthetics in comparison to other design decision-criteria such as constructability, fire-fighting operations etc., which are key interests of other fire design stakeholders. Although the architect has an important role in a building project, his bias to aesthetics may skew the judgement priority scores which may need to be managed in the decision-making process. In addition, these referenced AHP-applications present little understanding of the level of transparency in using the technique especially in scenarios where there is larger and skewed data sample from different categories of stakeholders who may have varying opinions in group decision-making situations.

3.1.2. Weighted sum and product models (WSM & WPM)

In multi-criteria decision theory, the *weighted sum model (WSM)* (Fishburn, 1967) simply measures decision options with respect to decision attributes, whereby the option having the most beneficial weighted score is the best option if all attributes are defined in the same unit condition. This also entails that in benefit-type decision attributes, the option with the maximum value is the best; while, in cost-type decision attributes, the option with the minimum value is the best option. In other words, higher benefits are desirable, while fewer costs are desirable too. WSM is defined mathematically thus:

$$O_i = \sum_{j=1}^{n} w_j o_{ij}, \text{ for, } i = 1,2,3,\ldots,m. \qquad 3.4$$

Where: O_i refers to the assessed option in terms of *m* decision options and *n* attributes;
w_j is the relative importance weight of the attribute a_j; and
o_{ij} is the preference score of O_i.

Example: Let an MCDA problem involve four criteria having the same unit, and three options. If the comparative weights of the 4 criteria were calculated to be: $W_1 = 0.30$, $W_2 = 0.25$, $W_3 = 0.20$, and W4 = 0.25. Assuming the associated o_{ij} values are as follows:

$$\boldsymbol{O} = \begin{pmatrix} 10 & 15 & 30 & 20 \\ 25 & 20 & 10 & 15 \\ 30 & 15 & 10 & 20 \end{pmatrix}$$

The decision matrix is thus:

	Decision Criteria			
	C1	*C2*	*C3*	*C4*
Options	[0.30]	[0.25]	[0.20]	[0.25]
O1	10	15	30	20
O2	25	20	10	15
O3	30	15	10	20

Using Equation 3.4, the preference scores of the options are:
$O_1 = (10 \times 0.30) + (15 \times 0.25) + (30 \times 0.20) + (20 \times 0.25) = 17.75.$

O_2 = (25 × 0.30) + (20 × 0.25) + (10 × 0.20) + (15 × 0.25) = 18.25.
O_3 = (30 × 0.30) + (15 × 0.25) + (10 × 0.20) + (20 × 0.25) = 19.75.

Hence, O_3 is the most preferred option because it has the highest preference score. The top to bottom ranking order is O_3, O_2, O_1.

The *weighted product model (WPM)*; (Bridgman, 1922) is like WSM; the key difference is that instead of summation, multiplication is used in the model. In the evaluation of two decision options, O_1 and O_2, WPM regards O_1 to be better than O_2 if the outcome of Equation 3.5 is greater than one if the attributes are benefit-type or less than one if attributes are cost type. The mathematical expression for WPM is given as:

$$o_{1,2} = \prod_{j=1}^{n} (\frac{o_{1j}}{o_{ij}})^{w_j} \qquad 3.5$$

Where: n is the number of attributes,
o_{ij} is the precise score of the i^{th} option in terms of the j^{th} attribute; and
w_j is the importance weight of the j^{th} attribute.

WSM and WPM are also known to be simple and easy to use due to their intuitive nature. In decision-making problems having single dimensional attributes (i.e. all units of conflicting criteria are the same, e.g. meters, dollars, Newton, etc.), WSM and WPM can be easily applied (Triantaphyllou *et al*. 1998). However, it has been criticised in the literature (Caterino *et al*., 2009) as MCDA techniques more suitable to solving decision-making problems that have the same type of decision criteria (i.e. costs or benefits). WSM and WPM are not suitable for solving decision problems having multi-dimensional attributes, e.g. quantitative and qualitative attributes (Kolios *et al*. 2016). In such cases, the decision attributes will need to be normalised using other techniques (*e.g. Technique of Order of Preference and Similarity to Ideal Solutions [TOPSIS]*) to enable assessment of the attributes across the board. Other single MCDA methods, e.g. ANP are more suitable in solving complex decision-making problems having costs, benefit attributes and interdependences within the decision attributes. Notably, WSM and WPM can also be used along with the AHP to solve complex decision-making problems, especially in weighting independent attributes.

The weighted sum/product model will not be used in the remainder of this thesis given that the techniques cannot manage large decision analysis data as well as combine multi-dimensional decision attributes as mentioned in Table 3.1.

3.1.3. The preference ranking organisation method for enrichment evaluations versions 1& 2 (PROMETHEE-1&2)

Brans and Vincke (1985) proposed PROMETHEE-1&2 which is premised on the variations shown by decision options when compared under each decision attribute. In this way, the method allows direct synthesis of different elements in a decision matrix without normalisation and may not support multidimensionality. PROMETHEE-1&2 aids decision-makers to determine the option that best fits their goal and comprehension of the decision problem. This is possible by measuring relationships and variations of decision attributes as well as group action plans toward ranking the key options. The techniques are known as outranking methods that avoid the strong hypothesis of decision-maker/s actual preference. Its application is also suitable for scenarios where comparison of key decision attributes is difficult due to multidisciplinary perspectives or tendencies of participant-decision-makers. This MCDA technique has been predominantly used in solving complex decision problems in transport planning, education and business management (Behzadian *et al*., 2010).

There are two main stages of applying the PROMETHEE-MCDA techniques in solving a complex decision problem. The stages are summarised thus:

i. *Allotting a preference function*

   Firstly, a decision matrix is set-up by placing the options in the left column and the different criteria on the top row. Here, each criterion is used to assess the performance of each option. Preference functions (ranging from 0 – 1) for each paired option are then determined from the assessment of the decision matrix. The preference function, ‘1’ means that there is a large difference between the paired options and ‘0’ indicates no difference between them. Notably, the nearness of preference function to ‘0’ also indicates greater indifference of the decision-maker and the nearness to ‘1’ is the decision-maker’s preference level. The ordering of the options can be expressed as preference flows allowing for incomparability scenarios with respect to their relative comparison.

ii. *Calculating the options’ outranking level*

   In this stage, the preferences are multiplied by the criteria weights and summed up; a preference matrix is then assessed. The criteria weights are assumed to be determined by the decision-makers before implementing PROMETHEE. In the preference matrix, the dominance of an option is obtained from the sum of the row associated to each option; while, the sum of each column shows how other options dominate the associated option.

The detailed mathematical assumptions and analytical calculation using PROMETHEE can be found elsewhere in Brans and Vincke (1985); Deshmukh (2013).

PROMETHEE-1 leads to a partial ranking of decision options, which is effectively the outcomes of Stage (i) of applying the PROMETHEE technique. This means that some options may not be compared and completely ranked especially for options having high-performance scores on the criteria for which they were relatively compared with other options (Balali *et al*. 2014). In this case, the options with low scores are considered incomparable and eliminated leading to a partial ranking of the high performing options. However, PROMETHEE-1 is adjudged as an advantageous technique in terms of pre-ranking decision options and eliminating poor performing options; though this may have some impact on data requirement (Geldermann and Rentz, 2001).

PROMETHEE-2 has been suggested as a better MCDA tool given that it completely ranks the competing options unlike PROMETHEE-1 (Caterino *et al*., 2009). In PROMETHEE-2, the pre-ranked options i.e. including the ‘comparable and incomparable’ options in PROMETHEE-1 are completely ranked by developing a logical outranking relation. Notably, PROMETHEE-2 can be appropriately applied to decision problems having benefits criteria or attributes only.

It is noteworthy that the PROMETHEE techniques lack a process of structuring decision problems, unlike the AHP. The techniques have also been criticised for not having a method of deriving the criteria weights used in assessing the decision matrix; instead, they rely on the decision-maker to have pre-determined weights before the assessment (Macharis *et al*. 2004).

The PROMETHEE technique will not used in the remainder of this thesis because it does not have a fundamental judgement structure to derive its own criteria weights towards decision synthesis and ranking unlike the AHP. In addition, its application may require the determination of fixed parameters which may complicate the process (see Table 3.1).

3.1.4. Analytic network process (ANP)

Analytic Network Process (ANP) is an MCDA technique which generalises and extends the AHP theory to include the concept of ‘influence’ (Saaty, 1999; Saaty, 2005; Ozturk, 2006). The concept of ‘influence’ was included to give decision-maker/s the opportunity to go beyond the top-down AHP-approach in decision-making processes. ANP was also developed to ensure that possible interaction between dependent and interdependent decision attributes in complex decision problems can be assessed. ANP substitutes hierarchies with networks to enable decision-maker/s to resolve all possible influences or dependencies in a decision-making process. The network consists of decision elements (sub-criteria) of parent key criteria grouped in clusters and connected by their respective dependencies (Saaty, 2005) as shown in Figure 3.3.

In ANP, two kinds of dependencies exist, they are inner dependence and outer dependence. Inner dependence deals with the influence of decision elements in a cluster on each element; while outer dependence deals with the influences among clusters (i.e. C_1 - C_5 in Figure 3.3) of different decision elements. The loops in C_2, C_4 and C_5 indicate that these clusters have inner dependencies in them. Feedback between clusters (C_3 and C_5) also exists in an ANP network structure which enables decision-makers to consider the future in dealing with the immediate decision problem (Saaty and Vargas, 2013).

One of the fundamental differences in using ANP compared with AHP is that the decision problems and their analysis can be modelled without arranging the decision components sequentially. However, AHP, which has a one-directional connection in its structure, is a unique case of ANP (Saaty, 2008). In the application of ANP, a control network or hierarchy is employed to guide the derivation of priorities or weights. The same procedure as in AHP is used given pairwise comparison and judgements of decision-makers. The ANP network is the structure of control criteria under which priorities of elements and clusters can be derived, giving way to the final analysis of the decision problem within the merits of *benefits, opportunities, costs* and *risks* (BOCR). Saaty (2005) mentioned that the BOCR merits are fundamental criteria and measures that drive human decisions in every activity.

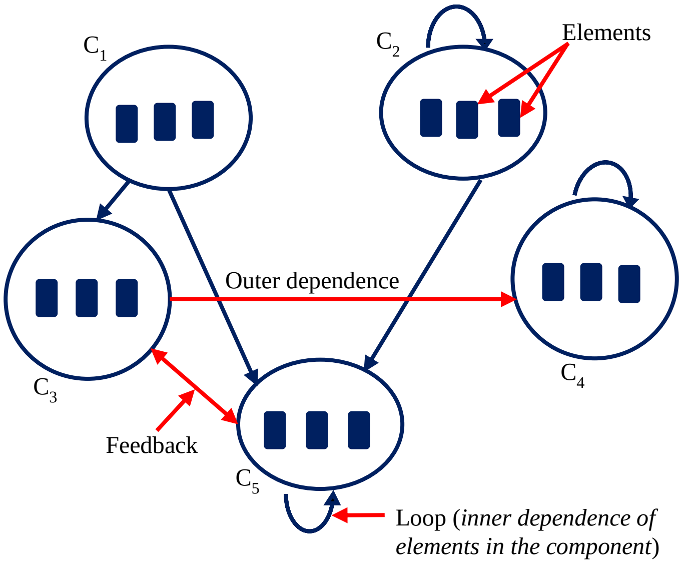

Figure 3.3. Clusters and dependencies in the network structure (Saaty and Vargas, 2013).

There have been several applications of ANP in solving multi-criteria decision-making problems ranging from market share assessment (Saaty, 1999); supplier evaluation process (Sarkis and Talluri, 2002) to USA economy resurgence forecast (Saaty and Vargas, 2013). In these applications, issues of dependencies and interdependencies among the attributes of the decision-making problem are common.

MCDA with ANP is generally carried out using seven basic steps, which are: *determine control network with BOCR merits (i.e. Benefits; Opportunities; Costs; Risks)*, *design network structures, construct cluster matrices with their weights, determine criteria influence priority scores, construct and synthesise supermatrices, normalise limiting priorities to preference scores*, and *synthesise preference scores for each BOCR merits to rank the competing options* as shown in Figure 3.4. A summarised description of the seven basic steps by Saaty (1999, 2008) is herein provided.

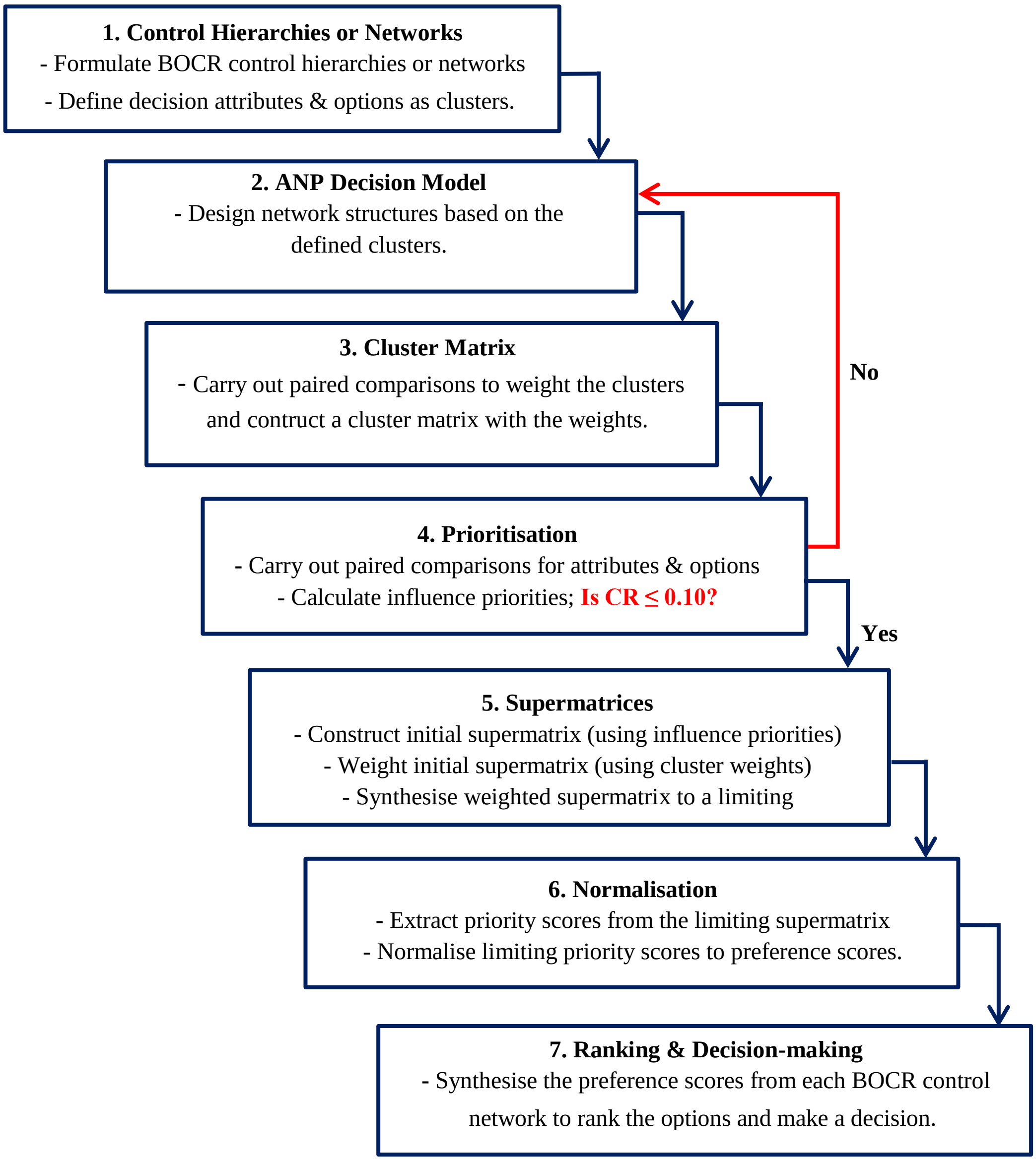

Figure 3.4. The steps for ANP application (Saaty, 1999).

Step 1

Firstly, control hierarchies or networks of the relevant BOCR merits are formulated. The criteria under which decision components are compared and their sub-criteria used in comparing decision elements must also be determined in the first step.

Step 2

In the second step, the ANP model is developed for each control criteria by determining the appropriate clusters and their respective decision elements. The inherent influences or dependences (inner and outer) and feedback between clusters are also determined in the second step.

Step 3

Thirdly, cluster matrices constructed with the clusters' respective influences/dependences and paired judgements, using the fundamental AHP-scale (Saaty, 1980; Coyle, 2004), are created for generating cluster weights.

Step 4

In the fourth step, paired comparisons are carried out among elements that influence each other within their respective clusters and elements that influence others in different clusters. These pairwise comparisons are made with respect to a control criterion or sub-criterion to generate priorities or weights of elements in their respective influence categories. The extraction of reasonable pairwise judgements from decision-makers depends on the careful use of the Saaty's reciprocal scale (i.e. Table 3.2) and the following question:

Given a critical element (criterion, sub-criterion) and comparing elements X (criterion, sub-criterion) and Y (criterion, sub-criterion) under it, which element has more influence on the critical element?

In addition, consistency checks for all paired judgements (based on AHP theory) are carried out in the fourth step given the influence priority scores generated.

Step 5

The fifth step entails the construction of supermatrices, namely: initial, weighted and limiting supermatrices, which are used to synthesise the derived priority scores from the pairwise judgements. Notably, the cluster weights generated from the third step are used to weight the initial supermatrix to make it a stochastic matrix and to generate a limiting supermatrix easily.

Step 6

In the sixth step, the priority scores from the limiting supermatrix are synthesised by modifying them with the weight of their respective control criterion. This synthesis is repeated for each control network of the BOCR merits.

Step 7

Finally, step seven entails a final synthesis of the outcomes from each control network by the appropriate mathematical ratio. For BOCR synthesis, this step entails the multiplication of benefits by opportunities and dividing by the product of costs and risks; while a benefits-costs ratio calculation is applied as the final synthesis to rank the competing options based on benefits and costs merits only.

3.1.4.1. ANP supermatrices

The synthesis step of ANP is also one of the differences between the AHP and ANP techniques. ANP is modelled as a non-linear structure, and the synthesis is non-linear as well, unlike AHP. The supermatrices mentioned previously are two-dimensional matrices developed by Saaty (1996) for the synthesis of the interactions of elements within and outside their respective clusters with respect to a control criterion. The *initial supermatrix* is the first of the supermatrices where the derived influence priorities from the paired comparison judgements are entered as sub-matrices in columns. Each column constitutes the influence priority score of the elements at the left on the element at the top of the supermatrix with respect to a specific control criterion (Saaty, 2008).

To explain the ANP supermatrices in Step 5, consider the clusters in the decision network, Figure 3.3, as C_p, $p = 1, 2\dots, m$ and consider each cluster as having n_p elements, denoted by s_{p1}, s_{p2}, …, s_{pmn}, then (a) (in Figure 3.5) represents the decision network's supermatrix. A typical entry block, W_{ij} of the network supermatrix is shown in (b) (see Figure 3.5). Here, the Eigenvectors that make up the columns of this sub-matrix are the influence priority scores derived from the decision-makers' paired comparisons; where W_{ij} is the principal Eigenvector depicting the influence of elements in the i^{th} cluster on the elements in the j^{th} cluster. Zero is entered for elements with no influence in the supermatrix (Saaty, 2005) on the premise that elements cannot influence themselves. When the entries into the *initial supermatrix* are completed, the primary aim of the ANP synthesis is to generate the limiting influence priorities from the *initial supermatrix*. This entails changing the form of the matrix whereby all the columns add up to unity, i.e. the supermatrix becomes column stochastic. The stochasticity of a supermatrix is achieved by weighting or multiplying each entry block in the *initial supermatrix* by the corresponding cluster weights from the generated cluster matrix at the third step of the ANP method. The column-stochastic supermatrix is also referred to as the *weighted supermatrix*. Saaty (2005) explained that achieving a stochastic supermatrix enables the influence priorities to be synthesised to converge to the desired identical values (limiting priorities) in each row of the matrix; this new supermatrix is referred to as the *limiting supermatrix*.

The general concern about the ANP is on its complexities, e.g. defining the appropriate dependences among clusters and elements, which may influence the final decision. Another issue is the time to set-up the ANP for stakeholder decision analysis in scenarios involving huge decision attributes leading to very large supermatrices, which may need a computer software.

$$\mathbf{W} = \begin{array}{cc} & \begin{array}{cccc} \begin{matrix} C_1 \\ s_{11}s_{12}\cdots s_{1n1} \end{matrix} & \begin{matrix} C_2 \\ s_{21}s_{22}\cdots s_{2n2} \end{matrix} & & \begin{matrix} C_2 \\ s_{N1}s_{N2}\cdots s_{NnN} \end{matrix} \end{array} \\ \begin{array}{l} C_1 \begin{matrix} s_{11} \\ s_{12} \\ \vdots \\ s_{1n1} \end{matrix} \\ C_2 \begin{matrix} s_{21} \\ s_{22} \\ \vdots \\ s_{2n2} \end{matrix} \\ \vdots \\ C_N \begin{matrix} s_{N1} \\ s_{N2} \\ \vdots \\ s_{NnN} \end{matrix} \end{array} & \begin{pmatrix} W_{11} & W_{12} & \cdots & W_{1N} \\ W_{21} & W_{22} & \cdots & W_{2N} \\ \vdots & \vdots & & \vdots \\ W_{N1} & W_{N2} & \cdots & W_{NN} \end{pmatrix} \end{array}$$

(a)

$$\mathbf{W_{ij}} = \begin{pmatrix} W_{i1}^{(j_1)} & W_{i1}^{(j_2)} & \cdots & W_{i1}^{(j_{nj})} \\ W_{i2}^{(j_1)} & W_{i2}^{(j_2)} & \cdots & W_{i2}^{(j_{nj})} \\ \vdots & \vdots & & \vdots \\ W_{inj}^{(j_1)} & W_{inj}^{(j_2)} & \cdots & W_{inj}^{(j_{nj})} \end{pmatrix}$$

(b)

Figure 3.5. ANP entry-matrices: (a) network supermatrix, (b) network sub-matrix (Saaty, 2005).

3.1.5. Technique for order of preference by similarity to ideal solution (TOPSIS)

Hwang and Yoon (1981) developed TOPSIS on the basis that the best decision option is the one having the closest geometric distance to the ideal solution. TOPSIS considers the following decision criteria: qualitative benefit criteria, quantitative benefit criteria, and cost criteria. In its decision analysis, two artificial options are hypothesised: (a) Ideal solution (i.e. the one which has the best level for all criteria considered); and (b) Negative Ideal solution (i.e. the one which has the worst criteria values). At the end of the analysis, TOPSIS selects the option closest to the ideal solution and farthest to the negative ideal solution.

The main assumptions in applying TOPSIS are: all decision criteria should be independent, and each decision criterion should be monotonic. These imply that design decision criteria, e.g. safety, economy etc., are assumed not to depend/influence each other in TOPSIS, unlike the ANP. This may not be the case in practice, given that the costs of different decision options may be influenced by societal and safety perceptions which may need to be accounted for by using a network model. For monotonicity, the judgement ratings and priority scores of decision criteria must follow a consistent increasing or decreasing sequence, i.e. the effect of a criterion (e.g. safety) relatively rated as higher than another criterion (e.g. economy), must be carried through in the analysis and vice-versa.

TOPSIS has been applied in many complex decision-making problems including supply chain, energy, engineering and human resources management, etc. (Behzadian *et al*. 2012).

The steps in implementing TOPSIS include: *constructing and weighting a normalised decision matrix; determination of ideal and negative ideal solutions; and evaluating the options' closeness to the ideal solution* (Behzadian, 2012). The detailed mathematical set-out for solving complex MCDA problems using TOPSIS is summarised based on (Hwang and Yoon, 1981; Caterino *et al*. 2009) as follows:

Step 1

Denote all options as O_1, O_2… O_n and all decision criteria as C_1, C_2, …, C_n and then construct a decision matrix with the options in the left end column and the decision criteria along the top row. TOPSIS considers that there are m options and n criteria. The variable x_{ij} is the score of option i with respect to criterion j which gives the $m \times n$ matrix $X = (x_{ij})$ (i.e. the input values in the decision matrix). Let J^* be the set of benefit attributes or criteria (where more is better) and let J' be the set of negative attributes or criteria (where less is better).

Step 2

Construct a normalised decision matrix to transform all criteria dimensions to non-dimensional criteria which allow comparisons across criteria using Equation 3.6, such that

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i}^{m}(x_{ij}^{2})}} \; i = 1,\ldots,m;\; j = 1,\ldots,n \qquad 3.6$$

Step 3

Construct a weighted normalised decision matrix (V_{ij}) by multiplying each column of the normalised decision matrix by its associated weight so that the element matrix is

$$V_{ij} = r_{ij} \times w_{ij} \qquad 3.7$$

where w_{ij} is the weighted value of decision criteria.

Step 4

Determine the ideal and negative ideal solutions; the considerations here are for the benefits criteria (more is better) and for the costs criteria (less is better). This entails selecting the maximum value or element (v_j*) in each column of the weighted matrix where more or less is better (i.e. ideal solution) and the minimum value (v_j') where more or less is worst (i.e. negative ideal solution).

Step 5

Calculate the separation measures for each decision option; from the ideal solution (S_i*) as:

$$S_i * = \left[\sum (v_j * - v_{ij})^2\right]^{1/2}, i = 1,\ldots,m \qquad 3.8$$

where v_{ij} is the element of the weighted decision matrix and from negative ideal solution (S_i'):

$$S_i' = \left[\sum (v_{ij} - v_j')^2\right]^{1/2}, i = 1,\ldots,m \qquad 3.9$$

Step 6: Calculate the relative closeness to the ideal solution (C_i*)

$$C_i * = \frac{S_i'}{(S_i * + S_i')}; 0 < C_i * < 1 \qquad 3.10$$

and then select the decision option that is closest to 1

TOPSIS can accommodate a large amount of decision criteria, and it is easy to apply using positive and negative decision criteria. However, some of the challenges that may arise in its application include its suitability in solving decision-making problems having interdependent decision criteria and scenarios of group decision-making.

3.1.6. Hybrid MCDA techniques

There are complex decision-making problems that may defy the use of a single MCDA technique such as analysing group judgments on interdependent decision attributes and the need to generate appropriate decision priority weights to assess competing decision options, etc. In such cases, an integration of suitable MCDA techniques can produce hybrid techniques to solve complex decision problems. In the literature, hybrid MCDA techniques have been developed and applied conveniently to particular complex decision problems (Jato-Espino *et al*., 2014). For instance, AHP + PROMETHEE + Monte Carlo Simulation (MCS) was proposed by Gervásio and Simões da Silva (2012) as a hybrid tool to investigate the life-cycle sustainability of three types of bridges. AHP and PROMETHEE were considered to robustly address the problem, while the MCS component was used to evaluate inherent uncertainties. In a construction project bidding process, Liu and Yan (2007) applied a combination of AHP + Multi-criteria Optimization and Compromise Solution (VIKOR) to select the best contractor out of four contractors assessed under five decision attributes. AHP was used in the prioritisation of decision attributes, while VIKOR was used to carry out the final synthesis and ranking of the competing contractors. Notably, the synthesis process of VIKOR (Opricovic, 1998) is somewhat like TOPSIS and may be used to validate ranking outcomes from TOPSIS or vice versa. In a different contractor selection scenario, ANP + MCS was used as a hybrid MCDA technique by El-Abbasy *et al*., (2013) to assess the interdependencies and uncertainties among the decision priorities and ranking the contractor performances based on the best probabilistic score. In this research work, there is a potential of integrating single MCDA techniques to investigate group stakeholder opinions/judgements on different structural fire design decision criteria, prioritising independent and interdependent decision criteria as well as ranking the competing fire protection options.

AHP has been combined with TOPSIS to comparatively select a cost-effective seismic retrofitting option with reference to a case study, which involved assessing other single and hybrid MCDA techniques (Caterino *et al*. 2009). In a tunnel study, Golestanifar *et al*. (2011) applied AHP+TOPSIS to rank three tunnel excavation options based on seven conflictual decision criteria within methods of rock excavation and characterisation. In these studies, AHP was applied to prioritise the established decision attributes, which were synthesised and ranked using TOPSIS. The strengths of AHP+TOPSIS in analysing larger decision attributes, by integrating quantitative and other analytical priority scores in an MCDA, have not been investigated given the relatively small decision attributes assessed and the decision-making scenarios in previous studies. The inclusion of GMM to the AHP+TOPSIS for group judgement elicitation may not have been previously considered given that in many cases, hybrid decision analysis techniques are developed for single decision-making scenarios. Importantly, the combination of GMM+AHP+TOPSIS may not address specific complex decision-making problems in other disciplines. For instance, the need to account for known interdependencies and outranking of competing options which can be achieved by using the ANP and PROMETHEE respectively. More review on AHP+TOPSIS application is detailed elsewhere in (Jato-Espino *et al*. 2014) and (Behzadian *et al*. 2012).

3.2. Group Decision-Making Techniques

Most MCDA techniques were originally developed as single decision-maker techniques; hence, they come short in scenarios involving multiple decision-makers acting individually or as a group in a collaborative environment. In many group decision-making situations, the challenge remains to achieve group consensus, and there have been different ways proposed in the literature to achieve that such as frequent face-to-face meetings, the Delphi technique, brainstorming (Donegan, 2008), Cooke’s classical method (Cooke, 1991) etc.

Delphi technique can help decision-makers reach a consensus; this will entail identifying the decision-makers and using a questionnaire to elicit their opinions anonymously in two or more rounds. Here a facilitator will be needed to manage the process and provide anonymous summaries of decision-makers’ opinions/judgements/priorities at the end of each round of answered questionnaire; a consensus may be reached after a few rounds. Delphi technique enjoys wide acceptance in risk identification, group decision-making as it helps to reduce bias and unilateral influence on decision outcome. In the case of brainstorming, it will entail the gathering of experts or decision-makers in one room to elicit group opinions on a decision-making problem. Here personal criticisms must be avoided to prevent chaos and to achieve comprehensive information for risk or decision analysis. The brainstorming and Delphi techniques are traditional and most frequently used methods for group consensus. However, they may be considered time-consuming and onerous; the need to achieve a quick and suitable agreement among multiple decision-makers necessitates a transparent technique to support this aspect of the decision-making process.

The classical expert judgement elicitation method proposed by Cooke (1991) considers four basic principles of ‘rational consensus’ (*i.e. a group decision process, as opposed to a group consensus*) in eliciting expert opinions. The basic principles are:

- Reproducibility/accountability: All information and assessments from the decision-makers including the elicitation tools must be accessible to reviewers and reproducible.
- Empirical control: The decision-makers’ assessments/judgements must be subjected to empirical observation.
- Neutrality: The process must be made to elicit honest views of the decision-makers without subjecting them to any sanction or reward.
- Fairness: Decision-makers must be considered equally before aggregating their judgements.

Therefore, the Cooke’s method was developed to satisfy these principles. The method is a performance-based weighted averaging technique, which employs attributes of scoring rules (*mainly expert uncertainty distributions*) and referred to as the classical model.

The mathematical assumptions and validation of Cooke’s method can be found elsewhere in (Cooke, 1991; Colson and Cooke, 2017). The Cooke’s method has been widely used as a risk assessment and probabilistic risk analysis method in combining group expert judgements in different disciplines including public health, policy-making and engineering. The main steps used in implementing Cooke’s expert judgement elicitation method are summarised thus:

i. The experts (stakeholders) are nominated.
ii. The stakeholders are engaged individually in eliciting their judgements on the uncertainty of possible observations within their field of expertise.
iii. Honest stakeholder judgements on known or knowable variables within their field of expertise are also elicited.
iv. The stakeholders are considered as a statistical hypothesis and calibrated (i.e. rated with respect to statistical probability and information scores).
v. The calibrations or ratings are aggregated to achieve weights. The weights are formed to conform to proper asymptotic sense strictly, i.e. stakeholders are allotted the

highest expected weight in the future by stating their exact level of belief. Given the achieved weights, it is adjudged that statistical accuracy strongly prevails over being highly informed.

vi. In the end and given the stakeholder uncertainty distributions, the probability and information scores are employed to develop the performance-based weights for combining stakeholder group judgements.

Cooke's method can be very useful in achieving administrative or political consensus on scientific issues, evidence-based consensus on scientific issues of concern, etc. (Aspinall *et al.* 2016). Nevertheless, the method has been criticised in the literature regarding its implementation rigour; that is the use of elicited data and software as opposed to simple averaging methods (e.g. equal weights averaging) which are readily understood and empirically more accurate (Clemen, 2008). Cooke's method was not applied in this research work given the amount of time and rigour required to engage and reengage the same chartered stakeholders. This was considered as impractical in a very busy and commercially driven professional environment. The stakeholder engagement plan approved and employed in this research considers that participant-stakeholders are to volunteer their time for an hour given their different locations, very busy work schedules and the commercial/business impact on their respective organisations regarding time spent outside work-related engagements.

In a participatory decision-making process involving single or multidisciplinary decision-makers, there are seamless aggregation methods used along with MCDA tools to achieve group decision-making. Examples of group decision-making techniques with MCDA tools include: extended goal programming (EGP), (Nordström *et al.*, 2012); weighted/arithmetic mean method (W/AMM) and weighted/geometric mean method (W/GMM) developed to support AHP. W/AMM and W/GMM are of interest to this research due to their simplicity and flexibility when used with several MCDA techniques.

3.2.1. Weighted arithmetic and geometric mean methods (W/AMM & W/GMM)

The AHP was originally developed as a single decision-maker MCDA technique; further development has introduced group decision-making (Saaty, 1989) for the aggregation of pairwise comparison judgements from several decision-makers. The pairwise comparison data aggregation in a group decision-making scenario is implemented at the third or fourth step of the AHP. Here decision makers' individual judgements from each category of decision criteria pairwise comparisons or individual priorities (i.e. criteria weights) are aggregated at the third or fourth steps respectively, using either the Weighted/Geometric Mean Method (W/GMM) or Weighted/Arithmetic Mean Method (W/AMM).

WGMM represents the weighted average ratio of decision makers' judgements in each category of pairwise or relative comparisons. It is used to aggregate individual judgements if a reciprocal scale (e.g. Table 3.2) was used in eliciting the judgements. The reciprocal scale includes ratio intervals (*e.g. ...3, 2, 1, 0, ½, 1/3...*). The idea is to satisfy unanimity and homogeneity (*i.e. if all stakeholders judged a ratio x times larger, then their aggregated judgements must be x times larger*). In mathematical terms, if $x_i \geq z_{i,\ i} = 1, 2\ldots, n$ then $\sqrt[n]{\prod_{i=1}^{n} x_i} \geq \sqrt[n]{\prod_{i=1}^{n} z_i}$ provided $x_i \geq 0$ *and* $z_i \geq 0$.

The arithmetic mean is the most conventional method for averaging elements if an ordinal scale of numbers (*i.e. a scale of numbers in a sequential order, e.g. 1, 2, 3, 4, 5..., n*) was used to elicit stakeholder judgements. W/AMM is the weighted average interval of the same decision-makers' judgements, but in this case, it is more suitable for aggregating individual priority scores (*i.e. Eigenvectors/performance scores/weights from AHP*) to achieve the desired unanimity and homogeneity.

In mathematical terms, if $x_i \geq z_{i,\ i} = 1, 2..., n$ then $\sum_{i=1}^{n} \frac{x_i}{n} \geq \sum_{i=1}^{n} \frac{z_i}{n}$ provided $x_i \geq 0$ *and* $z_i \geq 0$.

These methods are also referred to as GMM and AMM when decision-makers are assumed to have the same weight or have equal importance.

The WGMM and WAMM aggregation methods have attracted some criticisms with respect to their transparency and suitability in achieving group consensus. For instance, Ramanathan and Ganesh (1994) demonstrated that W/GMM and W/AMM satisfied the most common social choice axioms except "Pareto optimality" and "independence of irrelevant options" respectively. Pareto optimality axiom implies that if decision-makers DM1, DM2 and DM3 most preferred options O1 to O2 and O3, the outcome of aggregating the decision-makers' priorities must show the same decision-makers' preference. The effect of "independence of irrelevant options" (i.e. when a new and irrelevant decision option is introduced to the set of assessed options) on AHP outcomes was deemed negligible. Ramanathan and Ganesh (1994) and Donegan (2008) also mentioned the issue of unequal importance and influence of decision-makers in a decision panel, which may need strategies to weight the participating decision-makers. This issue was deemed as onerous in group decision-making using the WAMM or WGMM due to the need for a super decision-maker above the group; however, the super decision maker's acceptability by the group becomes another problem. Hence, Ramanathan and Ganesh (1994) proposed the Eigenvector method of weight derivation as an aggregation method that satisfies the major social choice axioms, achievable in social policy-making if a panel of experts can act as a group to weight themselves using the AHP-pairwise comparison. Nonetheless, Forman and Peniwati (1998) argued against the conclusions of Ramanathan and Ganesh (1994) in which they also demonstrated that neither WGMM nor WAMM violates the mentioned axioms especially in scenarios where individual decision-makers agree to act as a group for the common good of achieving a solution. The group is now treated as a "new individual", whereby individual priorities do not matter rather any individual-inconsistent judgement can be checked and revised. They also suggested that the proposed Eigenvector aggregation method holds if the weights for determining decision-makers' priorities are the same as those used in aggregating their preferences in the initial problem, which may not always be the case.

There have been further studies on group decision-making with the AHP/ANP for the aggregation of divergent or dispersed judgements of decision-makers towards appropriate consensus. Saaty and Vargas (2007) have shown in their work that GMM cannot be applied in scenarios where decision-makers are unable to achieve consensus, and there are significant dispersed judgements (i.e. non-homogeneity of group judgements). Building on this inadequacy of GMM, Scala *et al*. (2016) developed an approach referred to as the Principal Components Analysis (PCA) to account for judgement dispersions and when decision-makers are not keen and/or unavailable to revise their previous judgements. PCA regard the decision-makers as variables for each paired comparison and derive their weights from the first principal components (i.e. Eigenvectors from the covariance of the comparison matrices defined as logarithm matrices) for the aggregation of their judgements with the weighted geometric mean. Hence, Scala *et al*. (2016) assume that the variances of decision-makers' judgements are inversely proportional to their weights. This may not hold in all group decision-making scenarios. For instance, in the case of the current research problem, some decision-makers' influences on the overall design decision on fire protection of a specific steel building are intuitively or implicitly known and must be therefore appropriately accounted for. The PCA-based approach may produce weights unacceptable to the more influential stakeholders in the decision-making process.

Given the arguments on achieving aggregated group judgements or priorities, it is safe to say that the application of any of the aggregation methods in combination with the AHP is dependent on the group decision-making scenario and other limitations. When decision-makers are deemed to act together as a group or as separate individuals to provide their pairwise comparison ratings or judgements on decision criteria with the AHP, the WGMM is successfully used to aggregate individual ratings and criteria weights or priority scores (Forman and Peniwati, 1998). Xu (2000) demonstrated that, given individual consistent pairwise comparison ratings, the aggregated group judgement matrix would also be within consistency limit if WGMM is used for the aggregation process and the Eigenvalue method for the AHP-prioritisation. The GMM is deployed in AHP decision analysis using Equation 3.11 (Forman and Peniwati, 1998) such that:

$$Z^{[G]} = (z_{ij}{}^{[G]}), \text{where } z_{ij}{}^{[G]} = (z_{ij}{}^{[G]})^{a_p}, i, j\{1, n\} \qquad 3.11$$

Where $Z^{[G]}$ is the geometric mean of the group; $z_{ij}^{[G]}$ is the aggregated judgements for the compared criteria or options *i* and *j*; *a* represents the number of decision makers, *p* is the p^{th} decision-maker with weight represented as α_p. The value for α_p is dependent on the weights assigned to decision makers, and $\alpha_p = 1/p$ if the decision-makers are assumed to have the same weight.

3.3. Conclusion on Adaptable MCDA Techniques in Solving the Research Problem

After the review of relevant literature, the need to answer the research questions in Section 2.3.2 and achieve the research objectives, this research considers:

That MCDA has been employed in solving fire safety-related problems but was limited to fewer decision attributes, single decision-making scenarios, potential stakeholder skewed judgements and unresolved design decision uncertainties (see Section 3.1.1.2). Hence, this research project is carried out to extend the knowledge in applying decision analysis and stakeholder decision-making process in the fire safety engineering discipline i.e. to improve on the shortcomings of previous scholarly works as discussed in Section 3.1.1.1. To realise this, the research team considered as valuable: firstly, test the stakeholder decision-making process/tools on a general case study of steel framed buildings using larger data from multiple stakeholder views to understand their adaptability strengths and limitations in a group decision-making. Then develop an adaptable technique and narrow the process/technique to a specific case study using a virtual building. Therefore, this influences the broad research space/research title to cover the investigations to be achieved in the project. This research decision is without prejudice that human beings can be unconsciously biased to specific decision attributes, preferences or vested interests in particular technologies/suppliers. However, the essence of MCDA techniques is to capture these varying views or interests based on the intensity of the participant-experts' feeling, normalise and prioritise these views to show the criteria importance levels which may be revised for synthesis and ranking. Stakeholder judgement sensitivities can be tested as well to improve the process

The Analytical Hierarchy and Network Processes (AHP and ANP) provides the platform or goal-rating structure on which fire design stakeholder goals/views/opinions can be identified and extracted. This is premised on the fact that AHP/ANP have "trademark" structured questions for the decision-maker/s that put the decision goal, criteria and competing options in practical contexts and perspectives, unlike PROMETHEE and TOPSIS. The decision-maker/s views, judgements, and ratings are traditionally entered as numbers or elements in a judgement matrix, following a reciprocal fundamental scale. Hence, the AHP/ANP questions, reciprocal scale, and matrices can be easily used to develop a questionnaire or goal-rating document to engage fire design stakeholders.

The application of group multi-criteria decision analysis is considered to analyse fire design stakeholder views toward balancing their goals for suitable design decision-making. The adopted techniques for further investigation and application include Geometric Mean Method-Analytic Hierarchy Process (GMM-AHP); Weighted/Geometric Mean Method-Analytic Network Process (WGMM-ANP). The GMM-AHP and W/GMM-ANP are adopted to address the shortcomings of other AHP applications in fire safety research discussed in Section 3.1.1.2. These shortcomings include accounting for scenarios of multiple decision-makers' judgements, managing outright dominance of a decision criterion. The aggregation of individual stakeholder judgements using W/GMM can potentially manage multiple stakeholder views, while the AHP-synthesis in distributive and ideal modes can potentially address performance and dominance of decision criteria (*AHP-Step 5*).

AHP in comparison with the WSM, WPM, PROMETHEE-1 MCDA techniques typically considers the analysis of both benefits and costs attributes of a decision problem qualitatively and quantitatively. This is suitable for application in this research project because the structural fire design decision-making process may consider costs decision criteria such as constructability, financial risk management, and benefits decision criteria such as building aesthetics, structural fire resistance, etc. AHP also provides a logical and reciprocal pairwise comparison rating scale to support both single and group judgements (i.e. GMM) on decision elements; it uses transparent criteria weighting procedure and synthesis toward complete ranking of the competing options and allows consistency checks of stakeholder judgements.

The Analytic Network Process (ANP) is a generalisation and extension of AHP whereby possible interactions or influences between dependent and interdependent decision attributes in complex decision problems can be assessed. Therefore, ANP is built on the concept of 'influence' to give decision-maker/s the opportunity to go beyond the top-down AHP-approach in decision-making processes. Given that it is the state-of-the-art MCDA technique built on the AHP, it is considered here to account for possible interdependencies among steel structural fire design decision criteria which may not be feasibly achieved using other MCDA techniques.

The use of TOPSIS in many cases will depend on data generated from application of other risk or decision analysis techniques to complete the initial decision matrix. However, its procedure of synthesis whereby multidimensionality is managed through normalisation and its seamless analysis of both qualitative and quantitative conflicting decision attributes sets it up as a suitable ranking tool. Hence, the application of TOPSIS in this research is best considered as a component of a hybrid MCDA technique that integrates, Geometric Mean Method (GMM) + Analytic Hierarchy Process (AHP) + Technique for Order of Preference by Similarity to Ideal Solutions (TOPSIS), with the acronym, GAT. Importantly, GAT is potentially the hybrid decision analysis technique considered for development as a key deliverable of this research project, which depends on successful investigation and application of its adjoining components.

The considered MCDA techniques are geared toward achieving the clearest identification of fire design stakeholder goals, analysis of stakeholder views as well as ranking the competing steel structural fire protection options. The ranked options are expected to show stakeholder preferred options in protecting steel structures in fire. However, further evaluation may be needed to critically assess the ranked options due to the statistical significance of participant-stakeholders regarding data skewness. In many practical scenarios, most stakeholders may lean toward specific decision criteria, thereby causing a skewed overall decision, which may require optimisation.

The following chapters will investigate AHP through a pilot study, apply GMM+AHP and W/GMM+ANP to extract individual judgements of real fire design stakeholders and integrate quantitative structural fire analysis and fire protection options' costs using GAT to balance or optimise stakeholders design decision-making.

4. BALANCING STAKEHOLDER VIEWS FOR DECISION-MAKING IN STEEL STRUCTURAL FIRE DESIGN[1]

4.1. Introduction

There are many applied fire protection options to achieving specified design objectives, but there is the need to identify a strategy that can satisfy at best the different and sometimes conflictual stakeholder desires, thereby reducing structural fire design uncertainties.

This research proposes a three-stage approach to address this issue:

(i) stakeholder engagement to identify and extract stakeholder desires;
(ii) decision analysis, and;
(iii) risk-based parametric study.

This chapter focuses on the first two stages. The first stage describes the process of identification and extraction of stakeholder desires in steel structural fire design from literature and structured interviews through a stakeholder engagement process. The second stage of the decision-making process is demonstrated using simple stakeholder goal-rating of opinions on various decision criteria and multi-criteria decision analysis (MCDA). The use of analytic hierarchy process (AHP) is used to manage the multiplicity of stakeholder views on common decision-criteria, manage possible inconsistent goal-rating, and to rank the different proposed passive fire protection options. The final stage of the process includes benefits-costs calculation which supports fire design stakeholder decision-making.

In the following sections, building on findings from the literature, a decision management framework was developed and then proposed for the use of AHP to manage divergent desires of steel structural fire design stakeholders. The framework and a pilot study example are used to demonstrate the applicability of AHP in steel structural fire design decision-making.

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[1] Part of this chapter's contents has been published as Akaa, O.U., Abu, A., Spearpoint, M. and Giovinazzi, S. (2015). "Balancing stakeholder views for decision-making in steel structural fire design", *Proceedings of 2nd International Conference on Performance-Based and Life-Cycle Structural Engineering*, D. Fernando, J. Teng, J. L. Torero, eds., Brisbane, Australia, 983-992.

4.2. Proposed Framework

The first part of the approach in balancing stakeholder goals is to establish the decision-making problem, inherent attributes and the competing options. The stakeholders are then engaged in a structured discussion to elicit their views which are then analysed toward an optimised decision-making outcome. Figure 4.1 shows the proposed framework for balancing fire design stakeholders' goals for decision-making in steel structural fire design. The framework follows the risk management process in AS/NZS ISO 31000:2009 (Figure 2.9). Figure 2.9 says, establish the risk context, identify risks, analyse and evaluate risks and treat risks. The establishment of the risk context is covered by "defining the design decision problem and attributes" in Figure 4.1. The three-phase stakeholder engagement process provides the opportunity to identify risks. The stakeholder analysis stage which applies MCDA-AHP is related to risk analysis and evaluation. When making a balanced design decision at the end of AHP implementation, it can be inferred that risks are being treated as illustrated in the framework.

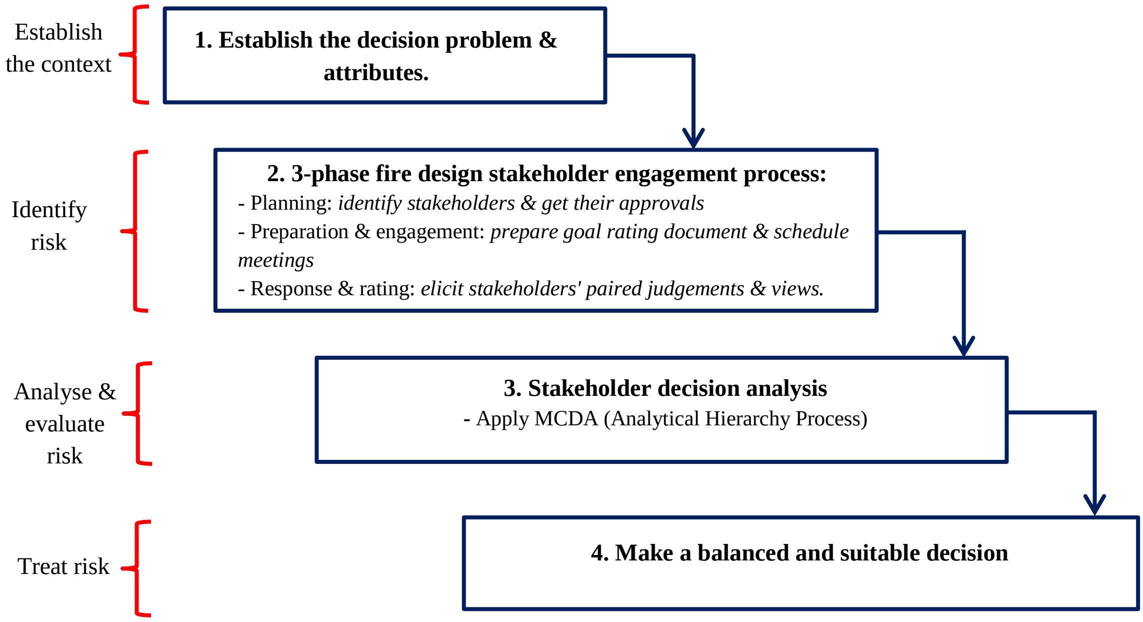

Figure 4.1. Proposed stakeholder decision management framework.

Notably, the critical stage in the decision management framework is the 3-phase stakeholder engagement process which involves planning, preparation and engagement, response and rating phases. The planning phase includes identification of the stakeholders involved in the decision-making for an appropriate design option and getting their consent for stakeholder meetings. Meetings are scheduled during the preparation and engagement phase as well as developing a structured questionnaire or goal rating document for participatory discussions during the response and rating phase. In the participatory discussion, the stakeholders are given the opportunity to rate their fire protection preferences and decision criteria in designing steel buildings for post-flashover fires.

In Section 0, the Analytic Hierarchy Process (AHP) has been discussed as a viable Multi-Criteria Decision Analysis (MCDA) Technique in balancing the divergent views of stakeholders toward suitable structural fire design decision-making. In the following Section, a pilot study is conducted to test the applicability and viability of AHP through the proposed stakeholder decision management framework (Figure 4.1).

4.3. Pilot Study Example

To implement Stage 1 of the proposed framework and the AHP-step 1, the goal of the pilot study was to *'choose a cost-effective fire protection option for a steel-framed building'.* In establishing the decision attributes and competing options, this study relied on literature. Research has identified key decision criteria and sub-criteria (NZFS 1975; Alvarez *et al*. 2014 and Park *et al*. 2014) as shown in Table 4.1.

Table 4.1. Key and sub-decision criteria desired by fire design stakeholders

Key decision criteria	Sub-decision criteria
Economy (costs)	Building cost, constructability, maintainability
Socio-environmental	Environmental sustainability, human comfort
Effectiveness	Fire spread beyond compartment, business continuity
Safety	Clarity in design details and specifications, building regulation approval, accessibility for fire-fighting operations

The following passive fire protection options are nominated from the literature: *compartmentation, intumescent coatings, concrete encasement of steel (full or partial), board systems (e.g. gypsum, plaster etc.) and unprotected steel* (Spearpoint 2008; Buchanan and Abu, 2017). Notably, part of the pilot study was also to allow the researcher to explore the effects of the inclusion or not of some fire protection options or decision criteria. For instance, the inclusion of *compartmentation* among the fire protection options which is not an applied passive fire protection to steel structures. Another example is the key decision criterion, *socio-environmental* which may be better assessed in practice by considering *societal* and *environmental* as separate variables. The decision attributes (criteria and sub-criteria) and options are assumed to be independent of each other; however, the decision attributes were combined to assess the competing options based on the AHP procedure (*AHP-Step 1*). Two hierarchical trees of benefits and costs were constructed as also mentioned in the AHP procedure; these are shown in Figure 4.2 and Figure 4.3. The 'economy', key decision criterion, is separated from 'safety', 'socio-environmental', 'effectiveness' (deemed as benefits) and all economy-sub-criteria were identified as costs in this context. This is to allow for a broader view of the decision problem and thorough analysis of the competing variables (benefits and costs) to enable balanced decision-making (Saaty, 1994a). The establishment of the problem, criteria, competing fire protection options and completion of the benefits and costs hierarchical tree concludes the first step of AHP (Figure 3.2) as well as the first stage of the proposed framework (Figure 4.1).

For conducting this pilot study, ten full-time and part-time postgraduate students from the fire engineering programme at the University of Canterbury were chosen. Several of the students had had a few years of professional engineering experience or were currently employed by fire engineering companies. They are also regarded herein as *quasi-stakeholders*. As part of the 3-phase stakeholder engagement process, the potential participant-stakeholders' consents must be appropriately sought for using approved information and consent documents. The quasi-stakeholders that participated in this pilot study gave their consent before the response and rating phase of the process.

4.3.1.1. The goal rating document

At the preparation and engagement phase, a goal rating document was developed to achieve meaningful discussion and elicitation of the fire design stakeholder views and preferences. It was structured for easy implementation of the pairwise comparisons and judgement matrices stages of the AHP (Figure 3.2). The document consisted of the following:

- A cover and participant-stakeholder details page;
- Saaty's reciprocal rating scale (as shown in Table 3.2);
- An AHP fundamental question which reads:

"Compare (criteria or element A) and (criteria or element B) with respect to choosing a cost-effective fire protection option for a steel-framed building";

- Pairwise comparison or judgement matrices of the key and sub-decision criteria, as illustrated in Table 4.1, as well as the competing options. The judgement matrices were presented in categories representing the AHP Categories A-C types of pairwise comparison as stated in *AHP-Step 2*; and
- A list of potential stakeholder category.

An example of the goal rating document used in the pilot study is shown in Appendix **1**. The goal rating document aided the participant-stakeholders in rating the fire protection options and decision criteria for steel structural fire design according to the intensity of their feelings during the scheduled meetings.

4.3.1.2.Pairwise comparisons, aggregation and analysis

The participants in this study carried out the pairwise comparison ratings of the decision criteria and options individually during the response and rating phase of the stakeholder engagement process. The pairwise comparisons were carried out as described in the AHP procedure in categories as described in *AHP-Step 2*. The fire service personnel's result from the pairwise comparison of the fire protection options with respect to the goal (Category A) in the pilot study is shown in Table 4.2.

In this matrix, it is seen that the participant having used Saaty's rating scale, rated board systems as 'much more important' (see Table 3.2) than compartmentation and allotted the value 5 to board systems in the column on the left of the matrix. By virtue of the binary nature of the preferences, this choice meant that the reciprocal of 5 i.e. 1/5 was entered into the first row in the column under board system to show compartmentation as being 'much less important than' board systems. After the goal-rating exercise, participants selected the stakeholder that best represented their rating. From a simple look at their ratings, the author categorised their desires and preferences as shown in Table 4.3. The completion of the goal rating exercise concluded the second stage of the framework and AHP (Figure 3.2).

The divergent views of the participants can be seen in Table 4.3 including the likely dominance of a specific decision criterion, fire protection option and data skewness. Therefore, decision analysis is considered necessary to assess the competing fire protection options with respect to the key and sub-decision criteria to rank the fire protection options appropriately.

Given that each participant carried out their ratings independently, there is the need to aggregate the results of the rated stakeholder desires to form a joint or single group judgement matrix for each category of pairwise comparisons. This was implemented at the AHP-judgement matrices stage (*i.e.* Step 3).

Table 4.2. Pairwise comparison matrix for fire protection options by the fire service personnel in the pilot study (Category A)

	Compartmentation	Intumescent coatings	Board systems	Concrete encasement	Unprotected steel
Compartmentation	1	1	1/5	1/3	1
Intumescent coatings	1	1	1/3	1	1
Board systems	5	3	1	3	1
Concrete encasement	3	1	1/3	1	1
Unprotected steel	1	1	1	1	1

GMM was used for all the aggregation calculation as given in Equation 3.11. One of the aggregated results is shown in Table 4.4. In this case, Table 4.4 (a) is $Z^{[G]}$; $z_{ij}^{[G]}$ is the result from the 10×10 matrix-multiplication of the individual pairwise comparisons of the benefits key decision criteria (Category A) from the 10 participants and to the power of α_p. Notably, this pilot study assumed that all the participants are decision makers having same weight ($\alpha_p = 1/a$), where $a = 10$ (number of participants). The completion of judgement aggregations concluded the third Step of AHP.

In the prioritisation stage (*i.e.* Step 4), the AHP-weighting calculation (Section 3.1.1.1) was employed to weight the aggregated ratings or judgements. Table 4.4 (b) shows the performance scores (weights) of the aggregated benefits key decision criteria. Here, 'safety' has the highest performance score, 0.48 from the weighting calculation and the summation of the performance scores equal 1.00.

Table 4.3. Divergent views of participants in the pilot study

Stakeholder role	No. of participants	Key decision criteria in order of importance to participants	Preferred passive fire protection option of participants
Building owners	1	Effectiveness, economy (costs), safety, socio-environmental	Compartmentation
Architects	2	Socio-environmental, effectiveness, safety, economy (costs)	Intumescent coatings
Building contractors	1	Economy (costs), safety, effectiveness, socio-environment	Concrete encasement of steel (full or partial)
Fire protection engineers	2	Safety, effectiveness, socio-environmental, economy (costs)	Compartmentation
Structural fire engineers	2	Safety, effectiveness, economy (costs), socio-environmental	Concrete encasement of steel (full or partial)
End-users (community)	2	Safety, effectiveness, socio-environmental, economy (costs)	Compartmentation

Consistency checks were carried out for all the aggregated pairwise ratings using the AHP guideline and Equation 3.1. The pairwise comparisons of the benefits key decision criteria gave $CR = 0.10$, which was in the margin of acceptability. The performance scores achieved from the AHP-weighting calculation of each category are indicated on the hierarchical trees in their respective levels as shown in Figure 4.2 and Figure 4.3.

The benefits sub-criteria aggregated matrices achieved from their pairwise comparisons with respect to their parent-key decision criteria, were also weighted. In this scenario, the sub-criteria initial weights were multiplied by the performance score of their respective parent-key decision criterion to achieve their performance scores. The calculated sub-criteria performance scores are indicated at Level 3 on Figure 4.2. In the benefits hierarchical tree, the summation of the sub-criteria performance scores (Level 3) under each key decision criterion of Level 2 equals the performance score of their respective parent-key decision criterion (Level 2). The performance scores of the sub-criteria under ‘economy’ were calculated using the same AHP-weighting procedure. Here ‘economy’ was treated as a single variable; hence all sub-criteria performance scores sum-up to 1.00 as indicated in Figure 4.3.

Table 4.4. Group aggregated matrix and weighting of key decision criteria category

(a) Group aggregated matrix **(b) AHP-Weighting**

	Safety	Socio-environmental	Effectiveness	Performance scores (weights)
Safety	1.00	1.62	2.19	0.48
Socio-environmental	0.61	1.00	0.81	0.24
Effectiveness	0.45	1.53	1.00	0.28
			Total =	1.00

In completing the decision analysis for this pilot study, the performance scores of the competing fire protection options, achieved from their pairwise comparisons with respect to all sub-criteria in the pilot study (i.e. Category C) were synthesised in the distributive and ideal modes. The synthesis of the decision problem was achieved by the process explained in *AHP-Step 5*; the results are presented in Table 4.5. In the distributive synthesis mode, compartmentation is the dominating fire protection option as shown in Table 4.5, hence the normalised benchmark value of 1.00 seen in the compartmentation column (CPT) in the ideal mode.

Finally, the benefits and costs ratios of the preference scores of the competing fire protection options were calculated using Equation 3.3. The calculation outcome showed that concrete encasement of steel in the distributive and ideal modes had the highest scores, 4.01 and 4.09 respectively and it was the top-ranked option. These benefits and costs ratios were also presented in a scatter plot for the ideal synthesis mode. The resultant top-ranked fire protection option, ‘concrete encasement of steel ‘had the highest benefit and least cost from the AHP-decision analysis of the different desires of the participants as shown in Figure 4.4. The ranking of the competing fire protection options concluded Stage 3 of the framework and *Step 5* and partly *Step 6* of AHP.

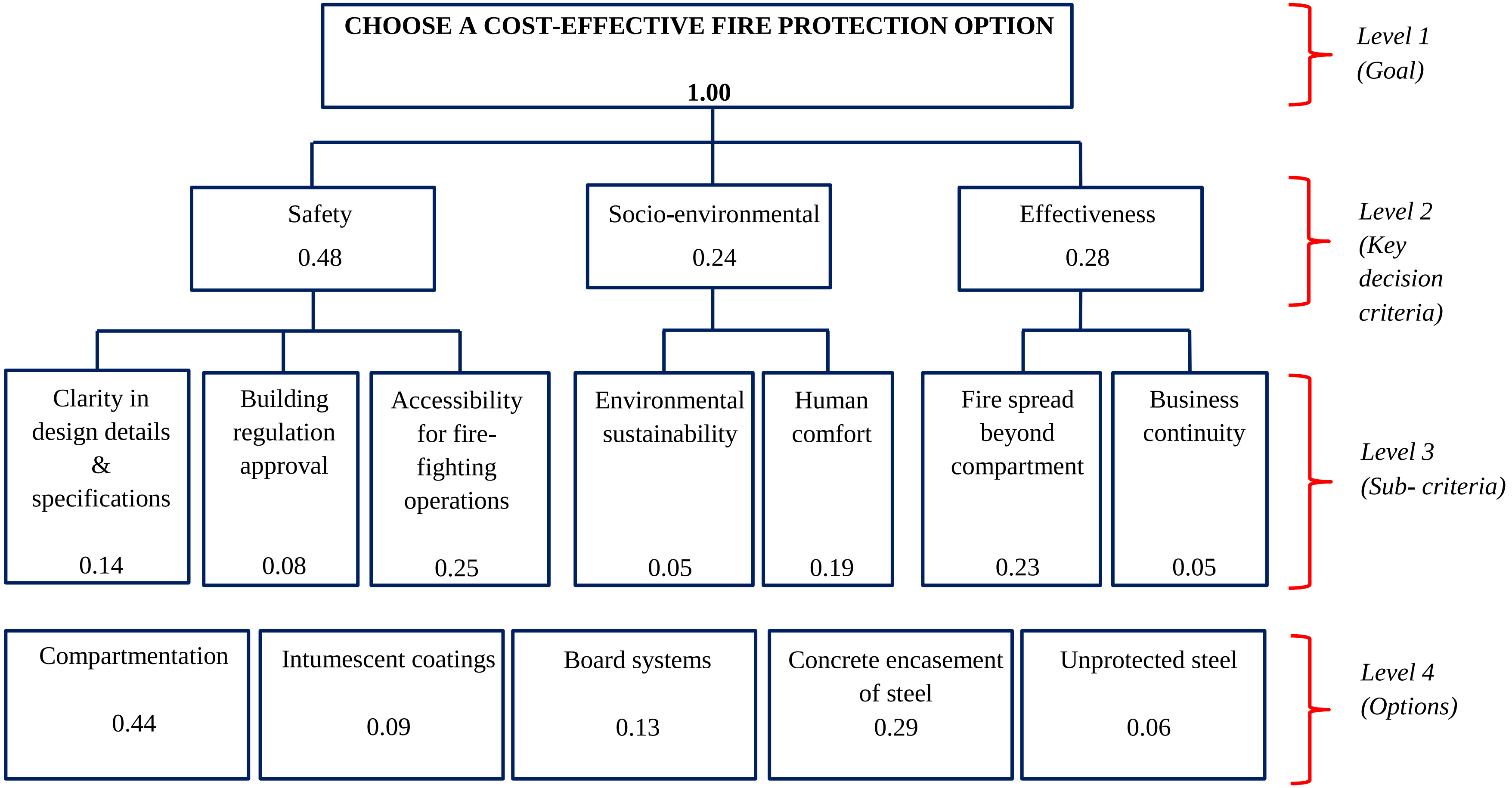

Figure 4.2. Ideal mode-AHP-benefits hierarchical tree of the decision criteria and passive fire protection options.

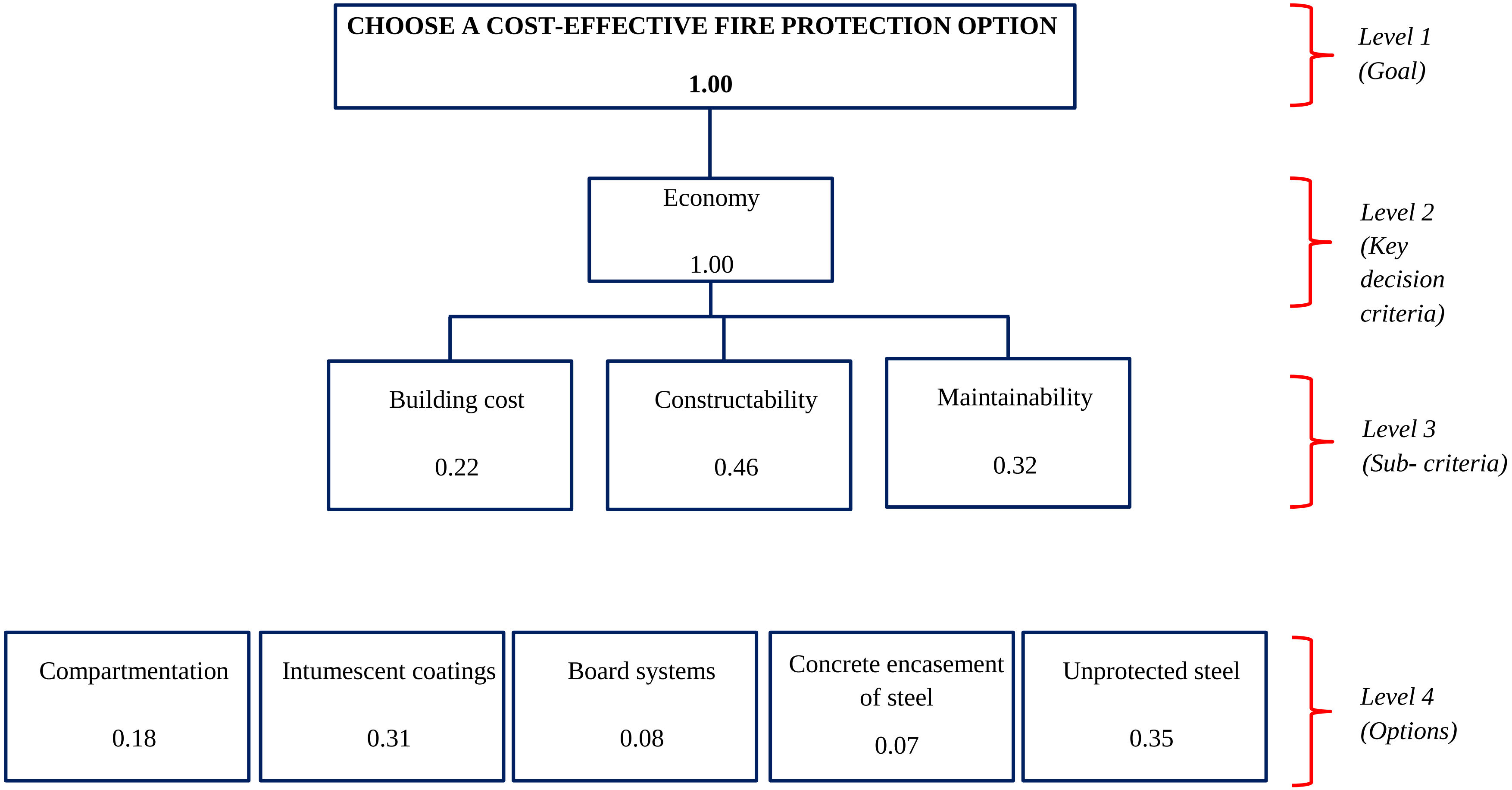

Figure 4.3. Ideal mode - AHP - costs hierarchical tree of the decision criteria and passive fire protection options.

Table 4.5. AHP-distributive and ideal mode synthesis to determine preference scores and ranking of options.

	Distributive mode						Ideal mode				
	Performance scores	CPT	ITC	BST	CES	UPS	CPT	ITC	BST	CES	UPS
Benefits sub-criteria											
Clarity in design details & specifications	0.14	0.44	0.07	0.12	0.31	0.06	1.00	0.16	0.27	0.70	0.14
Building regulation approval	0.08	0.44	0.07	0.12	0.31	0.06	1.00	0.16	0.27	0.70	0.14
Accessibility for fire-fighting operations	0.25	0.44	0.07	0.12	0.31	0.06	1.00	0.16	0.27	0.70	0.14
Environmental sustainability	0.05	0.52	0.07	0.18	0.18	0.05	1.00	0.13	0.35	0.35	0.10
Human comfort	0.19	0.36	0.15	0.11	0.33	0.05	1.00	0.42	0.31	0.92	0.14
Fire spread beyond compartment	0.23	0.57	0.05	0.13	0.21	0.05	1.00	0.09	0.23	0.37	0.09
Business continuity	0.05	0.27	0.14	0.22	0.27	0.09	1.00	0.52	0.81	1.00	0.33
Benefits preference scores (B_i)		**0.45**	**0.08**	**0.13**	**0.28**	**0.06**	**0.44**	**0.09**	**0.13**	**0.29**	**0.06**
Costs sub-criteria											
Building cost	0.22	0.06	0.32	0.10	0.07	0.46	0.13	0.70	0.22	0.15	1.00
Constructability	0.46	0.07	0.41	0.08	0.07	0.36	0.17	1.00	0.20	0.17	0.88
Maintainability	0.32	0.40	0.17	0.08	0.07	0.28	1.00	0.43	0.20	0.18	0.70
Costs preference scores (C_i)		**0.17**	**0.31**	**0.08**	**0.07**	**0.36**	**0.18**	**0.31**	**0.08**	**0.07**	**0.35**
B_i / C_i		**2.61**	**0.27**	**1.53**	**4.01**	**0.16**	**2.45**	**0.29**	**1.54**	**4.09**	**0.16**

Key: CPT – Compartmentation, ITC – Intumescent coatings, BST- Board systems, CES – Concrete encasement UPS – Unprotected steel.

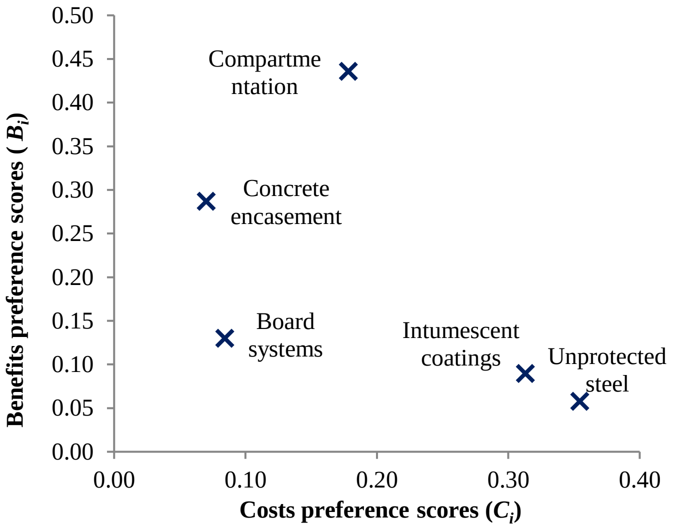

Figure 4.4. Ideal mode benefits versus costs preference scores for the passive fire protection options.

In the end, the stakeholder decision depends on whether the respective benefit decision attributes of each ranked option outweigh costs or costs decision attributes outweigh benefits. In other cases, the stakeholders may select the top-ranked option. Importantly, the stakeholder may test ranking sensitivities by revising their judgements. In any case, the process supports an informed decision, which effectively concludes the implementation of the AHP and the decision management framework (Figure 4.1).

4.4. Discussion

The decision criteria and fire protection options assessed in the pilot study were based on the general view of steel structural fire design objectives and stakeholder opinions in the literature. Importantly, *compartmentation* and *unprotected steel* are not applied passive fire protection materials on steel structures. Their use in this pilot study was to investigate the effects of their inclusion or not in the decision-making process toward preparing for the engagement of chartered and experienced fire design stakeholders. Notably, the inclusion of *compartmentation* may have influenced the ranking order achieved from the analysis, given its apparent dominance observed from the AHP-distributive synthesis mode. However, all the existing decision criteria and passive fire protection options in the design of buildings for post-flashover fires were not exhaustively used in this Chapter, given that it is a pilot study aimed at showing the potential of the chosen technique/process in optimising stakeholder decision-making. Other decision criteria, e.g., building aesthetics (Park *et al*. 2014), profit-making, code compliance etc.; and passive fire protection options, e.g. sprayed on cement-base material, water filling of hollow steel sections (Spearpoint 2008) could be included in the more formal investigation. Fire industry stakeholders should be allowed to include all decision criteria and options they deem necessary in structural fire design of steel buildings during the engagement stage.

In using AHP, the fire design stakeholders can participate in pairwise ratings as a collaborative group or as individuals at different times and places as in the pilot study, where GMM could be used to aggregate individual ratings to achieve single group judgements. The capability of AHP and other MCDA solutions to manage stakeholder desires and ranking of available options were designed to help stakeholders to rank their options, but not for the tool to make decisions for the users. For instance, in a scenario where the participants in the example had been more interested in the option with the highest benefits regardless of cost, then the second-ranked fire protection option, ‘compartmentation’ would be the obvious choice. This implies that a top-ranked option is not always the final choice. However, the analysis and ranking enable easy decision-making as it suits the stakeholders.

The dominant option from the benefits synthesis may not be top-ranked one, given the costs synthesis as seen between compartmentation and concrete encasement shown in Table 4.5. In addition, the dominant or popular option among the stakeholders before the MCDA may not also be the top-ranked one at the end of the analysis. This is clearly where the initial dominance of compartmentation before the decision analysis as shown in Table 4.3 is compared with its rank after the analysis shown in Table 4.5 and Figure 4.4. Another fundamental capability of the AHP shown in this decision-making process is the transition from the performance scores to the preference scores of the competing options using two distinct synthesis modes.

In the pilot study, the different calculation procedure for the distributive and ideal synthesis modes did not produce a difference in the ranking of the fire protection options. Instead there was only a minor change in the preference scores as shown in Table 4.5. This may not always be the case in practice or scenarios of complex decision hierarchies and data skewness. Saaty and Vargas (1993) showed that there were minor differences in results produced by the distributive and ideal modes in a simulation. A further study of balancing the views of fire industry stakeholders would be an opportunity to investigate these differences in a realistic scenario.

In relation to Millet and Saaty (1999), the ideal mode can be deemed appropriate for the synthesis of the competing passive fire protection options with respect to the benefits and costs sub-criteria in the pilot study. This is due to the assumed independence of the decision attributes and competing options as well as the need to evaluate the performance of each option relative to the dominant option. It is noteworthy that in practice, the relative importance of the options may be dependent on the considered decision criteria. In such case, the decision-making problem is solved using the analytic network process (ANP) as discussed in Section 3.1.4.

4.5. Conclusion

The purpose of this Chapter was to explain and demonstrate a decision-making process geared toward balancing divergent stakeholder views in steel structural fire design. The pilot study demonstrates the potential of the MCDA-AHP approach in solving decision problems. The sample population of ten student-participants was insufficient to test the process in real decision-making for fire protection of steel-framed buildings. This is because the student-participants may not be considered as having the requisite professional experience/expertise in many design decision-making scenarios. The expert views of chartered/experienced fire design stakeholders are needed for suitable design decision-making. However, the process explained here is not about the outcome rather it was to test the viability of AHP in analysing decision-making problems inherent in steel structural fire design. Hence, the results should not be used as a decision for fire protection.

This study also noted the effects of the weaknesses of AHP in analysing unbalanced stakeholder desires in complex decision problems, these weaknesses include but are not limited to: outright dominance of a criterion or option at different categories of comparisons and inconsistencies of pairwise judgements. For instance, the example revealed some inconsistencies in the participants’ pairwise comparisons where consistency ratio (CR) is exactly 0.10, which is the limiting CR value (Saaty 1980). Coyle (2004) also mentions that items for pairwise comparisons are usually not more than seven. There are five fire protection options compared in Table 4.2. Hence, there is the likelihood of a problem of consistent comparisons if the study is extended to include other fire protection options. A critical assessment of the AHP-ranked fire protection options through a risk-based parametric study has been identified as an additional process to manage the weaknesses from the decision analysis. The research attempts to address this limitation in subsequent chapters, which also entailed the use of the proposed stakeholder engagement process to extract the views of real/chartered fire design stakeholders.

AHP was found to be a viable decision analysis tool, and it is proposed for use due to its potential in managing views of fire design stakeholders and helping them make suitable decisions toward designing better steel buildings for post-flashover fires.

5. A GROUP-AHP DECISION ANALYSIS FOR THE SELECTION OF APPLIED FIRE PROTECTION TO STEEL STRUCTURES[2]

5.1. Introduction

As discussed in Chapter 3, a great many MCDA techniques exist; the Analytic Hierarchy Process (AHP), proposed by Saaty (1980) is employed to solve the research problem. This is due to its simplicity, its ability to handle both cost and benefit criteria and its wide range of use, with no high assumptions and contradictions. It is also preferably used in the general derivation of a decision-maker's priorities based on sets of relative comparisons.

A pilot study was carried out in Chapter 4 which tested the AHP decision-making process on ten ‘quasi-stakeholders’ through a decision management framework. In this chapter, a group AHP technique application, referred to as the Geometric Mean Method-Analytic Hierarchy Process (GMM-AHP) is used to manage fire design stakeholder opinions on different decision attributes toward selecting suitable fire protection for steel structures. The stakeholders considered herein are experienced and chartered professionals currently practicing in the New Zealand building and fire engineering industry. It is noteworthy that individual professionals in New Zealand become chartered with Engineering New Zealand (EngNZ) after a minimum of 5-7 years of professional work experience in their respective fields. The professional must undergo structured professional development training and assessments while working prior to a final evaluation by a panel of chartered experts who had undergone the same process in their professional career. Importantly, the EngNZ context requires a demonstration of on-going technical competence in the field of expertise. This was considered as an objective criterion in electing the participant-fire design stakeholders for this study. The investigation carried out in this chapter is a general case study of balancing fire design stakeholder goals in structural fire design of steel-framed buildings.

In this study, GMM-AHP is implemented also to overcome the shortcomings of other AHP applications in fire safety research discussed in 3.1.1.2. The shortcomings include accounting

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[2] Parts of the contents of this chapter have been published as Akaa, O.U., Abu, A., Spearpoint, M. and Giovinazzi, S. (2016). “A Group-AHP Decision Analysis for the Selection of Applied Fire Protection to Steel Structures”, *Fire Safety Journal*, 86, 95 – 105.

for multiple stakeholders’ judgements scenarios, group judgement consistencies, stakeholder bias or dominance of a criterion in the decision-making process. The GMM component of AHP can potentially aggregate a larger sample size of individual fire design stakeholder judgement compared to that achieved in other applications of AHP in fire safety studies. The GMM-AHP addresses group judgement consistencies following the prioritisation or weighting of aggregated stakeholder judgements. The probable outright dominance of a decision criterion in the process can be managed through AHP-synthesis in different modes toward a balanced decision.

This Chapter also discusses divergent stakeholder views in steel structural fire design as extracted from discussions with fire design stakeholders during structured interviews, to give more insight into the decision-making problem. The viability of the GMM-AHP is demonstrated by assessing five fire protection options against 22 different decision criteria. The study is conducted based on a general case of structural fire design of steel-framed buildings exposed to post-flashover fire conditions. This is to ensure that the benefits of the AHP are easily highlighted and not obscured in a complex structural fire design decision-making given the variabilities of fires as earlier mentioned in Section 2.5. The decision criteria have been compared by 36 individual stakeholders from 12 fire design stakeholder categories through stakeholder engagement and structured research interviews. The key analyses results show the seamless aggregation of individual judgments elicited at different times and places, the importance levels of different stakeholder opinions and the systematic approach in ranking the proposed fire protection options for suitable decision-making.

5.2. Method

This chapter followed the stakeholder decision management framework proposed in Chapter 4 (i.e. Figure 4.1) and the AHP-steps (Figure 3.2), to demonstrate the application of the GMM-AHP in selecting applied fire protection to steel structures. The GMM-AHP was used given its potential of eliciting and managing multiple stakeholder views on design decision problems irrespective of the stakeholders’ availability to participate in the decision-making process at the same time and place or not. A typical AHP approach would require gathering the experts (stakeholders) into a room to decide on the design criteria and options collectively. However, the number, diversity and geographical distribution of the fire design stakeholders in this research project meant that gathering them in one place was not possible.

As such, the participant-stakeholders were engaged individually at different times and places, and their multiple views were aggregated and analysed using the GMM-AHP.

5.2.1. The assumed structural fire design decision criteria

Firstly, the AHP decision elements, i.e. goal, key decision criteria, sub-criteria and options for the decision-making problem addressed in this research are outlined. This is also to aid the reader's clear understanding of the prioritisation of the outcomes and insights into the perceived stakeholder preferences. The goal was defined as *"to select the most suitable fire protection option for steel structures for post-flashover fires"*. The term '*suitable*' used in the defined goal implies 'cost-effective' passive fire protection in a general context of structural fire design of steel-framed buildings; this explanation was given to all participant-stakeholders during the interviews. Following the defined goal, four structural fire design key decision criteria, namely *economy, safety, environmental* and *societal* were identified from literature (NZFS, 1975; HSNO, 1996; Spearpoint, 2008; Alvarez *et al.*, 2014; Park *et al.*, 2014) for this study. These key decision criteria were the main groups under which design sub-decision criteria were classified, as shown in Table 5.1. The design sub-decision criteria were based on general goals or interests of the potential fire design stakeholders; their goals may be conflictual as explained in Section 2.3.1.

The fire design decision criteria used here are not exhaustive. In structural fire design of specific steel buildings, the design decision criteria may include carbon footprint, air pollution control (i.e. for buildings having chemical storage), adhesiveness and durability of fire protection options. Notably, the GMM-AHP is sufficiently robust for the decision-makers to vary the decision criteria and sub-criteria as they prefer. The formulated sub-decision criteria in Table 5.1 are used in this study to demonstrate the applicability of GMM-AHP in a stakeholder decision-making process. All fire design sub-decision criteria relating to costs were classified under *economy*, while other sub-criteria were deemed as benefits and classified under the *safety, environmental* and *societal* decision criteria. This was done to allow a broader view of the decision problem and analysis of the competing variables under *benefits and costs* decision merits to enhance suitable decision-making following the AHP-procedure (Saaty, 1994a). The benefits and costs criteria were rated and analysed separately but combined at the end of the AHP-synthesis using Equation 3.3.

Table 5.1. Structural fire design key and sub-decision criteria

Key decision criteria	Sub-decision criteria	Explanation
Economy	Constructability (CA)	Cost and ease of applying the fire protection.
	Business continuity (BC)	Quick rebound of business activities after fire.
	Profit-making (PM)	Stakeholder financial gains from using the fire protection.
	Minimum material use (MMU)	Less application of fire protection product.
	Maintaining supply chain (MSC)	Retain relationship with fire protection suppliers.
	Financial risk mgt. & loss prevention (FRM)	Monetary loss from property damage and building insurance.
Safety	Fire risk assessment (FRA)	Identification and evaluation of potential fire hazard triggering factors and their consequences for design.
	Structural fire resistance (SFR)	Potential to maintain structural capacity in fire
	Pre-fire building resilience (PF1)	Residual capacity of the structure, given accidental/incidental impacts (e.g., earthquake, vehicle impacts) on structures before fire.
	Clarity in design details & specs. (CDD)	Clear and detailed design of fire protection options.
	Fire-fighting operations (FFO)	Effect of fire protection options on fire-fighters during operations.
	Fire spread beyond compartment (FSC)	Guarantee structural fire integrity beyond compartment and building.
	Maintainability (MA)	Ease of maintenance of the fire protection option.
Environmental	Environmental sustainability (ES)	Ensuring low environmental damage after fire.
	Environmental act/HSNO compliance (EAC)	Meeting or general submission to HSNO and other environmental laws.
Societal	Building aesthetics (BA)	Ensure visual appeal of the building.
	Human comfort (HC)	Ensure the relaxed feeling of end users of the building.
	All stakeholder involvement in design (ASI)	Involving insurers and end users (*e.g. business investors/real estate, customers in commercial building etc.*) in design briefs.
	Building regulation approval (BRA)	Achieve building and resource consent.
	Building use and features (BUF)	Intended use and characteristics of the building.
	Health and safety (HS)	Installation safety of a fire protection product and health effects during the lifespan of the building.
	Post-fire building resilience (PF2)	The ability of the building to be reused after fire.

In this Chapter, the following four applied fire protection options were investigated based on single-element design: *intumescent coatings (ITC), board systems (BST), concrete encasement of steel (CES)* and *sprayed on cement-based material or cementitious spray (SCM).* Another design option that was considered for assessment is *unprotected steel (UPS).* The decision goal, attributes and options outlined here were used to construct the benefits and costs hierarchical trees to complete the decision model which concluded *Step 1* of the process.

5.2.2. Stakeholder engagement plan and interviews

Following the decision management framework, described in Chapter 4, the three-phase stakeholder engagement process was applied. At the planning phase, 12 categories of fire design stakeholders were nominated and called the '*decision-makers*'. Some of the stakeholder categories were extracted from the literature (Alvarez *et al*. 2013; Park *et al*. 2014) and the rest were nominated by the researcher based on their potential involvement in conceptual and formulated structural fire design decision-making processes. The fire design stakeholder categories were: *architects, building consent authorities (authorities having jurisdiction), building contractors, building insurers, building owners, end users, environmental professionals, fire engineers, fire service (operational/engineers), manufacturers/suppliers of passive fire protection products, structural engineers, and others (e.g. building services engineers).*

It is noteworthy that some of the nominated stakeholders may not be involved in the design decision-making process of a specific building project. For instance, end-users are not traditionally involved in a design project and in the case of this study; it may be difficult to elicit their views, as they may not have knowledge of structural fire engineering. In another instance, some building owners may not know about the performance of unprotected steel in an optimally designed steel-framed building without being expressively informed by the fire and structural engineers. However, the inclusion of the above-nominated stakeholders is on the premise that the design decision-making process investigated herein can be applied at a project's conceptual stage where all potential design options and decision attributes are considered. At this initial stage, the views of all stakeholders can be considered early in the project to manage whole-of-life risks (*i.e. from the design of the building, construction, use, maintenance to disposal*) of the potential building asset.

Prior to engaging the fire design stakeholders, human ethics approval was obtained from the University of Canterbury Human Ethics Committee. This was to ensure that the research was being carried out reliably and that personal and professional rights of participants were not being violated throughout the process, by seeking the appropriate consents to carry out the research investigation. The approved human ethics documents are shown in Appendices 2(a) and 2(b). Importantly, all participant-stakeholders read the approved information sheet and signed the consent document (Appendix 2(c)) before participating in the process. For consistency and to obtain meaningful results, the interviewed individuals were experienced and chartered practitioners from reputable organisations within the fire and building industries in New Zealand. The completion of fire design stakeholder identification and consenting concluded the planning phase of the stakeholder engagement process.

As earlier explained in Section 5.2, it was not possible to engage the stakeholders at the same place and time, as such, structured individual interviews were conducted face-to-face with each of the stakeholders, as the means of extracting fire design stakeholder opinions. In the preparation and engagement phase (Figure 4.1) and prior to conducting the interviews, this study considered that an hour per individual stakeholder interview was considered appropriate to elicit stakeholder opinions/judgements. Notably, a structured interview for each stakeholder was considered more appropriate than surveys on the basis that interviews would give the opportunity to also extract stakeholders' professional and other comments as opposed to surveys that are implemented through questionnaires, and questions are fixed. Time limitation may also affect the efficient use of questionnaires given the very busy work schedules of chartered professionals. Nevertheless, an online survey was used to elicit stakeholder opinions from other jurisdictions. Their views were synthesised to compare with the views of New Zealand stakeholders of the same categories as presented in Section 5.2.3.2.

For the structured interviews, the goal rating document developed in Chapter 4 was revised to contain the relevant items listed in Section 4.3.1.1. In this case, the information in Table 5.1 was used to set-up the judgement matrices according to Categories (A-C) of the AHP-pairwise comparisons (*Step 2*). The interview questions for pairwise comparisons of decision attributes and options were structured in such a way as to avoid ambiguity and to obtain a reliable judgement or rating from stakeholders. In the revised goal rating document, the fundamental AHP-pairwise comparison question was presented in this form:

"*Compare (criteria or element A) and (criteria or element B) with respect to selecting the most suitable passive fire protection on steel elements for fully developed fires"*.

This key comparison question was also applied to all pairwise comparisons presented in the matrix tables and representing the different hierarchical levels of the AHP decision model. A sample of the revised goal rating document is included in Appendix 2(d). The successful development of the goal rating document and schedule of interview meetings concluded the preparation phase as shown in the decision management framework (Figure 4.1).

In the response and rating phase, the fire design stakeholders were interviewed. Their paired judgements on the decision problem were elicited, and they also provided further comments on the competing fire protection options which are summarised in Section 5.2.2.1. Notably, the stakeholders were not asked about their previous experience in decision-making processes and use of MCDA tools to prevent bias in the process. At this stage of the research, 36 participants within the nominated 12 fire design stakeholder categories had participated in the interviews as shown in Figure 5.1. The fire service category had the highest participation with nine participants followed by fire engineers, while building owners, insurers and end-users had the least participation with one in each category.

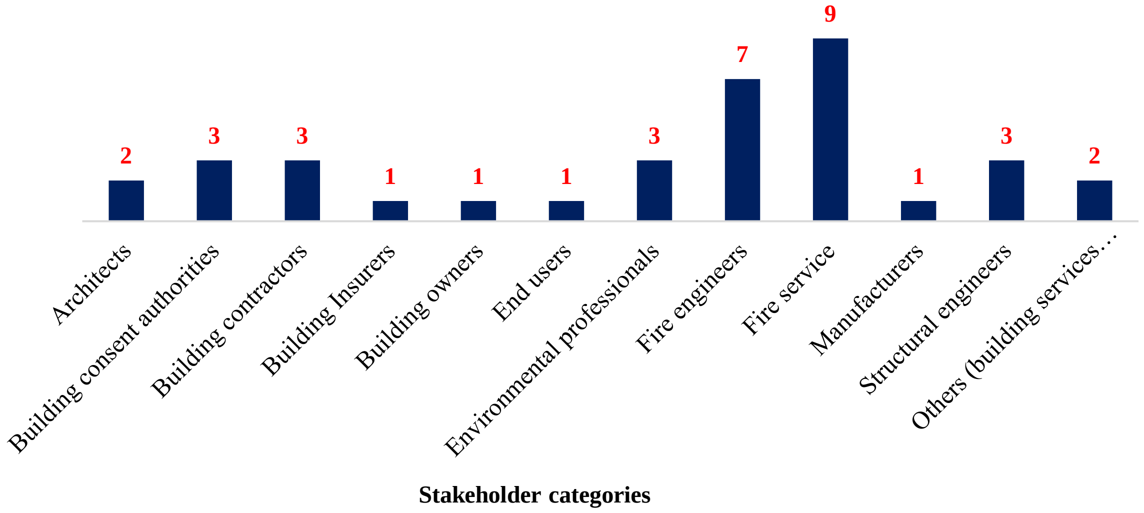


Figure 5.1. Fire design stakeholder participation.

5.2.2.1. Divergent Views of Expert Structural Fire Design Stakeholders

During the research interviews, discussions with some building contractors in New Zealand revealed that concrete encasement is hugely time-consuming regarding ease of construction, as a considerable amount of time goes into the casting of concrete and erection of the encased concrete elements. The focus of contractors is on cost and minimum material use, and they would prefer unprotected steel if it meets the required fire resistance or spray-on cement-based material because they are cheaper and consume less application time on site compared to concrete encasement. The view of unprotected steel structures as a fire protection measure is also shared by some structural fire engineers who may meet performance objectives by optimising the structure (e.g. using heavier unprotected steel members) to achieve cost-effectiveness. On the other hand, views of some structural fire engineers in New Zealand reveal the inclination to a minimal use of sprayed-on cement-based material. This is due to the paucity of skilled-manpower for thorough application and the high probability of being compromised in pre-fire events such as earthquakes/tremors, vehicle impacts on steel columns in car parks, etc. The research interviews also revealed that the confidence of building insurers and owners are challenged to accept partial or non-protection of steel elements at the expense of their key decision criteria of ensuring financial risk management, loss prevention and business continuity. Hence, the views of these building owners and insurers are in contrast with the structural engineer and fire engineers regarding unprotected steel structures. Further research interview/discussions with fire and structural engineers in New Zealand revealed the high use of gypsum plasterboard. However, some officials in the New Zealand Fire Service are also wary of the assembly of board protection especially the ability of installers to seal all gaps at joints and screwed points on the boards. As far as end users are concerned, their desires and targets are safety and comfort in buildings. End-users may not be involved as stakeholders due to a lack of sufficient knowledge in most structural fire design decision-making processes and it may be difficult to elicit their views in a design decision-making process. However, their primary concern is for occupancy or business activities, and for that matter care more for a functional building having perceived reliable (visible) fire protection. Though this may sound trivial to some designers, it cannot be disregarded in a decision-making context. Importantly, the end-users that participated in this research were experienced professionals who currently use steel-framed buildings on lease and were fully involved in the entire process of creating or maintaining the building asset. For environmental professionals in New Zealand, Hazardous Substances and New Organisms (HSNO) is a significant consideration during fire design decision-making and consenting, which may be different in other jurisdictions.

Outside the structured research interviews carried out in New Zealand, there were more discussions with stakeholders from different countries to extract their opinions on fire protection of steel structures for fully developed fires. This was done to gather a broader international perspective on the factors to consider in selecting suitable fire protection. These discussions revealed that the views of environmental professionals, fire and structural engineers vary in different jurisdictions. In some developing countries with little or no environmental conservation requirements stated in their building codes, environmental professionals are often swayed by the opinion of designers. However, in other parts of the world, environmental sustainability and strict compliance with environmental laws are likely to be enforced. For instance, the opinions of some fire design professionals in the United States and Australia are that concrete encasement of steel will produce massive waste during the demolition of fire-damaged commercial buildings, increasing the time to clean-up and building rehabilitation for business continuity. They mentioned the prevalent use of non-toxic intumescent coatings on steel structures concerning air pollution and control during fires, reduce waste material and building rehabilitation time after fires in these countries.

These divergent views on steel structural fire design from different stakeholder perspectives and in different countries are instructive, as the stakeholders have different backgrounds and operate in jurisdictions with very different regulatory environments. There is no dispute that managing inherent structural fire design decision uncertainties toward achieving better steel buildings will need a quality decision analysis technique deployed to balance divergent fire design stakeholder views, conflicting design decision criteria and competing options in a performance-based design environment.

5.2.2.2. Stakeholder paired comparison judgements

Using Saaty's rating scale (Table 3.2) each stakeholder implemented the AHP-pairwise comparison or judgement method as described in *AHP-Step 2*. For instance, the judgement matrices of three structural engineers (SE1, SE2, and SE3) for the paired comparison of benefits key decision criteria with respect to the goal (*Category A*) in this case are shown in Table 5.2. Recall that *economy* as a key decision criterion, and its associated sub-criteria were judged and analysed separately from the benefits criteria as mentioned earlier in Section 5.2.1.

In Table 5.2 structural engineer SE1 judged *safety* to be 'much more important' than *environmental* criteria and rated *safety* as 5 in the top row of the matrix. *Environmental* is rated as being 'much less important' than *safety* with a reciprocal value of 5 (i.e. 1/5) in the column on the left of the matrix. SE1 then rates *societal* to be 'somewhat more important' than *safety* with 3 in the column on the left of the matrix; consequently, SE1 rated *safety* to be 'somewhat less important' than *societal* with 1/3 in the top row of the matrix. For the pairwise comparison between environmental and societal criteria, SE1 judged *societal* to be 'very much more important' than *environmental* with 7 at the bottom in the *societal* row of the matrix and 1/7 for *environmental* as being 'very much less important' than *societal*. Using the AHP theory (Saaty, 1980) a value of 1 was entered for a paired comparison of an element against itself, which completed the matrix. The same pairwise judgement process is seen in Table 5.2 for SE2 and SE3 in which *safety* and *environmental* criteria are judged differently as compared to the judgements of SE1. The judgement matrices of other participant-stakeholders are not shown here but followed the same form.

Table 5.2. Judgement matrices from three structural engineer (SE) participants

SE1	Safety	Environmental	Societal
Safety	1	5	1/3
Environmental	1/5	1	1/7
Societal	3	7	1

SE2	Safety	Environmental	Societal
Safety	1	1	7
Environmental	1	1	7
Societal	1/7	1/7	1

SE3	Safety	Environmental	Societal
Safety	1	7	5
Environmental	1/7	1	1/3
Societal	1/5	3	1

The variation of SE1's judgement to SE2 and SE3 on the *societal* criterion may be attributed to *building aesthetics* (BA) and *building regulation approval* (BRA). As shown in Table 5.1, BA and BRA are sub-criteria under *societal*. Notably, the general engagement process is designed for stakeholders to give their expert judgements on the decision attributes based on the intensity of their feeling. The AHP-procedure does not include a method of understanding why an individual judged one element as more or less than the other. Decision-makers can revise their judgements to test sensitivities using the AHP. Here, the researcher leaned on the experience/expertise of the chartered fire design stakeholders. However, for providing further insight in this thesis and within the limits of confidentiality, SE1's comment on rating *societal* more than *safety* and *environmental* criteria was based on aligning to the architect's direction on BA and achieving BRA as the bottom line of design decision-making. SE2 and SE3's comments were focused on achieving safety as their top priority. Therefore, this illustrates the different stakeholder views in the decision-making process. The completion of stakeholder judgement elicitation using the goal rating document concludes the implementation of AHP-Step 2 and Stage 2 of the decision management framework.

5.2.3. Decision analysis

5.2.3.1. Aggregation of stakeholder ratings and AHP-prioritisation

As the purpose of the research is to incorporate all stakeholder opinions, all stakeholders were considered equally important, and therefore the stakeholder categories or groups have equal weight. The influence levels of the stakeholder categories were subsequently considered as unequal, and the groups were weighted as part of the decision analysis in Chapters 6 – 8. GMM was applied using Equation 3.11 to aggregate all individual stakeholder ratings to achieve single judgement matrices for the different categories of paired comparisons. Here GMM was used for two purposes. The first was to support the determination of priorities or importance levels of the decision criteria to the different groups of stakeholders. This implies that, once the individual judgements of a stakeholder group are aggregated and weighted, the group's priorities can be observed from the decision criteria scores and compared to other stakeholder groups' priorities. The second was to enable the holistic aggregation of all stakeholder groups' judgement ratings toward the determination of weights of all decision criteria and options, preference scores and ranking of the fire protection options.

An initial decision analysis was considered where data from 30 out of 36 interviewed stakeholders was used to firstly manage data skewness, given the unequal number of stakeholder participants in the various categories as shown in Figure 5.1. Secondly, to test how the ranking outcomes may be altered in design decision-making using the GMM-AHP. In this chapter, the excluded data was later considered in a re-analysis, and the outcomes were compared to that achieved in the initial analysis.

To carry out the initial decision analysis, stakeholder categories having only one participant-stakeholder were excluded i.e. in view of managing data skewness. In addition, the data from the two participants in the "Others" category (*mainly building services professionals*) were excluded to test potential rank alteration in the application of GMM-AHP as mentioned earlier. This may not be the case in practice; in some design projects, the views of a service engineer may be considered very important in deciding a suitable fire protection system considering installation pathways/channels of building services. The 30 stakeholders used in the initial decision analysis cover 7 out of the 12 fire design stakeholder categories shown in Figure 5.1.

Ideally, this study recognises that it would have been better to interview more participants to ensure that all stakeholder categories have equal participants as this may skew the results from the decision analysis, but to get their engagement was not easy. Nevertheless, the data from 30 stakeholders was considered sufficient to demonstrate the viability of the GMM-AHP and the fact that other research using AHP in the fire safety engineering literature has had smaller samples. Importantly, in practice, one stakeholder in each category is expected to participate in the design decision-making process especially at both the conceptual and formulated design stages of a building project.

Table 5.3 (a) and (b) show the outcome of the application of GMM to aggregate the key decision criteria ratings given by the three structural engineers and seven fire engineers in this study. This also shows the varying views of fire engineers to that of the structural engineers especially between *safety* and *societal* criteria where the fire engineers had rated *societal* to be slighted more important than *safety* based on the aggregated scores, 1.06 and 0.94 respectively. This may be attributed to the high consideration of *building regulation approval* sub-criteria given it was classified under *societal* criteria as deduced from some participant-fire engineers' comments. The fire engineers opined that in many design cases, achieving regulatory approvals remained their primary goal which they will do by meeting minimum safety requirements in the design codes without having to go overboard on safety. However, the aggregated judgement on *societal* may not be the case in practice if *building regulation approval* is considered under a different key decision criterion or not considered at all rather assumed as the overarching design goal.

Table 5.3. Group judgement matrix from (a) three structural engineers, SE1, SE2, and SE3 (b) seven fire engineers.

(a)

	Safety	Environmental	Societal
Safety	1.00	3.27	2.27
Environmental	0.31	1.00	0.69
Societal	0.44	1.44	1.00

(b)

	Safety	Environmental	Societal
Safety	1.00	6.68	0.94
Environmental	0.15	1.00	0.18
Societal	1.06	5.65	1.00

Table 5.4. Criteria weights from structural engineers' matrix

	Safety	Environmental	Societal	Weights
Safety	1.00	3.27	2.27	0.57
Environmental	0.31	1.00	0.69	0.18
Societal	0.44	1.44	1.00	0.25

Table 5.5. Criteria weights from fire engineers' group matrix

	Safety	Environmental	Societal	Weights
Safety	1.00	6.68	0.94	0.47
Environmental	0.15	1.00	0.18	0.07
Societal	1.06	5.65	1.00	0.46

The transition from individual to group judgement matrices using the GMM reduced many individual matrices to single group matrices at different levels of the AHP-hierarchy for each stakeholder category. It can be observed from Table 5.3 (a) that the GMM component of the decision technique reduced the three structural engineers’ matrices of paired comparisons to one judgement matrix. This also applies to many individual judgement matrices from the fire service personnel, having the highest participation rate at the stakeholder engagement phase.

This transition from individual to group judgement matrices also allowed for AHP-prioritisation or weighting calculation using the group judgement matrices.

The completion of aggregating fire design stakeholders' judgements concluded the AHP-*Step 3*.

5.2.3.2. Importance levels of stakeholder views

The AHP-prioritisation calculation followed the example in *AHP-Step 4*. The outcome of this calculation is the decision criteria priorities (performance scores or weights) determined from the stakeholder group judgements. Table 5.4 and Table 5.5 show the weights of the *benefits* key decision criteria calculated from the group judgement matrices of structural engineers and fire engineers. Table 5.6 shows the full set of weights of the benefits key decision criteria for the seven stakeholder categories initially analysed in this study.

As part of the AHP decision analysis, the consistencies of the stakeholder paired comparisons (*Categories A and B*) from the group judgment matrices are assessed using Equations 3.1 and 3.2. The determination of consistency ratios (CR) of fire design stakeholder group judgements follows the example demonstrated in *AHP-Step 4*. An illustration is also given below using the fire engineers' weights for the benefits key decision criteria (Table 5.5) where the new criteria or priority weights are found from:

Safety = (1.00 × 0.47) + (6.68 × 0.07) + (0.94 × 0.46) = 1.37;
Environmental = (0.15 × 0.47) + (1.00 × 0.07) + (0.18 × 0.46) = 0.22;
Societal = (1.06 × 0.47) + (5.65 × 0.07) + (1.00 × 0.46) = 1.35.

Thus, the normalized weights for each benefits key criterion are

Safety= 1.37/0.47 = 2.91;
Environmental= 0.22/0.07 = 3.14;
Societal = 1.35/0.46 = 2.93

so that the mean (λ_{max}) is

$$\lambda_{max} = (2.91 + 3.41 + 2.93) / 3 = 3.08$$

The consistency index (CI) is found using Equation 3.1,

$$CI = (3.08 – 3) / (3 - 1) = 0.04$$

and thus, the consistency ratio (CR), using Equation 3.2 and Table 3.3 , is

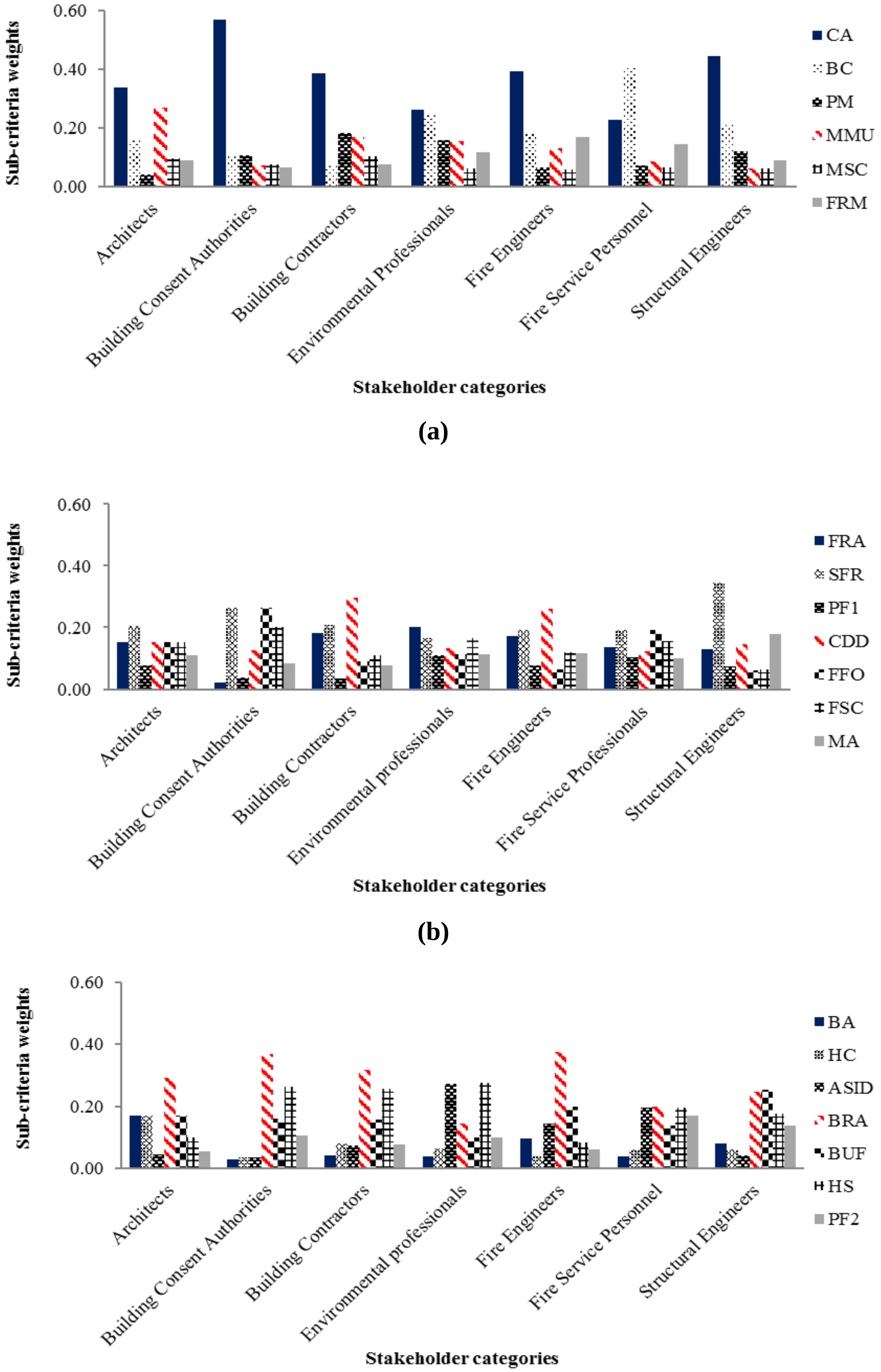
$CR = 0.04 / 0.58 = 0.07$.

As specified by Saaty, (1980), since $0.07 < 0.10$, the paired ratings are acceptable. The acceptable consistency ratio demonstrated with the group judgement matrix of 7 fire engineers (Table 5.5) gives credence to the capability of GMM to retain acceptable consistency if individual judgements were within consistency limits before aggregation (Xu, 2000). Table 5.7 shows the calculated *CI* and *CR* values from the weights of benefits decision criteria of the seven stakeholder categories (i.e. Table 5.6). The CR values were rounded to three decimal places; the zero CR values for FSP and SE in Table 5.7 were 0.00023 and 0.00020 respectively.

Table 5.6. Weights of key decision criteria (benefits) from some fire design stakeholders' group judgements matrices

	ARCH	**BCA**	**BCT**	**EVP**	**FE**	**FSP**	**SE**
Safety	0.22	0.66	0.54	0.57	0.47	0.65	0.57
Environmental	0.39	0.06	0.27	0.29	0.07	0.14	0.18
Societal	0.39	0.28	0.19	0.14	0.46	0.21	0.25

Given that the first GMM-aggregation of individual ratings (i.e. from *Categories A* and *B pairwise comparisons* only) was restricted to each fire design stakeholder category, the importance levels of stakeholder views were determined. Figure 5.2 (a), (b) and (c) show the importance levels of the sub-decision criteria to different stakeholder categories. With these figures, the views of the fire design stakeholders can be seen and compared. These provide insights into the stakeholder perceptions of the decision problem. Here, the AHP-prioritisation enables the fire design stakeholders to observe the importance levels of the different decision criteria, which demonstrates the viability of the GMM-AHP technique. For example, *'safety'* is of relatively high importance to the fire design stakeholders compared to the *'environmental'* criterion, except for the architects who valued *societal* and *environmental* criteria equally and above *safety* as shown in Table 5.6.



(a)

(b)

(c)

Figure 5.2. Benefits sub-criteria importance under (a) economy (b) safety (c) societal

Table 5.7. Consistency indices and ratios of benefits key criteria from some stakeholders' group judgement matrices

Stakeholder Category	**Consistency Index (*CI*)**	**Consistency Ratio (*CR*)**
Architects (ARC)	0.000	0.000
Building Consent Authorities (BCA)	0.037	0.064
Building Contractors (BCT)	0.002	0.003
Environmental Professionals (EVP)	0.010	0.017
Fire Engineers (FE)	0.040	0.069
Fire Service Personnel (FSP)	0.000	0.000
Structural Engineers (SE)	0.000	0.000

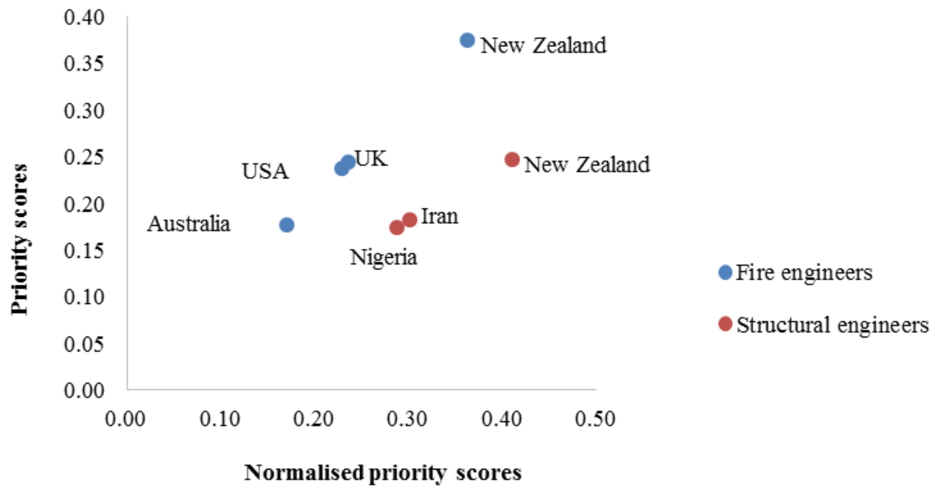
The trend of the architects' views on the '*societal'* criterion in Table 5.6 can be further understood by comparing the bars representing *structural fire resistance (SFR)* and *building regulation approval* (BRA) sub-criteria in Figure 5.2 (b) and (c) respectively. In Figure 5.2 (a), we can observe that *constructability* (CA) receives a high priority among all stakeholders, except the fire service which considers *business continuity* (BC) to be higher in importance level, by the mission of the New Zealand fire service. The interesting priority trend from these figures is the large difference in importance levels between fire engineers and building consent authority officers regarding the sub-criterion *fire risk assessment* (FRA) under '*safety*' as shown in Figure 5.2 (b). Notably, the trend of the '*societal*' sub-criteria priorities shown in Figure 5.2 (c) indicates that all the interviewed stakeholders greatly prioritise *building regulation approval* (BRA), which to a reasonable extent represents the general opinion of fire design stakeholders within the jurisdiction or domain of this research.

To give further insight on the consistency of the various judgements from the participant-structural engineers on *societal* key decision criterion (i.e. Table 5.2), their judgements on all sub-criteria under *societal* and *safety* were analysed. The SE1's best three performance scores of safety and societal sub-criteria were then selected to compare to the performance scores of the same sub-criteria from SE2 and SE3 as shown in Table 5.8. From Table 5.8, the three structural engineers mostly prioritised structural fire resistance (SFR) across the board. However, SE1 highly prioritised the sub-criteria BRA and BA (i.e. under *societal* criterion) than *clarity in design details* (CDD) and *maintainability* (MA) (i.e. under *safety* criterion) compared to SE2 and SE3. Conversely, SE2 and SE3 mostly prioritised MA than BRA and BA in the decision-making process.

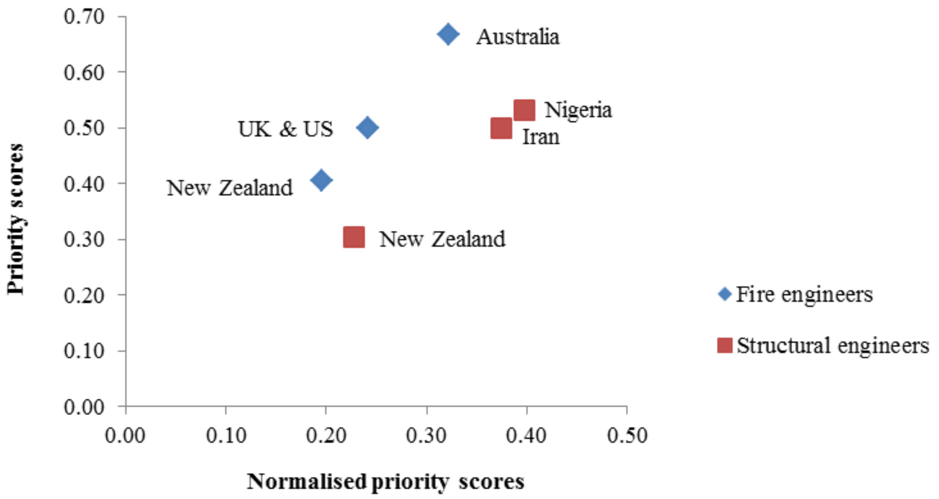
Table 5.8. Performance scores of *societal* and *safety* sub-criteria from structural engineers' individual paired judgements

Key Criteria	Sub-Criteria	SE1	SE2	SE3
Societal	BA	0.23	0.03	0.05
	BRA	0.34	0.18	0.16
	BUF	0.23	0.18	0.27
Safety	CDD	0.21	0.12	0.10
	MA	0.14	0.20	0.17
	SFR	0.41	0.32	0.27

GMM-AHP can also simply show the disposition of stakeholders from different jurisdictions on varying decision criteria or understand how they prioritise design decision attributes. To show this, the paired judgements of 10 experienced stakeholders from other jurisdictions were extracted from the online survey (*mentioned earlier in Section 5.2.2*) for this study. The stakeholders include 2 Australian fire engineers, 1 American fire engineer, 2 UK fire engineers, 1 Iranian structural engineer and 4 Nigerian structural engineers. Their judgements were aggregated and prioritised accordingly using the GMM-AHP and then used to compare to New Zealand structural and fire engineers involved in this process. Figure 5.3 (a) and Figure 5.3 (b) show how the sub-criteria weights or priority scores are used to compare the importance levels of *building regulation approval*; and *environmental sustainability* to New Zealand engineers and engineers from other jurisdictions. It was observed that *building regulation approval* strongly drives the design decisions in New Zealand compared to other jurisdictions; while in New Zealand *environmental sustainability* is not as strongly prioritised in its design decision-making process when compared to other jurisdictions. This may not be a consensus among stakeholders of the investigated jurisdictions shown in the charts (Figure 5.3) given the small sample set used from the online survey.



(a)



(b)

Figure 5.3. Importance levels of design decision criteria to engineers in New Zealand and other jurisdictions (a) building regulation approval (b) environmental sustainability.

However, AHP-prioritisation can ascertain stakeholder jurisdictional priorities if sufficient data is available. In a practical sense, given a design decision-making scenario involving international experts (i.e. from different jurisdictions), the AHP-prioritisation can be used to assess the importance level of stakeholder judgements on contentious design decision criteria owing to varying stakeholder jurisdictional backgrounds.

Figure 5.3 is also useful as it illustrates the effect the jurisdiction of operation may have on a designer/engineer/stakeholder, as it may influence the way they perceive design criteria and options. The aggregated judgement matrices from the participants of the online survey used in determining the result in Figure 5.3(a) are shown in Appendix 2(e).

On the other hand, criteria priorities through AHP can support simple cluster analysis to understand synergies among stakeholders of same categories but of different responsibility hierarchy. For instance, the charts in Figure 5.4 illustrates the relative synergy between the national and local building consent authorities in greatly prioritising safe *fire-fighting operations* (FFO) more than other safety criteria. In comparison to engineers' priorities, it shows a glimpse of implicit disagreement between engineers and regulators on *fire-fighting operations* (FFO) in New Zealand.

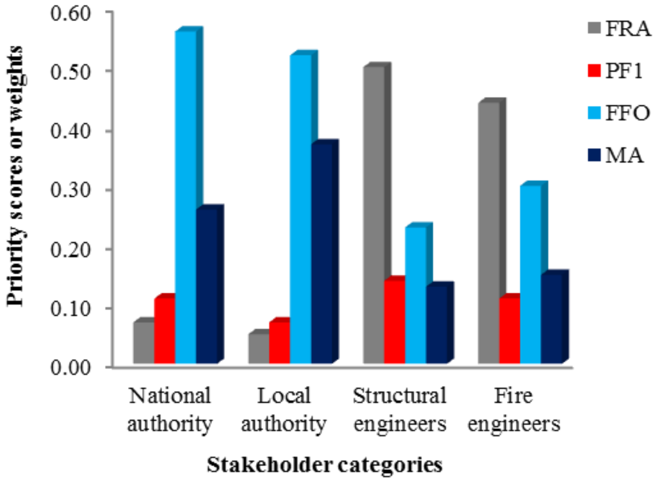


Figure 5.4. Safety elements' influence on building regulation approval with respect to fire protection options between building authorities and engineers.

The sub-criteria weights determined from the completed prioritisation of 'final aggregated matrices' were normalised by multiplying the criteria weights of their respective parent criteria based on the AHP theory (Saaty, 1994a) and as explained in Section 3.1.1.1.

The normalised sub-criteria weights sum up to their respective parent key criteria weights, and the key criteria weights sum up to unity, which represents the hierarchical process toward achieving the goal of the AHP decision analysis as shown in Figure 5.5 and Figure 5.6. This also marks the end of implementing the third and fourth steps of the AHP (Figure 3.2). It is noteworthy that the hierarchical models (Figure 5.5 and Figure 5.6) were developed in AHP-step 1 but shown at this stage to present the numerical outcomes of the decision analysis and not to confuse the process explained in Section 3.1.1.1.

In completing the *AHP-prioritisation* (step 4) of the decision analysis and satisfying holistic aggregation using the GMM as an AHP support tool (discussed in Section 3.2.1), all individual paired comparisons' (*Categories A, B, and C*) judgement matrices were aggregated to group judgement matrices. Following this holistic aggregation of individual judgements, step 4 was re-applied with respect to hierarchical levels of the AHP models shown in Figure 5.5 and Figure 5.6.

5.2.3.3. Synthesis and ranking of the competing options

In implementing the fifth step of the AHP, the normalised sub-criteria weights (as shown in Figure 5.5 and Figure 5.6) were used to determine the preference scores of the competing fire protection options by synthesis in the distributive and ideal mode, as described in Section 3.1.1.1. In the distributive mode, each weight of the competing options derived from the group judgement matrices of *Category C* paired comparisons and Eigenvalue process, were multiplied by each normalised sub-criteria weight. The products were then summed up to determine the preference scores of the fire protection options. This was carried out for both the *benefits* and *costs* hierarchical structures as shown on the left-hand sides of Table 5.9 and Table 5.10. A worked example showing the transition from the sub-criteria scores to options' scores regarding the distributive synthesis mode is presented in Appendix 6.

As an error check, the calculated preference scores for each *benefit* sub-criteria sum up to unity. From the distributive synthesis, the ideal mode calculation was carried out by firstly benchmarking the dominant option under each sub-criterion (i.e. the option having the highest weight on each row) as 1.00 by dividing its weight by itself. Then the rest of the weights were also divided by this value, multiplied by the normalised sub-criteria weights and summed up. The total of the summed-up values from the ideal synthesis was used to normalise them for achieving the preference scores, which sum to unity as well. The *benefits* and *costs* preference scores of the fire protection options are indicated at the bottom level of their respective hierarchical models. This concluded the fifth step of the AHP.

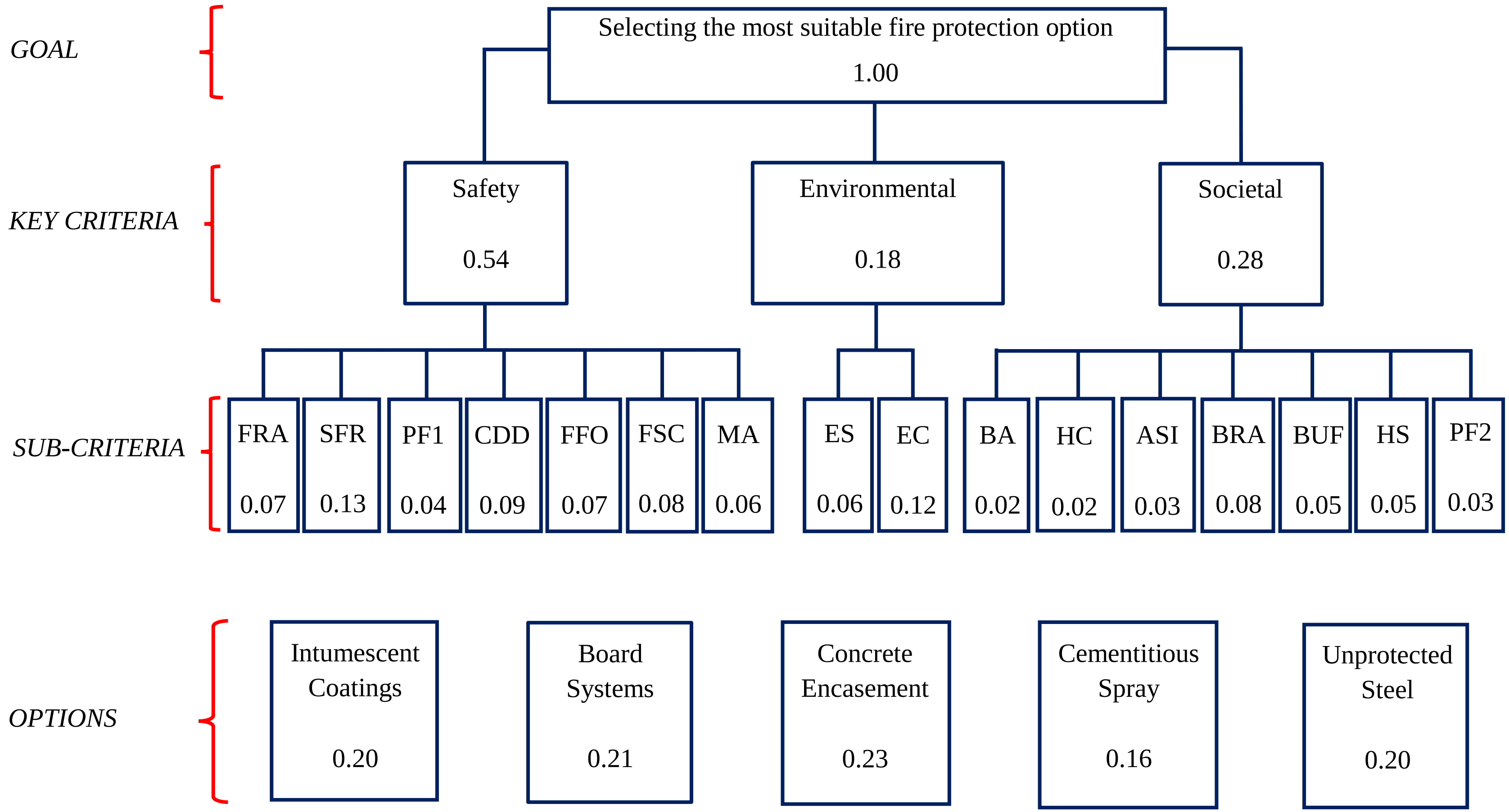


Figure 5.5. Fire design stakeholder AHP-benefits hierarchical model

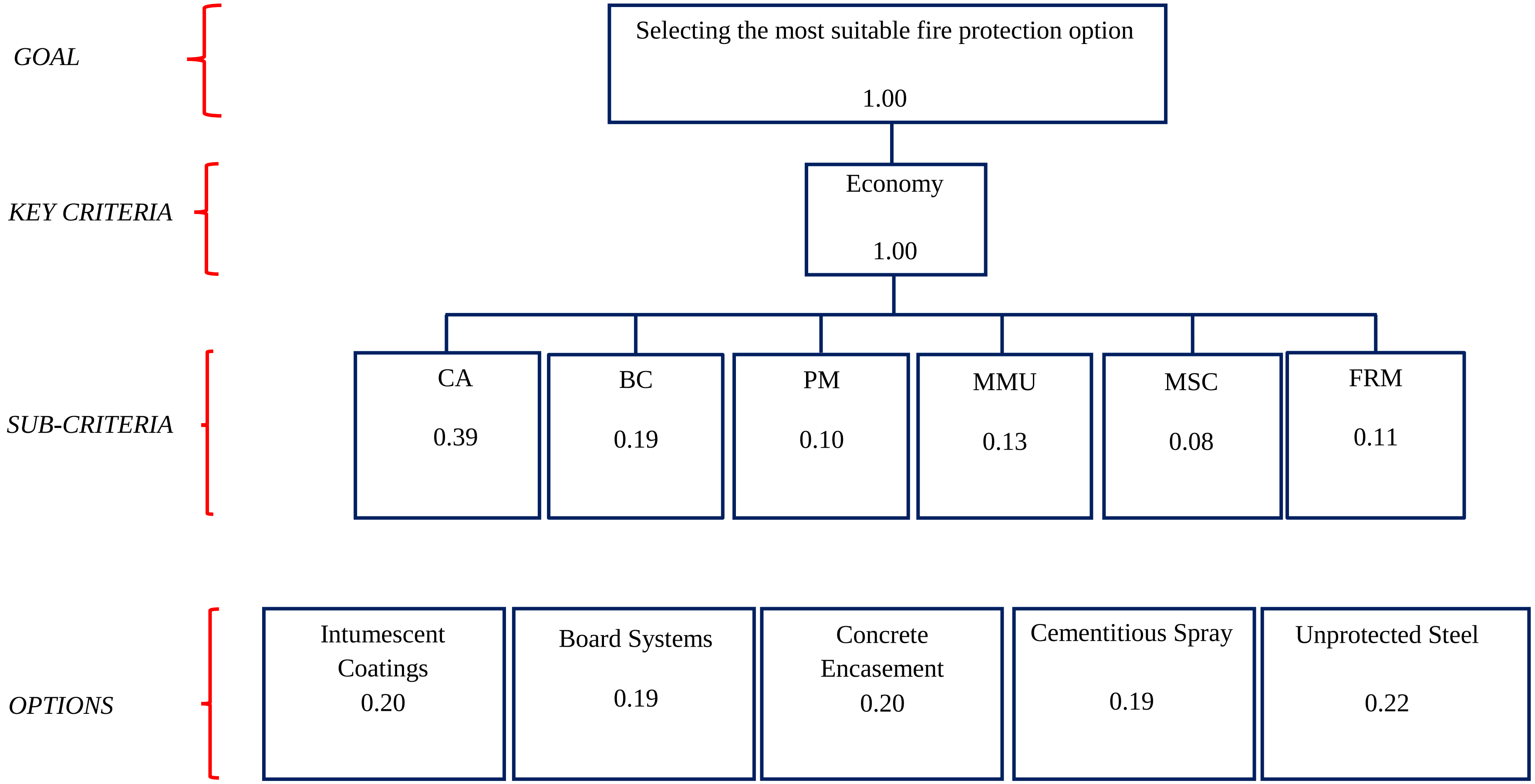


Figure 5.6. Fire design stakeholder AHP-costs hierarchical model.

Table 5.9. AHP-distributive and ideal mode benefits synthesis of the competing fire protection options

Distributive mode							***Ideal mode***				
Benefits sub-criteria	Normalised weights	ITC	BST	CES	SCM	UPS	ITC	BST	CES	SCM	UPS
FRA	0.07	0.22	0.20	0.21	0.18	0.18	1.00	0.91	0.98	0.83	0.83
SFR	0.13	0.17	0.23	0.31	0.16	0.13	0.55	0.76	1.00	0.53	0.43
PF1	0.04	0.17	0.25	0.30	0.14	0.15	0.55	0.83	1.00	0.45	0.49
CDD	0.09	0.22	0.18	0.17	0.14	0.30	0.76	0.59	0.56	0.46	1.00
FFO	0.07	0.20	0.20	0.23	0.20	0.17	0.85	0.85	1.00	0.85	0.73
FSC	0.08	0.12	0.30	0.37	0.12	0.09	0.32	0.81	1.00	0.31	0.24
MA	0.06	0.22	0.15	0.18	0.12	0.33	0.65	0.46	0.54	0.36	1.00
ES	0.06	0.27	0.12	0.13	0.15	0.34	0.79	0.37	0.38	0.44	1.00
EAC	0.12	0.19	0.18	0.20	0.20	0.23	0.81	0.76	0.88	0.88	1.00
BA	0.02	0.32	0.14	0.13	0.09	0.32	1.00	0.44	0.42	0.28	1.00
HC	0.02	0.20	0.23	0.23	0.15	0.18	0.89	1.00	1.00	0.68	0.80
ASI	0.03	0.21	0.21	0.25	0.18	0.15	0.82	0.81	1.00	0.70	0.59
BRA	0.08	0.23	0.21	0.25	0.17	0.13	0.93	0.85	1.00	0.68	0.52
BUF	0.05	0.26	0.20	0.21	0.16	0.18	1.00	0.75	0.80	0.61	0.69
HS	0.05	0.18	0.21	0.20	0.14	0.26	0.69	0.77	0.77	0.55	1.00
PF2	0.03	0.16	0.25	0.30	0.16	0.13	0.54	0.85	1.00	0.54	0.43
Benefits preference scores (B_i)		**0.20**	**0.21**	**0.23**	**0.16**	**0.20**	**0.20**	**0.21**	**0.23**	**0.16**	**0.20**

Table 5.10. AHP-distributive and ideal mode costs synthesis of the competing fire protection options

		Distributive mode					***Ideal mode***				
Economy (costs) sub-criteria	Normalised weights	ITC	BST	CES	SCM	UPS	ITC	BST	CES	SCM	UPS
CA	0.39	0.21	0.19	0.16	0.21	0.24	0.86	0.77	0.65	0.86	1.00
BC	0.19	0.17	0.24	0.28	0.15	0.15	0.61	0.86	1.00	0.53	0.52
PM	0.10	0.20	0.20	0.25	0.20	0.16	0.79	0.79	1.00	0.79	0.63
MMU	0.13	0.24	0.09	0.10	0.22	0.35	0.67	0.26	0.27	0.63	1.00
MSC	0.08	0.20	0.17	0.19	0.20	0.24	0.84	0.72	0.78	0.84	1.00
FRM	0.11	0.15	0.26	0.29	0.16	0.13	0.53	0.92	1.00	0.57	0.47
Costs preference scores (C_i)		**0.20**	**0.19**	**0.20**	**0.19**	**0.22**	**0.20**	**0.19**	**0.20**	**0.19**	**0.22**

In the sixth and final step, the benefits/costs (B_i/C_i) ratio (i.e. Equation 3.3) of the respective preference scores of the fire protection options were then calculated to obtain the final scores for their ranking. An illustration of the benefits/costs ratio and ranking of the competing options is shown in Figure 5.7. Here the preference scores of the competing options (*with respect to the benefits and costs decision models*) from the ideal mode synthesis were used to plot the benefits vs costs values.

It can be observed from Table 5.9 and Table 5.10 that the results from the distributive and ideal mode synthesis did not produce any difference in preference scores of the competing options irrespective of their different calculation procedure. This is an interesting observation in the AHP-synthesis, given the initial criticisms of the AHP on rank reversals. Saaty and Vargas (1993) in their experiments/simulations on rank preservation and reversal showed that there are minor changes produced by the AHP-distributive and ideal mode synthesis.

The benefits and costs preference scores in Table 5.9 and Table 5.10 respectively are almost evenly split among the competing options; this may not be the case if the fire design stakeholder engagement and decision analysis are carried out in a more extensive or global scale. The increase in participant-stakeholders from other jurisdictions and consideration of weighting the stakeholders may produce different sets of benefits and costs preference scores of the competing fire protection options. Therefore, in this Chapter, the ranking of the competing fire protection options from the initial decision analysis (i.e. using data from 30 stakeholders) has been determined in this order: *concrete encasement of steel (CES); board systems (BST); intumescent coatings (ITC); unprotected steel (UPS); sprayed on cement-based material (SCM).*

To test the sensitivity of the ranking order to the judgements of the six stakeholders that weren't included in the decision analysis, the AHP-procedure was reapplied to the aggregated judgements of the 36 participant-stakeholders. Table 5.11 shows the ranking order obtained from the benefit/cost ratio of the synthesised preference scores of the competing fire protection options. Comparatively, there was no significant alteration to the ranking order of the competing fire protections previously achieved. However, there were little changes in the ranking scores as shown in Table 5.11. In another sensitivity test, additional stakeholders were interviewed, this included one building owner, three end-users and two services engineers in the *others* category. This increased the sample set to 42 individual stakeholder paired judgements. The data were reanalysed using the GMM-AHP and the ranking order achieved from the reanalysis is also presented in Table 5.11. In comparison to the cases of 30 and 36 fire design stakeholders' views, there was no significant alteration of the ranking order rather the ranking scores of UPS, and ITC significantly increased and decreased respectively. This may be attributed to the inclusion of more services engineers in the decision-making process studied in this Chapter. Furthermore, if there were ten stakeholder categories or groups with only one participant for each group, then the rank of each option will be affected by pairwise rating scores given to the different criteria by each unweighted stakeholder. In another hand, if each participant of the groups is weighted to account for their influence level in the decision-making process, the ranking result will be affected by the weights of the participant-stakeholders. The inclusion of stakeholder weighting in the design decision-making process is demonstrated in Chapter 6.

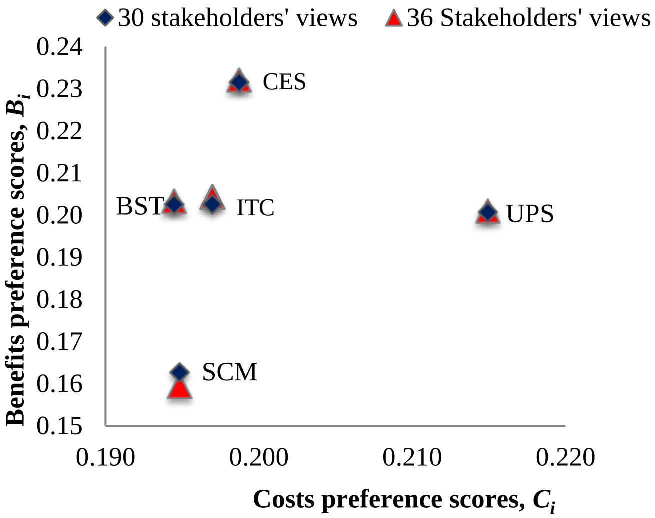


Figure 5.7. Benefits vs costs preference scores and ranking of fire protection options from 30 and 36 fire design stakeholders' views.

To complete the process, the decision or selection to be made by the fire design stakeholders may then depend on: the justification of the benefits of the options to their costs, if costs outweigh benefits or both are too close to call. Notably, the top-ranked option may not be the stakeholders' decision. For example, Figure 5.7 presents an interesting scenario, where the stakeholder may select either the 2nd or 3rd ranked option i.e. *board systems* or *intumescent coating* respectively as the most suitable applied fire protection to steel structures. This would mean that the decision-makers considered the relatively low costs and high benefits of the later options than the higher benefits and costs of the former. Whichever be the decision, the

GMM-AHP has clearly supported and presented the stakeholders with a better-informed decision-making situation. The GMM-AHP is designed to support stakeholder decision-making and not to force a decision on the stakeholders. The ranking, sensitivity test and the presented decision-making situation concluded the AHP-procedure and the implementation of the proposed decision management framework (Figure 4.1).

Table 5.11. Ranking scores from the judgements of 30, 36 and 42 unweighted fire design stakeholders

Fire Protection Options	B_i/C_i (30 Unweighted Stakeholders)	B_i/C_i (36 Unweighted Stakeholders)	B_i/C_i (42 Unweighted Stakeholders)	Rank
ITC	0.2056	0.2070	0.1986	3rd
BST	0.2081	0.2106	0.2050	2nd
CES	0.2329	0.2333	0.2349	1st
SCM	0.1669	0.1640	0.1634	5th
UPS	0.1866	0.1850	0.1981	4th

5.3. Critical Notes

It is important to note here that this research investigated the criteria for selection of passive fire protection options in a general case of steel-framed buildings. The use of this information for a specific building would need the selection of decision criteria that suit the specific scenario.

On the other hand, the inclusion of monetary values (i.e. actual fire protection costs) to the cost criteria might also affect the final ranking of the options. This will be ideal, far-reaching and a look beyond qualitative consideration in the decision-making process. Also, the unequal number of participant-stakeholders for the fire design stakeholder categories may have skewed the ranking order of the competing options. This may require further analysis whereby the options are assessed quantitatively and combined with the qualitative stakeholder views to achieve a final ranking. A critical assessment of the ranked options through quantitative analysis and integration into the decision analysis is the subject of the study in Chapter 7.

The results of this Chapter also present an opportunity to compare results achieved from applying GMM-AHP on stakeholder structural fire design decision-making process for actual steel-framed buildings in New Zealand were such data available. Importantly, if there were unforeseen constraints in using GMM or AHP in this study, the author would have considered the Arithmetic Mean Method (AMM) (Section 3.2.1) in aggregating the multiple individual stakeholder views. The Weighted Sum/Product Model (WSM/WPM) would have been used to derive the weights of the different decision criteria; while the Technique for Order of Preference and Similarity to Ideal Solution (TOPSIS) would then be used to synthesise and rank the competing options. However, this will mean that *stakeholder priorities*, not *individual ratings or judgements* would be aggregated to ensure homogeneity or unanimity of group judgements as explained in Section 3.2.1. The opportunity to check the consistencies of stakeholders' judgements and assess benefits and costs criteria in the same decision analysis process will be lost given the use of WSM/WPM.

In many design decision-making problems, some decision criteria may have dependences and interdependences which limit the use of GMM-AHP in solving the decision problem. For instance, ensuring *pre-fire building resilience* (PF2) during the life of a steel-framed building may be dependent on achieving *clarity in design details and specifications* (CDD). According to the Analytic Network Process (ANP) theory (Section 3.1.4), this is an inner dependency condition, given that PF1 and CDD are sub-decision criteria under *safety* in Table 5.1. Another possible dependency condition in a design decision-making scenario is outer dependency, e.g. to ensure a level of *structural fire resistance* (SFR) may be dependent on the *building use and features* (BUF). In this condition, SFR is a sub-criterion under *safety*; while BUF is a sub-criterion under *societal*. The possibility of these conditions may need to be accounted for using the ANP to understand how they may influence the ranking of the competing fire protection options. The application of ANP to this research's general case design decision-making problem is investigated in Chapter 6.

5.4. Conclusion

The framework of stakeholder engagement and the group AHP decision-making process drawn from the pilot study in Chapter 4 was a useful first step to this work. The goal, decision criteria and options (Section 5.2.1) of the decision-making problem described was formulated from a general perspective. The fire design stakeholder engagement and decision analysis were carried out in the most general sense, without any reference to a specific scenario. The 36 participant-stakeholders were experienced practitioners from reputable organisations in New Zealand and although several of the stakeholders had previous professional experience from outside of New Zealand their opinions on selecting applied fire protection to steel structures may not reflect the views of stakeholders in other jurisdictions. This is evident given the different priorities expressed by stakeholders of the same category from different jurisdictions illustrated in Figure 5.3. This also depicted the viability of AHP-prioritisation in simply assessing jurisdictional effects on stakeholders in design decision-making processes as well as synergies among some stakeholders as shown in Figure 5.4.

In the application of the GMM-AHP to select a suitably applied fire protection to steel structures, modification at the third step of the AHP was necessary. This was aimed to account for the scenarios of multi-decision-makers as demonstrated by the seamless aggregation of stakeholder individual judgements to group judgements. Notably, judgements from building owners, insurers and end-users were not used in the initial decision analysis simply to manage data skewness given that they had one participant only in the stakeholder engagement. The data from the ‘others’ category were also excluded in the initial decision analysis to enable a comparison to when there are included regarding rank alteration in the decision-making process. It is recognised that by excluding these stakeholder categories, the outcome of this study may be biased towards ‘*safety*’ over the other criteria. The 30 individual judgements within seven fire design stakeholder categories were considered sufficient to carry out the initial stakeholder decision analysis and demonstrate the viability of the GMM-AHP in comparison to the previous attempts to apply AHP in fire safety engineering mentioned in Section 3.1.1.2. Nevertheless, the inclusion and reanalysis of the data from the previously excluded fire design stakeholders did not alter the ranking order initially achieved.

The proposed GMM-AHP approach is also applicable for supporting the fire design decision-making process for 'structural system design' of a specific steel building. This is exemplified by the different judgements of the three structural engineers (Table 5.2 and Table 5.8); as such, their opinions may remain divergent in the structural fire design.

Interestingly and maybe somewhat surprisingly, the ranking order of the competing steel structural fire protection options shows that *concrete encasement of steel (CES)* is the top-ranked option, irrespective of the initial stakeholder opinions discussed in Sections 2.3.1 and 5.2.2.1. However, this may not be the design decision for a specific steel-framed building in which there will be characteristics that will result in the selection of a passive protection option. These characteristics may include dependency and interdependency of design decision criteria and design/parameter uncertainties which are investigated in the subsequent chapters. The ranking order of the fire protection options may also be because of choices made while applying GMM-AHP. For instance, in this study, all stakeholders were considered equally influential and were unweighted in the aggregation of their judgements using the GMM (Equation 3.11). The ranking order may change in scenarios where participant-stakeholders are considered unequal or having different influence in the decision such that they are weighted during the aggregation of individual judgements. A weighting of the stakeholder influence is investigated in subsequent chapters. Furthermore, the least ranked option, i.e. *sprayed on cement-based material (SCM)* may rank better in jurisdictions where it is extensively and historically used such as in the United States, United Kingdom etc. The inclusion of more participants in the *others'* stakeholder category, e.g. building services engineers, acoustic engineers etc., may also affect the rank of *concrete encasement of steel (CES)* as this option could be undesirable to them. It is noteworthy that the emphasis of this study is the "process" of ranking the competing fire protection options and not their "ranking order" which can be influenced by specific structures or building type. As mentioned earlier in Section 5.2.3.3, the GMM-AHP is designed to support or lead multiple stakeholders toward decision-making and not to force the decision on the stakeholders.

Nonetheless, this chapter has further demonstrated the applicability and adaptability strengths of the GMM-AHP in solving complex decision-making problems. This is owing to the general sense of the decision-making problem, the time-consuming stakeholder engagement and its jurisdiction, the quality of data from multi-fire design stakeholders (i.e. multi-decision-makers). The acceptable consistencies of the group judgements and the transparent approach used in the MCDA are included as well.

Notwithstanding the criticisms against the AHP and its adjoining GMM component also mentioned in Chapter 3 and addressed in other scholarly works, the GMM-AHP has shown to be a viable decision-making technique without contradictions and substantial assumptions. This endears the technique to wide applications in solving decision problems, which will also be practicable in the contemporary structural fire design environment.

6. GROUP-ANALYTIC NETWORK PROCESS FOR BALANCING STAKEHOLDER VIEWS ON FIRE PROTECTION OF STEEL-FRAMED BUILDINGS[3]

6.1. Introduction

In the pilot study (Chapter 4), the viability of AHP in balancing divergent views of stakeholders for suitable decision-making was tested. A framework was developed in which a small group of quasi-stakeholders were engaged to pairwise compare some assumed design decision criteria in choosing the most cost-effective fire protection. AHP with an adjoining GMM component was used to aggregate individual judgements and then assess and rank the competing fire protection options. Given the success in applying the *AHP-procedure* on the quasi-stakeholder judgements, the pilot study became a precursor to demonstrate the viability of GMM-AHP technique in aggregating and managing multiple expert stakeholders' views in Chapter 5. However, the GMM-AHP has deficiencies in balancing complex design decision-making scenarios which include accounting for dependency and interdependency among decision attributes and competing options as outlined in Section 5.3. As also explained in Section 3.1.4, dependencies/interdependencies in decision-making problems are considered as relevant interactions that can influence the final decision. The interactions negate the one-directional link between criteria and options hierarchically modelled with the AHP rather the decision problems are suitably modelled as a network of decision elements in clusters.

For instance, a car manufacturing company supplies cars to a steel manufacturing plant and an electricity company, which in turn supply the car manufacturing company with steel and electricity. The car, steel and electricity companies may be classified as elements in a cluster of 'production companies' given a decision-making problem of choosing a company for financial investment. Hence, this example demonstrates an element's inner dependencies in a decision cluster. Likewise, in the structural fire design decision-making, ensuring clarity in

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[3] Parts of this chapter's contents have been published as Akaa, O.U., Abu, A., Spearpoint, M. and Giovinazzi, S. (2016). "Decision Analysis of Stakeholder Views in the Design of Steel Structures in Fire, *Proceeding of ISPE International Conference on Transdisciplinary Engineering: Crossing Boundaries*, Curitiba, Brazil, 4: 523 – 532; and
Akaa, O.U., Abu, A., Spearpoint, M. and Giovinazzi, S. (2017). "Group Analytic Network Process for Balancing Stakeholder Views on Fire Protection of Steel Framed Buildings", *J Multi-Crit Decis Anal*. 24: 162 – 176.

design details and specifications for a fire protection option may depend on the effect it would have on fire-fighting operations and fire spread beyond compartments. Conversely, fire spread beyond compartments may depend more on ensuring the safety of fire-fighters in the event of fire than it would depend on design details of the fire protection option. The clarity in design specifications, fire spread and safe fire-fighting operations may be classified as elements in a ‘safety cluster’ exerting dependency which may influence design decision-making outcomes. These kinds of dependencies between different decision attributes can be accounted for using the Analytic Network Process and its adjoining component, Weighted/Geometric Mean Method for group judgement elicitation.

Therefore, this Chapter aims to use the Weighted/Geometric Mean Method-Analytic Network Process (W/GMM-ANP) to balance the expert opinions of fire design stakeholders extracted from 42 structured stakeholder interviews on selecting the most suitable fire protection option for buildings constructed of steel frames. The views extracted from 42 stakeholders are the expanded sample set of the 36 stakeholder judgements aggregated and analysed in Chapter 5.

W/GMM-ANP is a generalised Multi-Criteria Decision Analysis (MCDA) approach of the GMM-AHP used in addressing possible influences and/or interdependences among decision attributes in group decision-making scenarios. Different categories of interdependent decision elements were developed from the same twenty-two structural fire design decision criteria and five proposed fire protection options investigated in Chapter 5. The established dependencies resulted in a network of decision clusters for MCDA. The decision elements were then analysed and ranked.

In this Chapter, the limitations of the AHP are firstly discussed leading to the need for a more logical and all-inclusive MCDA technique. The Chapter then considers ANP (Saaty, 1996), which is widely used as the generalisation of AHP. The applicability of the ANP and its adjoining component for the aggregation of group judgements, W/GMM is demonstrated with a general case study of selecting suitable fire protection for steel structures against destructive fires. This approach is based on the proposed stakeholder decision management framework shown in Figure 4.1, which have been used to test the AHP in a pilot study (Chapter 4) and the initial general case study in Chapter 5. The result achieved here accounts for the multi-dependencies of weighted and unweighted stakeholder views and supports the balancing of the complex decision-making problem.

6.2. Limitations of AHP in Structural Fire Design Decision-making

In applying the GMM-AHP to solve the decision-making problem in Chapter 5, this research identified potential interdependencies among the different design decision criteria which may influence the outcome of the MCDA. For instance, consider the two examples of dependencies among the structural fire design decision criteria given earlier in Section 2.3.1: *maintaining supply chain of fire protection products with manufacturers or suppliers* and *constructability* (i.e. cost and ease of applying the fire protection) versus *profit-making* (i.e. stakeholder profit from using the fire protection). These can be classified within the *economy* decision criteria such that their interaction within economic consideration presents an inner-dependency scenario (Saaty, 2005). Examples of inner dependency scenarios have been presented earlier in Section 6.1. On the other hand, *building regulation approval* (BRA) which was considered a *societal* decision criterion in Chapter 5 may be influenced mainly by other sub-decision criteria under a different decision criterion. For instance, *fire risk assessment*, *fire-fighting operations* or *maintainability* may influence BRA, resulting in a cross or outer-dependence scenario (Saaty, 2005), given that the influencing elements could be classified as *safety* criteria in a design decision-making process. A simple outer-dependency scenario can be derived from the worked example of choosing a suitable mobile phone as shown in Appendix 6. The price of deciding on a preferred mobile phone option may depend more on the picture quality than the memory capacity of the mobile phone. Here price may be classified under an '*economy cluster*' which exerts outer dependence on picture quality and memory capacity, which may be classified under an '*efficiency cluster*'.

Most decision-making problems that confront humans cannot be decomposed into a hierarchy of components and elements. Given the likely interactions within decision elements and across decision components, the importance of decision criteria determines the importance of the competing options and vice versa (Saaty, 1996). This is typified by a design scenario where *constructability* is taken as a more important decision criterion than *building aesthetics* (i.e. ensuring visual appeal of the building) in selecting a fire protection option. For example, as mentioned in Section 2.2.3, the *cement-based spray* option might be adjudged as less expensive and more readily applied on site (Goode, 2004), it may be taken as more desirable than the more aesthetic *gypsum plasterboard* option. In this case, the sub-criteria *constructability* may influence the preference for sprays; while, *building aesthetics* may directly influence the preference for boards. This kind of interaction highlights the concept of 'influence' in solving a decision-making problem. The scenario of dependency/influence increases the complexity of decision-making and so limits the application of AHP as a sufficient MCDA technique to solve the decision problem (Saaty, 1996). Influence in decision-making forces changes, positively or negatively, which can potentially alter the choice of decision-maker/s (Saaty, 2005). Therefore, it is imperative that the potential dependencies/influences within the design decision components and elements of the steel structural fire protection decision problem be appropriately balanced by looking beyond the top to bottom AHP approach. This will entail modelling the decision problem as a network of dependencies and apply the ANP in carrying out the decision analysis. In group decision-making scenarios which are investigated in this research, the W/GMM is used alongside the ANP to manage the views of multi-stakeholders and the complexity of the multi-criteria decision problem.

6.3. Method

The general steps used in applying the ANP are shown in Figure 3.2. However, to demonstrate the application of W/GMM-ANP in balancing fire design stakeholders' views, this chapter follows the decision management framework (Figure 4.1). At the stakeholder decision analysis stage, AHP is replaced by ANP. The ANP is implemented by modifying ANP-step 4 to accommodate the aggregation of multi-stakeholder views using W/GMM.

6.3.1. Determining the structural fire design decision clusters and elements

The control hierarchy, comprising of a goal and decision criteria, has been formulated. This was formulated from the general perspective of steel structural fire design without reference to a specific design scenario. The goal is the same as formulated in Chapter 5, i.e. *"to select the most suitable fire protection option for steel structures for destructive fires".* The control criteria are *benefits* and *costs,* i.e. within the BOCR merits as explained in *ANP-Step 1*. The assumed design decision attributes are the criteria and sub-criteria in Table 5.1. However, the attributes are herein referred to as *clusters or components* (i.e. formerly key criteria) and *elements* (i.e. formerly sub-criteria). Hence, the *decision clusters* are *economy, safety, environmental* and *societal*. The *decision elements* relating to *economy* were classified under the *costs* control criteria; while the *elements* relating to *safety, environmental* and *societal* were classified under the *benefits* control criteria. The design decision options investigated in this study are the same as Chapter 5; however, in this study, the options were considered and analysed as elements in the '*fire protection options cluster'*. The options include *intumescent paints (ITC), board systems (BST), concrete encasement of steel (CES), sprayed on cement-*

based material (SCM) and *unprotected steel (UPS).* These considered steel structural fire protection options are based on single-element design rather than the decision analysis being obscured in a complex sophisticated structural system design. The establishment of the control hierarchy and criteria, decision attributes and options concluded the implementation of Stage 1 of the decision management framework (Figure 4.1) and *ANP-Step 1*.

6.3.1.1.Clusters and elements' dependences or influences

During the stakeholder engagement planning phase, the possible interactions among the identified decision attributes in Table 5.1 were determined by a structural fire design expert panel, which includes chartered and highly experienced fire and structural engineers in New Zealand. The panel considered a general steel structural fire design scenario and based on expert judgement; they identified very likely influences/interactions among the design decision criteria extracted from the literature. These interactions include inner and outer dependencies. For instance, to select a suitable fire protection option toward reducing monetary loss from property damage in the event of a fire, the panel determined that *financial risk management (FRM)* may depend on the quantity of the applied fire protection, i.e. *minimum material use (MMU)* and the need for a quick reinstatement of a business after a fire, i.e. *business continuity (BC)*. Note that FRM and MMU are elements in the *economy* cluster. Hence, FRM was considered as an element that exerts inner dependence in the *economy* cluster. *Health and safety (HS) of installers and end-users* (see Table 5.1), *all stakeholder involvement in design (ASI)* and *building regulation approval (BRA)* in the *societal* cluster were determined as outer influencing elements on *clarity in design details and specifications (CDD)* in the *safety* cluster. These inner and outer dependencies are a few examples of the many determined interactions among the decision attributes. The expert panel also determined that interdependencies exist between elements in the *economy, safety, environmental, societal* clusters and the *fire protection options'* cluster.

6.3.2. Designing and applying the network of decision clusters

In the preparation and engagement phase, the determined influences of the decision attributes were used to design the *benefits* and *costs* network structures. Figure 6.1 shows the *benefits* control network model designed for the decision-making problem in this Chapter. The *costs* control network is not shown here. However the interactions in both networks were used to develop the ANP aspect of the *goal rating document*.

Pertinently, the revised goal-rating document used in eliciting stakeholder judgements with the Analytic Hierarchy Process (AHP) (Section 0) also contained the Analytic Network Process (ANP) judgement matrices with respect to dependencies/interdependencies of decision attributes. The new contents of the revised goal rating document were considered necessary to enable a single engagement of each participant-stakeholder. This manages the difficulty of expending more time and money in re-interviewing the stakeholders to implement the ANP, given stakeholders' busy work schedule and different location in New Zealand. Other contents of the goal rating document have been listed in Section 4.3.1.1, and a sample of the document is included in Appendix 2(d). The stakeholder views on the decision cluster/elements/options and their associated dependences were extracted at the same response and rating phase of the stakeholder engagement process explained in Section 0. This entailed that the AHP and ANP type of paired comparison judgements were extracted at the same time from each participant-stakeholder.

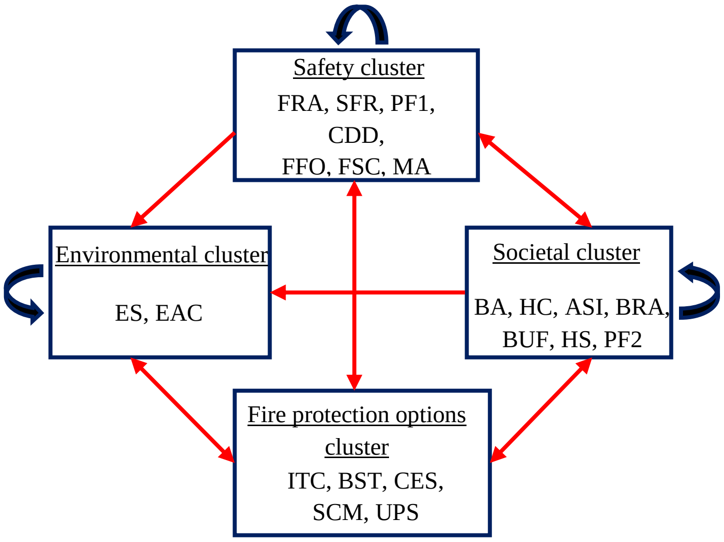

Figure 6.1. Structural fire design decision 'benefits' criteria network model.

The loops on the *safety*, *environmental* and *societal* clusters in Figure 6.1 indicate that inner dependencies exist in the clusters, such as observed with $C_{2,}$ C_4 and C_5 in Figure 3.3. The one and two-way arrows among the clusters in Figure 6.1 indicate outer dependencies same as C_1 – C_5 in Figure 3.3.

6.3.2.1. Determination of the cluster weights (cluster matrix)

The cluster weights of the *benefits* and *costs* network models were also determined at this point based on relative influences/interactions of each cluster in the networks using the pairwise comparison and AHP-weighting procedure. Table 6.1(a) shows the weights of the clusters in the *benefits* control criteria network. From the *benefits* network model (Figure 6.1), the elements in the options cluster were considered as not inner dependent. This consideration was depicted with the zero influence weight for the options cluster in the matrix (Table 6.1{a}); zero was also entered for *environmental* as it had no outer influence on the *safety* and *societal* clusters. The *costs* network cluster weights are shown in Table 6.1(b), here the interaction is between the economy cluster and the fire protection options' cluster which follows the same explanation given above for Table 6.1(a).

Table 6.1. Cluster matrixes (a) benefits control network (b) costs control network

(a)

	Safety	Environmental	Societal	Fire protection options
Safety	0.42	0.00	0.06	0.33
Environmental	0.06	0.50	0.06	0.33
Societal	0.11	0.00	0.44	0.33
Fire protection options	0.42	0.50	0.44	0.00

(b)

	Economy	Fire protection options
Economy	0.25	1.00
Fire protection options	0.75	0.00

6.3.2.2.Stakeholder engagement and paired comparison ratings

This research considered the response and rating phase of the stakeholder engagement process as a continuous phase given that the decision analyses stages and tools (GMM-AHP and W/GMM-ANP) had been automated. Therefore, at this research stage, 42 chartered and experienced stakeholders within the building and fire industry in New Zealand have been interviewed. This includes the previous sample set (i.e. 36 stakeholders) in Chapter 5. As mentioned earlier, all participant-stakeholders in this research are interviewed once using the same goal rating document whereby their views are elicited given the AHP and ANP type of questions, decision models and judgement matrices. The fire design stakeholder categories and rate of individual participation are shown in Figure 6.2.

Although it would be desirable to increase the number of participants in this study, the 42 participant-stakeholders from the 12 fire design stakeholder categories are considered sufficient to carry out the stakeholder decision analysis. Also, the sample-set is sufficient to demonstrate the viability of the W/GMM-ANP in comparison with previous attempts to apply AHP in fire safety studies discussed earlier in Section 3.1.1.2. There is no fixed amount of stakeholder/s or decision-maker/s' judgements needed to achieve the best-ranking result through AHP or ANP. As discussed in Section 3.2.1, the techniques were initially developed as single decision-maker techniques before the advent of W/GMM and W/AMM for group decision aggregation. Therefore, in a general case study as carried out here, the number of stakeholders involved may be considered as the more, the better.

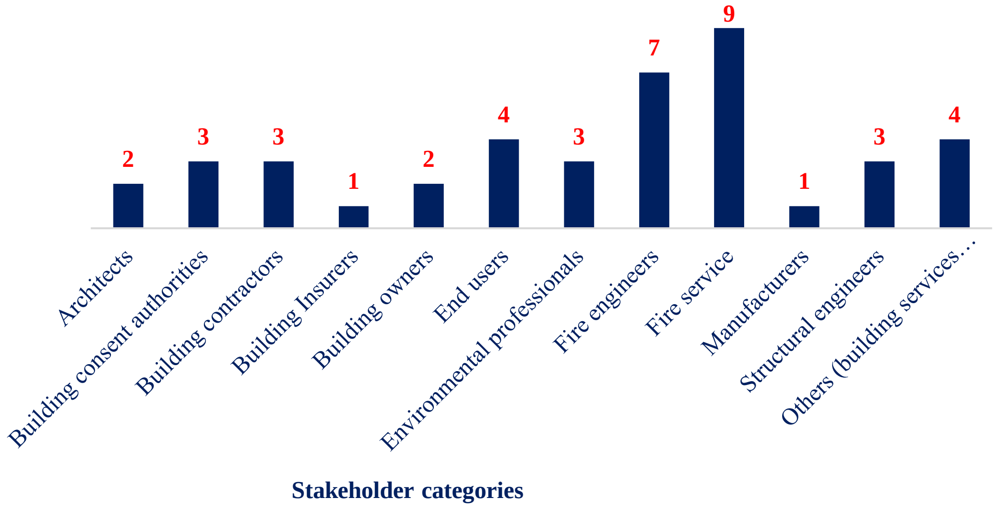

Figure 6.2. The fire design stakeholder categories and individual participation.

Based on the fundamental scale (Saaty's reciprocal scale) and ANP question in the goal-rating document, each stakeholder carried out the pairwise comparison rating of the decision elements at the response and rating phase of the stakeholder engagement. Table 6.2 shows the judgement matrices of the outer dependence of *clarity in design detail and specifications (CDD)* on *all stakeholder involvement in design (ASI)*, *building regulation approval (BRA)* and *health and safety (HS)* (described in Section 6.3.1.1) from the two stakeholders in building owners' category (BDO1 and BDO2).

Table 6.2. Building owners' judgements of some social cluster elements influence on 'clarity in design details and specifications'.

(a) Judgement matrix from BDO1

CDD	ASI	BRA	HS
ASI	1	1/9	1/9
BRA	9	1	1
HS	9	1	1

(b) Judgement matrix from BDO2.

CDD	ASI	BRA	HS
ASI	1	1/5	1/5
BRA	5	1	1
HS	5	1	1

Here, *building owner 1* (BDO1) and *building owner 2* (BDO2) have the same view that *building regulation approval* (BRA) and *health and safety* (HS) have equal influence on *clarity in design details* (CDD) as they rated both elements as '1' in Table 6.2 (a) and (b). However, their judgements differ regarding the influence of *all stakeholder involvement in design* (ASI) on CDD. BDO1 [Table 6.2 (a)], rated BRA and HS as having more influence on CDD than ASI with the value '9' and its reciprocal value, 1/9 which means that ASI has less influence on CDD relative to BRA and HS. On the other hand, BDO2 judged BRA and HS as having much more influence on CDD with the value '5' and vice versa. As previously seen in Table 5.2 (*i.e. structural engineers' judgements*), Table 6.2 also shows the different views of fire design stakeholders within the same category. Similar variations were also observed in other stakeholder categories not shown here.

During the stakeholder interviews, the building owners commented that they cared more about achieving building consent. Hence, they would naturally insist that the structural and fire engineers ensure clarity in their designs and also to reduce uncertainties during the construction of the steel-framed building. Importantly, the building owners informed the researcher that they do not prefer all the stakeholder categories in this research to participate in design decision-making processes especially environmental professionals and end-users. Their views were based on managing potential conflicts in a decision-making process. These views were reflected in their judgements, as shown in Table 6.2. Other stakeholder views on some decision elements and competing options had been summarised earlier in Section 5.2.2.1.

The determination of the cluster weights and the collection of individual judgements of the 42 stakeholders concluded *ANP*-*Step 3* and the stakeholder engagement process (Figure 4.1).

6.3.3. Aggregating and deriving influence priorities of stakeholders

To achieve group consensus by aggregating the individual judgements of the fire design stakeholders, this Chapter considered the probable influence level of each stakeholder category in a structural fire design decision-making process. Different methods of extracting group judgements which help to determine stakeholder weights have been reviewed in Section 3.2. The methods include the Cooke's classical method, principal components analysis (PCA) method, the 'super' stakeholder weighting method and stakeholders weighting each other with the arithmetic or geometric mean methods (AMM/GMM).

Notably, in Chapter 5 the stakeholder groups were considered as equally important and were unweighted during the aggregation of their judgements which also affected the outcomes of the decision analysis. In keeping with the AHP/ANP procedure for group decision-making, the weighted/geometric mean method (W/GMM) was considered to weight and aggregate individual stakeholder judgements. However, there were constraints in bringing the stakeholders together in one room due to varying locations and work schedules, mentioned earlier in Section 0. Hence, it was not possible for the stakeholders to weight each other or elect a 'super' stakeholder to weight them as earlier suggested in Section 3.2.1. Here, the consultation fees of building design professionals published in the literature (CEEC, 2016) have been normalised and used in weighting each fire design stakeholder category as an 'individual' in this study. This then assumes that stakeholders' consultation fees represent their input and/or influence in a design decision-making process. Importantly, this may not be the ideal basis on which stakeholder influence can be quantified. For instance, the importance of the building owner/client (i.e. the one paying the fees to the professionals) needs to be accounted for in the stakeholder weighting. A more acceptable method will be for stakeholders to weight each other in the decision-making process which was difficult to achieve here as explained earlier. Nevertheless, the normalisation of stakeholder professional fees does provide some form of objective measure used herein to investigate the decision-making technique/process. The normalised stakeholder weights were:

Architects (0.212); building owners (0.183); structural engineers (0.183); others {e.g. building services} (0.125); fire engineers (0.111); environmental professionals (0.073); building insurers (0.037); building contractors (0.029); end-users (0.018); manufacturers/suppliers (0.015); building consent authorities (0.007); and fire service personnel (0.007).

Following the stakeholder weighting, WGMM, equation (Forman and Peniwati, 1998) was applied to aggregate fire design stakeholder judgements, from which influence priority scores were derived, and consistency of group judgements was checked according to the AHP theory. Table 6.3 shows the aggregated judgment matrix from Table 6.2 (i.e. BDO1 and BDO2 judgments) and their derived influence priority scores.

Table 6.3. Aggregated judgement and derived influence priority scores from BDO1 and BDO2.

(a) Aggregated Judgement matrix from BDO1 and BDO2 scores.

CDD	ASI	BRA	HS
ASI	1.00	0.50	0.50
BRA	2.01	1.00	1.00
HS	2.01	1.00	1.00

(b) Influence priority

Scores
0.20
0.40
0.40

Table 6.3 (a) reduced the individual judgement matrices from Table 6.2 (a) and (b) to a group judgement matrix allowing the determination of group influence priority scores for each category of paired judgements. The influence priority scores in Table 6.3 (b) sum up to unity and BDO1 and BDO2 judgements have a consistency ratio of 0.00001, which is within the consistency limit of 0.10 (Saaty, 1980). The consistency indices and ratios of the same judgement category for each group of fire design stakeholder are shown in Table 6.4. From the table, the stakeholders' judgements were within the consistency limit.

The influence priority scores in Table 6.4 were plotted in the chart (Figure 6.3) to give further insight into the variation and priority trends of stakeholder judgements. Figure 6.3 shows that *health and safety* (HS) has the least priority to the fire engineers regarding influence on clarity on design details (CDD) with respect to selecting a suitable fire protection option. This can be attributed to the interview comments extracted from fire engineers. The fire engineers' opinions were that the process of safe installation and use of any of the competing fire protection options assure the health and safety of fire protection installers and end-users. As such, they consider building regulation approval (BRA) to highly influence CDD than HS. However, the building owners' view on HS is reflected in their priority score (i.e. 40% against the fire engineers' 15% score). This can be attributed to their risk perception (as understood from their interview comments) on fire protection materials given the problems they had a long time ago regarding asbestos in buildings.

Table 6.4. Consistency indices and ratios from fire design stakeholder judgements on the influence of ASI, BRA and HS on CDD.

Stakeholder Category	Influence priority scores	Consistency indices (*CI*)	Consistency ratios (*CR*)
Architects	ASI = 0.22; BRA = 0.45; HS = 0.33.	0.001	0.001
Building Consent Authorities	ASI = 0.32; BRA = 0.34; HS = 0.34.	0.000	0.000
Building Contractors	ASI = 0.31; BRA = 0.35; HS = 0.34.	0.000	0.000
Building Insurers	ASI = 0.34; BRA = 0.34; HS = 0.32.	0.000	0.000
Building Owners	ASI = 0.20; BRA = 0.40; HS = 0.40.	0.000	0.000
End Users	ASI = 0.33; BRA = 0.34; HS = 0.33.	0.000	0.000
Environmental Professionals	ASI = 0.33; BRA = 0.32; HS = 0.35.	0.000	0.000
Fire Engineers	ASI = 0.25; BRA = 0.60; HS = 0.15.	0.001	0.001
Fire Service Personnel	ASI = 0.33; BRA = 0.34; HS = 0.33.	0.000	0.000
Manufacturers	ASI = 0.33; BRA = 0.33; HS = 0.34.	0.000	0.000
Structural Engineers	ASI = 0.21; BRA = 0.48; HS = 0.31.	0.002	0.002
Others (e.g. Building Services)	ASI = 0.32; BRA = 0.40; HS = 0.28.	0.001	0.001

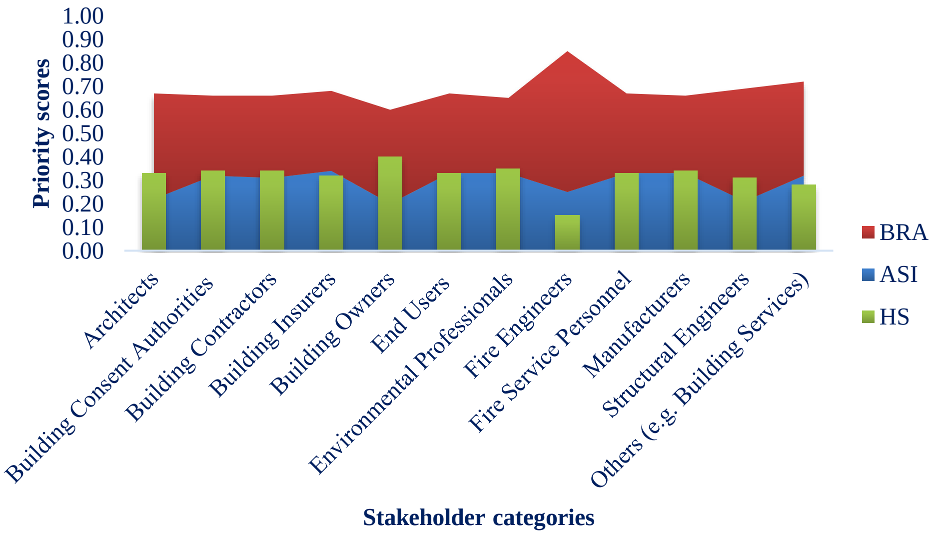

Figure 6.3. Stakeholders' priorities for some decision elements' influence on CDD with respect to selecting a suitable fire protection option.

Notably, *building regulation approval* (BRA) was highly prioritised across the board consisting of the fire engineers' priority score (60%) as the highest (Figure 6.3). This was also the same case in the judgement category shown in Table 5.8 which indicates the high intent of 'achieving building regulation approval' among fire design stakeholders in New Zealand.

The determination of the stakeholder weights, aggregation of their judgements and derivation of influence priority scores of the design decision elements concluded ANP *Step 4*.

6.3.4. Establishing the structural fire design decision supermatrices

Given that all group judgements were within consistency limits, the aggregated influence priority scores of the 42 stakeholders were entered in their respective column blocks of the constructed *benefits* and *costs* initial supermatrices as described in Section 3.1.4.1. Table 6.5(a) shows the initial supermatrix of *benefits* control network developed in this study. The 22 decision attributes and their associated dependences analysed in this study resulted to a large volume of elements in the supermatrices. Hence, the fonts of the elements in the supermatrix tables have been reduced to fit into their respective pages in this chapter.

The weighted supermatrices were calculated by multiplying the cluster column blocks in the initial supermatrices by their respective cluster weights. For instance, Table 6.5(b) shows the weighted supermatrix of the *benefits* control network, which was calculated by multiplying the cluster weights in Table 6.1(a) accordingly. It can be observed that all columns in the *benefits* weighted supermatrix, Table 6.5(b), add-up to unity, i.e. the initial supermatrix, Table 6.5(a), is transformed to a stochastic matrix toward generating the limiting priorities of the decision elements according to the ANP theory (Section 3.1.4.1). The weighted supermatrices were raised to large powers. In this case, the weighted influence priority scores converged to row-identical values (i.e. the limiting priority scores) at the 6th power of the weighted supermatrix as shown in Table 6.5(c). The limiting priorities from one column of the limiting supermatrix, Table 6.5(c), were further synthesised by normalising them for each cluster and adding-up to unity. Table 6.5(d) shows the normalised limiting priority scores of the design decision *benefits* control network.

The relative importance of elements can be deduced from the normalised scores in Table 6.5(d). For instance, FRA (0.2024), ES (0.6357), ASI (0.3163) and UPS (0.2056) have the highest priority scores in the *safety*, *environmental*, *societal* and *fire protection option* clusters respectively. Hence, under the *benefits* merits, they are of highest relative importance to the fire design stakeholders. The elements MA (0.0923), PF2 (0.0779) and SCM (0.1944) have the least *benefits* priority scores as analysed in this study. The ANP synthesis was also applied to the limiting supermatrix of the *costs* control network to produce the normalised limiting priority scores of the elements in the *economy* and *fire protection* options' clusters not shown here. Establishing and synthesising the *benefits* and *costs* network super matrices toward ranking the competing fire protection options concluded ANP *Step 5* and *Step 6*.

Table 6.5. ANP-Synthesis of the structural fire design decision benefits network.

(a) *Initial super matrix*

Clusters	Elements	FRA	SFR	PF1	CDD	FFO	FSC	MA	ES	EAC	BA	HC	ASI	BRA	BUF	HS	PF2	ITP	BST	CES	SCM	UPS
Safety	FRA	0.0000	0.1850	0.0000	0.3481	0.1650	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.2856	1.0000	0.0000	0.0000	0.1488	0.1515	0.1499	0.1579	0.1588
	SFR	0.0000	0.0000	0.5115	0.0000	0.1757	0.2655	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.1530	0.1553	0.1565	0.1509	0.1519
	PF1	0.3078	0.1503	0.0000	0.0000	0.1541	0.2248	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2217	0.0000	0.0000	0.0000	0.1303	0.1288	0.1311	0.1271	0.1315
	CDD	0.3575	0.1831	0.4885	0.0000	0.1706	0.2608	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.1450	0.1536	0.1511	0.1580	0.1474
	FFO	0.0000	0.1534	0.0000	0.3146	0.0000	0.2489	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.2602	0.0000	0.0000	0.0000	0.1377	0.1327	0.1322	0.1363	0.1413
	FSC	0.3348	0.1607	0.0000	0.3373	0.1697	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1337	0.1375	0.1425	0.1343	0.1245
	MA	0.0000	0.1675	0.0000	0.0000	0.1648	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2324	0.0000	0.0000	0.0000	0.1515	0.1406	0.1366	0.1355	0.1447
Environmental	ES	0.0000	1.0000	1.0000	1.0000	0.0000	0.4792	0.5003	0.0000	1.0000	1.0000	0.0000	1.0000	0.4682	0.0000	0.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	EAC	1.0000	0.0000	0.0000	0.0000	1.0000	0.5208	0.4997	1.0000	0.0000	0.0000	1.0000	0.0000	0.5318	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Societal	BA	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1624	0.0000	0.0000	0.0000	0.3252	0.0000	0.0000	0.0000	0.0000	0.0000	0.1459	0.1315	0.1283	0.1351	0.1367
	HC	0.0000	0.0000	0.0000	0.0000	0.0000	0.2130	0.1501	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1283	0.1237	0.1262	0.1284	0.1293
	ASI	1.0000	0.4436	1.0000	0.2916	0.0000	0.2213	0.1485	0.0000	0.0000	0.0000	0.3173	0.0000	0.3262	1.0000	1.0000	1.0000	0.1256	0.1254	0.1297	0.1282	0.1320
	BRA	0.0000	0.0000	0.0000	0.3907	0.0000	0.3069	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1647	0.1749	0.1724	0.1744	0.1637
	BUF	0.0000	0.5564	0.0000	0.0000	1.0000	0.2588	0.1875	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.1578	0.1524	0.1545	0.1531	0.1549
	HS	0.0000	0.0000	0.0000	0.3177	0.0000	0.0000	0.1843	0.0000	0.0000	0.0000	0.3574	0.0000	0.3493	0.0000	0.0000	0.0000	0.1421	0.1529	0.1489	0.1499	0.1424
	PF2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1672	0.0000	0.0000	0.0000	0.0000	0.0000	0.3245	0.0000	0.0000	0.0000	0.1358	0.1391	0.1401	0.1309	0.1411
Fire Protection Options	ITC	0.2005	0.1937	0.1970	0.2052	0.1982	0.1924	0.2025	0.2072	0.1969	0.2155	0.2005	0.2006	0.2022	0.2038	0.1964	0.1951	0.0000	0.0000	0.0000	0.0000	0.0000
	BST	0.2002	0.2075	0.2047	0.1955	0.1977	0.2125	0.1955	0.1912	0.1998	0.1947	0.2038	0.2016	0.2033	0.1974	0.2008	0.2105	0.0000	0.0000	0.0000	0.0000	0.0000
	CES	0.1999	0.2097	0.2100	0.1950	0.2015	0.2160	0.1980	0.1908	0.2013	0.1931	0.2038	0.2026	0.2053	0.2019	0.2005	0.2126	0.0000	0.0000	0.0000	0.0000	0.0000
	SCM	0.1993	0.1950	0.1878	0.1887	0.1996	0.1909	0.1866	0.1944	0.1974	0.1814	0.1942	0.1991	0.1975	0.1952	0.1897	0.1937	0.0000	0.0000	0.0000	0.0000	0.0000
	UPS	0.2001	0.1941	0.2005	0.2157	0.2029	0.1882	0.2173	0.2164	0.2045	0.2154	0.1977	0.1961	0.1917	0.2017	0.2126	0.1882	0.0000	0.0000	0.0000	0.0000	0.0000

(b) *Weighted super matrix*

Clusters	Elements	FRA	SFR	PF1	CDD	FFO	FSC	MA	ES	EAC	BA	HC	ASI	BRA	BUF	HS	PF2	ITP	BST	CES	SCM	UPS
Safety	FRA	0.0000	0.0770	0.0000	0.1449	0.0687	0.0000	0.4162	0.0000	0.0000	0.0000	0.0000	0.0625	0.0179	0.0625	0.0000	0.0000	0.0496	0.0505	0.0500	0.0526	0.0529
	SFR	0.0000	0.0000	0.2129	0.0000	0.0731	0.1105	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0625	0.0510	0.0518	0.0522	0.0503	0.0506
	PF1	0.1281	0.0626	0.0000	0.0000	0.0641	0.0935	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0139	0.0000	0.0000	0.0000	0.0434	0.0429	0.0437	0.0424	0.0438
	CDD	0.1488	0.0762	0.2033	0.0000	0.0710	0.1086	0.0000	0.0000	0.0000	0.0625	0.0000	0.0000	0.0000	0.0000	0.0625	0.0000	0.0483	0.0512	0.0504	0.0527	0.0491
	FFO	0.0000	0.0639	0.0000	0.1309	0.0000	0.1036	0.0000	0.0000	0.0000	0.0000	0.0625	0.0000	0.0163	0.0000	0.0000	0.0000	0.0459	0.0442	0.0441	0.0454	0.0471
	FSC	0.1393	0.0669	0.0000	0.1404	0.0706	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0446	0.0458	0.0475	0.0448	0.0415
	MA	0.0000	0.0697	0.0000	0.0000	0.0686	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0145	0.0000	0.0000	0.0000	0.0505	0.0469	0.0455	0.0452	0.0482
Environmental	ES	0.0000	0.0587	0.0587	0.0587	0.0000	00281	0.0294	0.0000	0.5000	0.0625	0.0000	0.0625	0.0293	0.0000	0.0000	00625	0.3333	0.3333	0.3333	0.3333	0.3333
	EAC	0.0587	0.0000	0.0000	0.0000	0.0587	0.0306	0.0293	0.5000	0.0000	0.0000	0.0625	0.0000	0.0332	0.0625	0.0625	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Societal	BA	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0177	0.0000	0.0000	0.0000	01423	0.0000	0.0000	0.0000	0.0000	0.0000	0.0486	0.0438	0.0428	0.0450	0.0456
	HC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0232	0.0163	0.0000	0.0000	0.4375	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0428	0.0412	0.0421	0.0428	0.0431
	ASI	0.1089	0.0483	0.1089	0.0317	0.0000	0.0241	0.0162	0.0000	0.0000	0.0000	0.1388	0.0000	0.1427	0.4375	0.4375	0.4375	0.0419	0.0418	0.0432	0.0427	0.0440
	BRA	0.0000	0.0000	0.0000	0.0425	0.0000	0.0334	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0549	0.0583	0.0575	0.0581	0.0546
	BUF	0.0000	0.0606	0.0000	0.0000	0.1089	0.0282	0.0204	0.0000	0.0000	0.0000	0.0000	0.4375	0.0000	0.0000	0.0000	0.0000	0.0526	0.0508	0.0515	0.0510	0.0516
	HS	0.0000	0.0000	0.0000	0.0346	0.0000	0.0000	0.0201	0.0000	0.0000	0.0000	0.1564	0.0000	0.1528	0.0000	0.0000	0.0000	0.0474	0.0510	0.0496	0.0500	0.0475
	PF2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0182	0.0000	0.0000	0.0000	0.0000	0.0000	0.1420	0.0000	0.0000	0.0000	0.0453	0.0464	0.0467	0.0436	0.0470
Fire Protection Options	ITC	0.0834	0.0806	0.0820	0.0854	0.0825	0.0801	0.0843	0.1036	0.0984	0.0943	0.0877	0.0878	0.0885	0.0892	0.0859	0..854	0.0000	0.0000	0.0000	0.0000	0.0000
	BST	0.0833	0.0864	0.0852	0.0814	0.0823	0.0885	0.0814	0.0956	0.0999	0.0852	0.0892	0.0882	0.0890	0.0863	0.0879	0.0921	0.0000	0.0000	0.0000	0.0000	0.0000
	CES	0.0832	0.0873	0.0874	0.0812	0.0839	0.0899	0.0824	0.0954	0.1007	0.0845	0.0892	0.0886	0.0898	0.0883	0.0877	0.0930	0.0000	0.0000	0.0000	0.0000	0.0000
	SCM	0.0830	0.0812	0.0782	0.0785	0.0831	0.0794	0.0777	0.0972	0.0987	0.0793	0.0850	0.0871	0.0864	0.0854	0.0830	0.0847	0.0000	0.0000	0.0000	0.0000	0.0000
	UPS	0.0833	0.0808	0.0834	0.0898	0.0845	0.0783	0.0905	0.1082	0.1023	0.0942	0.0865	0.0858	0.0839	0.0882	0.0930	0.0823	0.0000	0.0000	0.0000	0.0000	0.0000

(c) *Limiting super matrix*

Clusters	Elements	FRA	SFR	PF1	CDD	FFO	FSC	MA	ES	EAC	BA	HC	ASI	BRA	BUF	HS	PF2	ITP	BST	CES	SCM	UPS
Safety	FRA	0.0410	0.0410	0.0410	0.0410	0.0410	0.0410	0.0410	0.0410	0.0410	0.0410	0.0410	0.0410	0.0410	0.0410	0.0410	0.0410	0.0410	0.0410	0.0410	0.0410	0.0410
	SFR	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274
	PF1	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251	0.0251
	CDD	0.0365	0.0365	0.0365	0.0365	0.0365	0.0365	0.0365	0.0365	0.0365	0.0365	0.0365	0.0365	0.0365	0.0365	0.0365	0.0365	0.0365	0.0365	0.0365	0.0365	0.0365
	FFO	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254	0.0254
	FSC	0.0285	0.0285	0.0285	0.0285	0.0285	0.0285	0.0285	0.0285	0.0285	0.0285	0.0285	0.0285	0.0285	0.0285	0.0285	0.0285	0.0285	0.0285	0.0285	0.0285	0.0285
	MA	0.0187	0.0187	0.0187	0.0187	0.0187	0.0187	0.0187	0.0187	0.0187	0.0187	0.0187	0.0187	0.0187	0.0187	0.0187	0.0187	0.0187	0.0187	0.0187	0.0187	0.0187
Environmental	ES	0.1654	0.1654	0.1654	0.1654	0.1654	0.1654	0.1654	0.1654	0.1654	0.1654	0.1654	0.1654	0.1654	0.1654	0.1654	0.1654	0.1654	0.1654	0.1654	0.1654	0.1654
	EAC	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948	0.0948
Societal	BA	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176	0.0176
	HC	0.0219	0.0219	0.0219	0.0219	0.0219	0.0219	0.0219	0.0219	0.0219	0.0219	0.0219	0.0219	0.0219	0.0219	0.0219	0.0219	0.0219	0.0219	0.0219	0.0219	0.0219
	ASI	0.0710	0.0710	0.0710	0.0710	0.0710	0.0710	0.0710	0.0710	0.0710	0.0710	0.0710	0.0710	0.0710	0.0710	0.0710	0.0710	0.0710	0.0710	0.0710	0.0710	0.0710
	BRA	0.0202	0.0202	0.0202	0.0202	0.0202	0.0202	0.0202	0.0202	0.0202	0.0202	0.0202	0.0202	0.0202	0.0202	0.0202	0.0202	0.0202	0.0202	0.0202	0.0202	0.0202
	BUF	0.0528	0.0528	0.0528	0.0528	0.0528	0.0528	0.0528	0.0528	0.0528	0.0528	0.0528	0.0528	0.0528	0.0528	0.0528	0.0528	0.0528	0.0528	0.0528	0.0528	0.0528
	HS	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235
	PF2	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175
Fire Protection Options	ITC	0.0631	0.0631	0.0631	0.0631	0.0631	0.0631	0.0631	0.0631	0.0631	0.0631	0.0631	0.0631	0.0631	0.0631	0.0631	0.0631	0.0631	0.0631	0.0631	0.0631	0.0631
	BST	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621	0.0621
	CES	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624
	SCM	0.0608	0.0608	0.0608	0.0608	0.0608	0.0608	0.0608	0.0608	0.0608	0.0608	0.0608	0.0608	0.0608	0.0608	0.0608	0.0608	0.0608	0.0608	0.0608	0.0608	0.0608
	UPS	0.0643	0.0643	0.0643	0.0643	0.0643	0.0643	0.0643	0.0643	0.0643	0.0643	0.0643	0.0643	0.0643	0.0643	0.0643	0.0643	0.0643	0.0643	0.0643	0.0643	0.0643

(d) *Normalised limiting priority scores of structural fire design decision elements from benefits control network*

Clusters	Elements	Limiting priority scores of elements	Normalised priority scores
Safety	FRA	0.0410	0.2024
	SFR	0.0274	0.1352
	PF1	0.0251	0.1239
	CDD	0.0365	0.1801
	FFO	0.0254	0.1254
	FSC	0.0285	0.1407
	MA	0.0187	0.0923
Environmental	ES	0.1654	0.6357
	EAC	0.0948	0.3643
Societal	BA	0.0176	0.0784
	HC	0.0219	0.0975
	ASI	0.0710	0.3163
	BRA	0.0202	0.0900
	BUF	0.0528	0.2352
	HS	0.0235	0.1047
	PF2	0.0175	0.0779
Fire Protection Options	ITC	0.0631	0.2018
	BST	0.0621	0.1986
	CES	0.0624	0.1996
	SCM	0.0608	0.1944
	UPS	0.0643	0.2056

6.3.5. Final preferences and ranking of competing fire protection options

To implement *ANP-<u>Step 7</u>* and achieve the last stage in the framework (Figure 4.1), a final ANP synthesis was carried out on the normalised priority scores from both the *benefits* and *costs* network models. The benefits-costs ratios of the decision elements were calculated as mentioned in *ANP-<u>Step 7</u>*; the outcomes from this synthesis were the final preference scores used in ranking the competing fire protection options. An illustration of the benefits-costs ratios is plotted in Figure 6.4. Here, the top-bottom ranking order is *UPS, CES, BST, ITC* and *SCM* as determined from this weighted stakeholder decision analysis with the WGMM-ANP.

Under the weighted stakeholder scenario, this study also derived stakeholder weights using the principal components analysis (PCA) approach (Scala *et al*. 2016) described in Section 3.2.1 for the aggregation of stakeholder individual judgements assuming that judgements are either dispersed or not. Here, comparison matrices were generated from fire design stakeholders' individual judgements in each set of paired comparisons. The comparison matrices were transformed into logarithm matrices; their respective covariance matrices were then determined to calculate their first principal components (Eigenvectors). The Eigenvectors are squared to give the stakeholder weights, which are then used to aggregate the individual judgements with the WGMM-ANP towards achieving group consensus/influence priority scores. PCA-based stakeholder weights derived from their paired comparison on the key design decision criteria (clusters) in this study are:

Structural engineers (0.530); architects (0.150); others {e.g. building services} (0.080); end users (0.072); fire engineers (0.060); building owners (0.033); fire service (0.030); building contractors (0.014); environmental professionals (0.012); manufacturers/suppliers (0.010); building consent authorities (0.001); and *building insurers (0.000002).*

The PCA-based stakeholder weights may not hold in a specific steel structural fire design decision where the opinion of the fire engineer, architect or building owner are implicitly known to influence the overall design decision. For instance, the presented PCA-based stakeholder weights show a higher weight for the *end user* than the *fire engineer* and *building owner* in the paired comparison of decision key criteria. This may be debatable or unacceptable to the fire design stakeholders, given that end-users are traditionally not involved in the formulated and technical stages of structural fire design decision-making of steel-framed buildings. The stakeholder weights obtained from the PCA-based approach is worse than that initially achieved by normalising stakeholder professional fees because the former reflected the potential hierarchy of stakeholders in a fire design decision-making process than the later i.e. the architect, client and engineers weight more than end-users, insurers etc.

Nevertheless, the stakeholder judgements were re-aggregated using their respective PCA-derived weights. Then ANP prioritisation and synthesis were reapplied to rank the competing options as shown in Figure 6.4. The achieved ranking order is *UPS, CES, ITC, BST, and SCM*. Here, the positions of ITC and BST were altered representing the impact of the PCA-based aggregation approach with the WGMM-ANP. The application of PCA did not wholly alter the ranking order of the competing options; however, the altered positions of ITC and BST may be considered significant in a system design decision-making for steel-framed buildings.

To test the sensitivity of the fire protection options' ranks to the scenario of unweighted stakeholders, this study re-aggregated the stakeholder judgements without applying the derived stakeholder weights in Section 6.3.3. In this case, the stakeholder categories were assumed as equally important or having equal influence in the decision-making process; hence, α_p in Equation 3.11 was taken as $1/p$ (Xu, 2000). The ANP prioritisation and synthesis are then reapplied accordingly; the ranking of the competing fire protection options from this unweighted stakeholder decision analysis with the GMM-ANP is also shown in Figure 6.4. Here, the top-bottom ranking order is *UPS*, *ITC*, *CES*, *BST,* and *SCM*. The ranking order of the competing options in the weighted stakeholder scenario is altered, given the consideration of unweighted fire design stakeholders. The ranks of *CES*, *BST* and *ITC* in the weighted stakeholder scenario changed in the unweighted scenario, which can be seen in Figure 6.4. The achieved ranking orders in this study based on the applied stakeholder weighted, and unweighted scenarios are also shown in Table 6.6 for more clarity. Table 6.6 also shows that UPS is consistently the best-ranked option.

Table 6.6. Ranks of competing fire protection options based on 42 weighted and unweighted stakeholders' scenarios.

Fire Protection Options	**B_i/C_i (GMM-ANP) & Rank**	**B_i/C_i (WGMM-ANP) & Rank**	**B_i/C_i (PCA-WGMM) & Rank**
ITC	0.2104 (2nd)	0.1985 (4th)	0.2006 (3rd)
BST	0.1907 (4th)	0.1997 (3rd)	0.2003 (4th)
CES	0.2065 (3rd)	0.2028 (2nd)	0.2018 (2nd)
SCM	0.1680 (5th)	0.1951 (5th)	0.1939 (5th)
UPS	0.2244 (1st)	0.2038 (1st)	0.2035 (1st)

The weighted and unweighted stakeholder scenarios considered herein are possible scenarios in typical structural fire design decision-making processes of building projects. For example, many building design decision-making scenarios may depend on an architect (ARC) or building owner (BDO) as the stakeholders driving the entire design process. However, in other design scenarios, other stakeholders may have equal decision-making input. Therefore, the application of W/GMM-ANP accounts for these decision-making scenarios albeit the PCA-based approach removes the decision-makers' importance and relevance to account for scenarios of non-homogeneity of group judgements (Scala *et al*. 2016). This may not be the case in a typical structural fire design of steel-framed buildings whereby the stakeholders come together in the same room to achieve design decisions, and the influence of some stakeholders are key to decision-making in different fire engineering industries. Nonetheless, in this research, the fire design stakeholders have the potential to weight themselves or revise their judgements which is a subject of the case study design decision analysis for a specific steel portal frame building in Chapter 8.

In both the weighted and unweighted stakeholder scenarios, unprotected steel (UPS) is the top-ranked structural fire protection option based on the highest benefits-costs ratio. This analysis gave a ranking of stakeholder judgements across a general design of steel-framed buildings whereas a specific building will have unique aspects and that might mean a protection option has a different cost/benefit ratio.

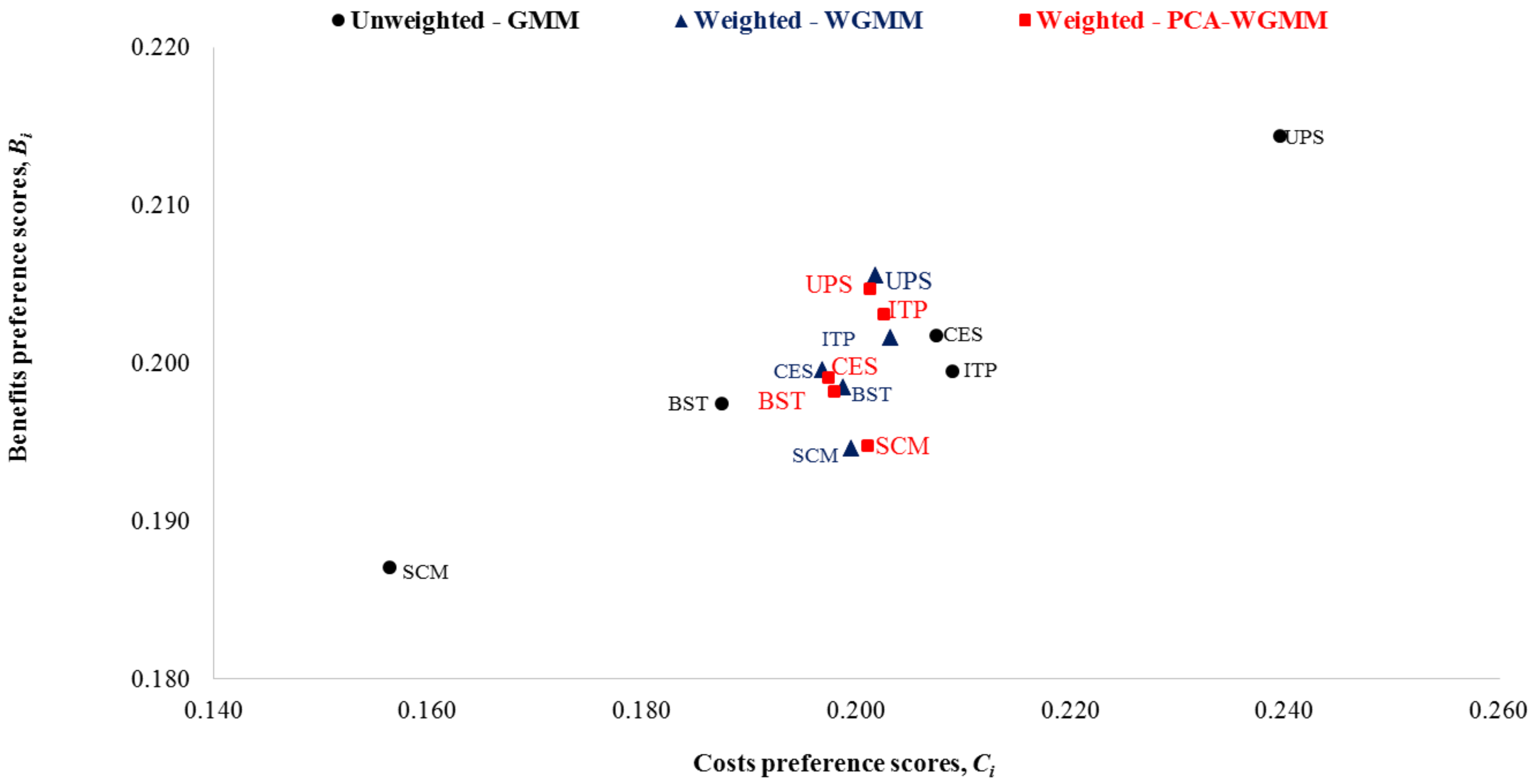

Figure 6.4. Benefits vs costs preferences of fire protection options from weighted and unweighted stakeholders.

Given the structural fire design decision-making problem and attributes investigated in this study were formulated from a general perspective, the fire design stakeholder views were extracted and analysed as such. Nevertheless, the application of W/GMM-ANP as an MCDA technique can be replicated in the system design decision-making process for a specific steel building. This is illustrated by the different views of the two building owners in Table 6.2 and different priorities of other stakeholders in Table 6.4. These variations may be similar or different in structural fire design decision-making processes of specific steel buildings.

Notably, the W/GMM-ANP applied here has provided the fire design stakeholders with the needed information and support for suitable decision-making. For instance, in Figure 6.4, if the unweighted case is assumed, the choice of UPS by the stakeholders will mean their consideration on benefits outweigh costs. However, the stakeholders can opt for the second or third-ranked options (ITC or CES) based on the moderate benefits-costs ratio. In the weighted stakeholder case, the decision-makers can select the second-ranked option, CES as their decision if costs consideration outweigh benefits. Effectively, given the outcome of the decision analysis the stakeholders' decision concludes the decision-making process.

6.4. Comparison of AHP and ANP Ranking Results

In comparing the results in this Chapter with the previous application of GMM-AHP (Chapter 5), there is a significant alteration of the ranking order of the competing fire protection options. In the previous study, CES was the top-ranked option given a general selection of a suitable fire protection option by 36 unweighted stakeholders, where these 36 stakeholders are a subset of the 42 used in this Chapter as explained in Section 6.3.2.2. Comparatively, Table 6.6 shows that CES is the second and third ranked option in the weighted and unweighted scenarios respectively which can be attributed to the application of a more robust and logical network process with possible dependences among the conflictual design decision criteria. In a sensitivity test to ascertain the effect of ANP and the expanded sample set on the ranking outcome achieved in Table 6.6, the judgements of the 36-unweighted stakeholders used in Chapter 5 are reanalysed using GMM-ANP. Table 6.7 shows the ranks of the competing options from the GMM-AHP and GMM-ANP decision analysis of 36 unweighted stakeholders' judgements. The alteration of the competing options' ranking order from this reassessment is the same as the outcome from applying the GMM-ANP on 42 stakeholders albeit the rank of BST changed from fourth (Table 6.6) to fifth

(Table 6.7). Therefore, the ranking result is more sensitive to the technique used than the sample set.

Table 6.7. The ranks of fire protection options from the GMM-AHP and GMM-ANP decision analysis of 36 unweighted stakeholders' judgements respectively.

Fire Protection Options	B_i/C_i (GMM-AHP: 36 Stakeholders & Rank)	B_i/C_i (GMM-ANP: 36 Stakeholders & Rank)
ITC	0.2070 (3rd)	0.1982 (2nd)
BST	0.2106 (2nd)	0.1881 (5th)
CES	0.2333 (1st)	0.1979 (3rd)
SCM	0.1640 (5th)	0.1945 (4th)
UPS	0.1850 (4th)	0.2212 (1st)

Notably, the ranking order achieved in Chapter 5 from the application of GMM-AHP may not hold in maintaining the consensus of steel structural fire design. The participant stakeholders may prefer the ranking orders achieved from the different scenarios investigated here using the W/GMM-ANP. The top-ranked option, UPS achieved in this Chapter from the weighted and unweighted stakeholder scenarios conform to the current consensus of structural fire design of steel-framed buildings than that determined in Chapter 5. This also gives more credence to the viability of ANP and its adjoining component W/GMM in solving complex and interdependent decision-making problems. However, the decision analysis carried out in this chapter may be insufficient to optimise or balance the fire design stakeholder goals considering inherent structural fire design uncertainties explained in Table 2.2. Importantly, the 42 stakeholder judgements assessed thus far consist of an unequal number of stakeholders in the different stakeholder categories. The outcomes achieved in this chapter may be skewed toward the views of the groups that had more participants and as such may affect the final decision. Therefore, there is a need to assess the competing fire protection options further quantitatively and integrate into the decision analysis process toward achieving an optimal outcome.

6.5. Conclusion

This Chapter proposes a group-analytic network process (W/GMM-ANP) for balancing stakeholder's views and reducing design decision uncertainties in selecting suitable fire protection options for steel-framed buildings. The technique is proposed as a transparent multi-criteria analysis technique in balancing group stakeholder views on steel structural fire protection for suitable design decision-making. This Chapter entails a paradigm shift from modelling decision problems in a top-down approach to a generalised and network approach of the ANP to achieve balanced decision-making given the conflicting and interdependent fire protection design strategies for specific steel buildings.

The stakeholder decision management framework and the applicability test of the AHP stemming from the pilot study in Chapter 4 have been valuable to this study. The successful aggregation of individual judgements from 42 fire design stakeholders, synthesis of 22 structural fire design decision elements with their inherent dependencies and ranking of five competing fire protection options, demonstrate the viability of the W/GMM-ANP in solving complex decision-making problems. The consideration of the weighted and unweighted stakeholder conditions captured design decision-making scenarios inherent in the building and fire safety design environments which affect design decisions. This is exemplified by the altered ranking order of the competing fire protection options in the unweighted stakeholder scenario (Figure 6.4; Table 6.6) and the outcome of the ANP reassessment of the 36 stakeholder judgements (Table 6.7) used in Chapter 5.

The stakeholder weighting method used herein (i.e. normalising professional fees) may not be suitable to account for stakeholder influence in the decision-making process as noted in Section 6.3.3. This method was only used herein to investigate the decision-making technique/process given the limitations of engaging stakeholder individually at different places and time. A more suitable method in which the stakeholder weight each other in the design decision-making process is reported in Chapter 8.

Importantly, the analysis achieved in this chapter may not sufficiently balance stakeholder goals. There is still the need to account for other design uncertainties, e.g. parameter uncertainties, etc., (Table 2.2) toward optimal design decisions. Quantitative assessments of the competing fire protection options which include uncertainty evaluation toward optimised design decision-making are addressed in the following chapters.

Nonetheless, this work has shown that the ranking of decision options is sensitive to the applied decision analysis technique and decision-makers' weights using the W/GMM-ANP.

7. OPTIMISING DESIGN DECISION-MAKING FOR STEEL STRUCTURES IN FIRE USING A HYBRID ANALYSIS TECHNIQUE[4]

7.1. Introduction

Fire phenomenon is highly dynamic. To achieve fire safety regarding life, property or environmental safety, there must be thoughtful consideration and optimisation of fire safety design decisions. In the structural fire design of steel buildings, the use of different fire protection options, design codes and diverse interests of multiple stakeholders may lead to design uncertainties in achieving steel structural fire design adequacy. In many practical scenarios, stakeholder views may lean toward a design decision criterion, e.g. safety among others as observed in Chapter 5. These scenarios can benefit from critical assessment of the stakeholder ranked preferences to manage skewed final decisions. Therefore, there is the need to develop a quality decision analysis tool to extract and manage varying stakeholder views, integrate structural fire analysis outcomes and rank competing design options for optimum decision-making. This will help balance stakeholder desires and reduce structural fire design uncertainties.

This chapter demonstrates the applicability of a hybrid decision-making technique, referred to here as GAT. GAT consists of the joint implementation of three approaches, namely: *the geometric mean method* (**G**MM), coupled with the *analytic hierarchy process* (**A**HP), and the *technique for order of preference by similarity to ideal solution* (**T**OPSIS). The use of the hybrid decision-making GAT technique is proposed in this Chapter for the effective integration of fire design stakeholder priorities, failure probabilities and costs of steel structural fire protection towards optimum design decision-making. As discussed in Chapter 3, the other MCDA techniques, e.g. the weighted sum/product models (WSM/WPM) etc., are deficient in solving the design decision problem investigated in this project. This is regarding weighting and aggregation of multiple stakeholders' views seamlessly as well as integrating qualitative and quantitative analysis outcomes in the decision-making process.

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[4] Parts of the contents of this chapter has been published as Akaa, O.U., Abu, A., Spearpoint, M. and Giovinazzi, S. (2017). "Optimising Design Decision-making for Steel Structures in Fire using a Hybrid Analysis Technique", *Fire Safety Journal,* http://dx.doi.org/10.1016/j.firesaf.2017.03.018

In this Chapter, the GAT process is described; the use of GMM+AHP for the selection of applied fire protection to steel structures in Chapter 4 is a precursor to this Chapter. The benefits and costs decision criteria used in assessing competing fire protection options, as well as the stakeholder engagement and paired judgement process on the decision criteria in Chapter 5 are also used here. The design decision criteria and options are formulated based on single-element design. Structural system design is not being investigated for simplicity and to highlight the benefits of the proposed technique as earlier mentioned (Section 2.5). Here, the priority scores of qualitative benefits and costs design decision criteria from aggregated paired judgements of 46 fire design stakeholders are used. This is an expanded sample set compared to the 36 and 42 stakeholder views analysed in Chapters 5 and 6 respectively, given that four additional stakeholders (building consent authorities) were interviewed before implementing GAT. The fire protection options used in the investigation are board systems (*BST*), sprayed on materials (*SCM*), intumescent paint (*ITC*), concrete encasement of steel (*CES*) and the design solution of using unprotected steel (*UPS*). The competing fire protection options are critically assessed through deterministic and probabilistic analyses of structural steel in fire.

The outcomes from the probabilistic structural fire analysis are integrated into the decision analysis using TOPSIS. The result accounts for the multidimensionality in synthesising qualitative expert opinion and quantitative information as well as optimising the structural fire design decision-making.

7.2. Methodology

To thoroughly address the structural fire design decision-problem in this research, the use of GAT, a hybrid MCDA technique, which integrates GMM+AHP+TOPSIS, is proposed. Hybrid MCDA techniques have been developed and applied conveniently to complex decision problems (Section 3.1.6). The choice of GAT in this context is due to its capability to aggregate multiple expert or stakeholder judgements into a single group judgement through GMM. It seamlessly weights or prioritises the group judgements on the different decision criteria through AHP and synthesises qualitative/quantitative criteria weights to assess and rank the competing options through TOPSIS. The choice of incorporating GMM in GAT instead of AMM was because of GMM’s capability to aggregate individual judgements and incorporate stakeholder weights at the judgement level. This allows the decision-maker/s to see how the process/technique may be affected in the weighted and unweighted stakeholder scenarios. In addition, it also ensures the retention of judgement consistency after aggregation and prioritisation of multiple stakeholder judgements. These capabilities are not achievable with AMM. As described in Section 3.2.1, AMM is used to aggregate stakeholder individual priorities (not judgements) to ensure homogenous outcomes that satisfy 'Pareto Optimality". On the other hand, ANP which is the generalisation of AHP was not incorporated in GAT because it will require a separate stakeholder engagement to determine potential interdependencies/interactions of decision attributes regarding the fire protection of representative steel element investigated here. This was not possible given limited resources and time considering the busy schedules of the stakeholders and their different locations. However, the incorporation of ANP in GAT should be considered in the future to compare to the current study.

As discussed in Section 3.1.6, AHP + TOPSIS applications were designed for single decision maker scenarios. There is need to account for scenarios of multiple decision-makers having varying opinions/interests and integrating quantitative analysis outcomes of the competing options, which may impact the overall decision. GAT's capability to address this shortfall through aggregation of multiple decision-maker judgements, and through prioritisation and integration of quantitative design priorities to rank competing options will be explored here.

An example of a decision-making problem that may require GAT-implementation include deciding on a suitable fire protection/design option for a monumental building. This decision-making problem may be mainly influenced by views of either the architect or building owner among other stakeholders (such as engineers, regulators etc.), and the outcomes from the structural fire analysis of the proposed building. Another example is deciding on a suitable road asset treatment option which may involve the influences of road control authorities, end-users' opinions as well as outcomes from the deterioration analysis of the road pavements. The application of GAT may be suitable to aggregate and synthesise the different decision criteria and competing options in the mentioned decision-making problems.

In this study, GAT is applied to also demonstrate its adaptability in steel structural fire design as an advancement of decision analysis application in fire safety decision-making processes discussed in Section 3.1.1.2.

Figure 7.1 shows the generic GAT flowchart, and its application in a decision-making process is presented as follows:

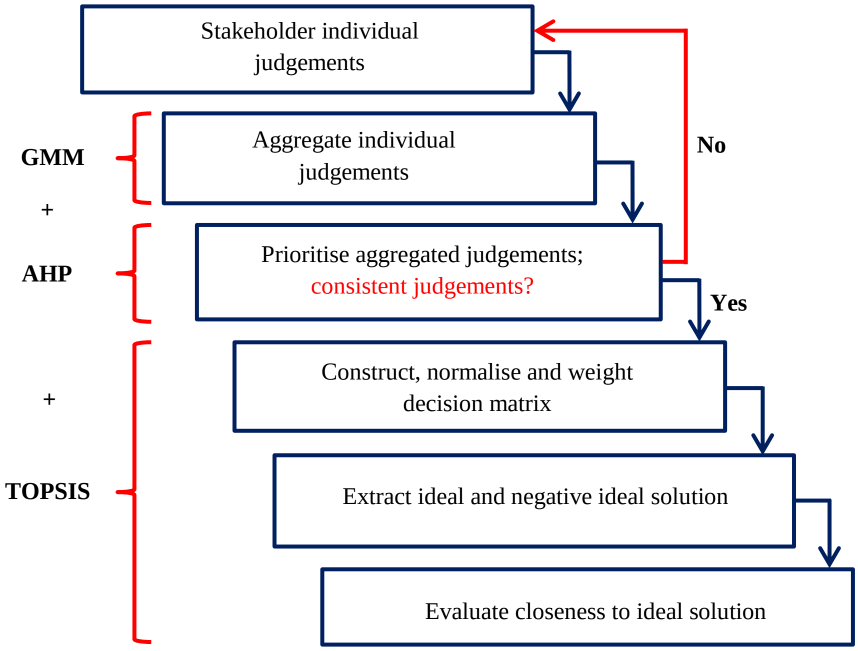


Figure 7.1. Generic GAT process.

In the GAT process, the decision-makers (i.e. stakeholders) are engaged to elicit their views at the beginning of the project, based on a defined decision goal, criteria and options. The stakeholders' individual paired judgements on the considered decision criteria are aggregated to form single group judgements using GMM as described in Chapter 3. The fire design stakeholders can be considered equally important or weighted based on their level of influence in the specific project at hand. Their weights can then be used in the aggregation of their judgements (Forman and Peniwati, 1998). The aggregated judgments are then weighted or prioritised using an Eigenvalue calculation detailed in the AHP to produce criteria weights or priority scores; GMM and AHP have been defined in Chapter 3. Within the AHP stage, consistency of the stakeholder judgments can be checked based on the AHP procedure and judgements revised if the consistency ratio is greater than 0.10 (Saaty, 1980). The remaining steps involve the implementation of TOPSIS which has been presented in Section 3.1.5 (*Step 1* - *Step 5*). The TOPSIS-steps include constructing and weighting a normalised decision matrix; determination of ideal and negative ideal solutions; and evaluating the options' closeness to the ideal solution.

The generic process (Figure 7.1) used in implementing GAT can be adapted for different complex decision-making scenarios. In applying GAT to solve structural fire design decision-making problems, the qualitative priority scores from stakeholder judgements and quantitative outcomes from structural fire analysis can be integrated to assess a suitable design option. This is feasible given the capability of GAT to normalise multidimensional values to non-dimensional elements in a decision matrix, which will be demonstrated in this Chapter. To achieve this, a joint risk management and design decision analysis framework is proposed as shown in Figure 7.2. The framework is a modified version of the decision management framework initiated in Chapter 4 and used in Chapter 5 and 6. The framework was used to guide the application of GAT through stakeholder engagement and decision analysis. It was developed within the concept of the risk management process (Section 0; Figure 2.9) detailed in the risk management standard (AS/NZS ISO 31000:2009).

The framework consists of a decision problem, stakeholder engagement, qualitative analysis (aggregation and prioritisation) and quantitative analysis (probabilistic analysis) using GAT to approach a balanced design decision. The relationship of the modified decision management framework (Figure 7.2) to the risk management process (Figure 2.9) is the same as the framework proposed in Chapter 4 (i.e. Figure 4.1). In Figure 7.2, defining the design decision problem and attributes relates to establishing the risk context, which is the first phase of risk management process. The stakeholder engagement provides the opportunity to identify risks; the qualitative and quantitative analyses are also related to risk analysis and evaluation given that probabilistic structural fire analysis is mainly for uncertainty evaluation. When making a balanced design decision at the end of GAT implementation, it can be inferred that risks are being treated as illustrated in the framework.

Notably, the modified framework (Figure 7.2) is mainly used for the design decision-making of a specific building. In this chapter, the GAT process was tested on a general case of steel structural fire design in which fire design stakeholders have previously been engaged. The framework was adapted to suit the purpose of this Chapter, as shown in Figure 7.3. In this case, the GMM+AHP components of the framework had been implemented in Chapter 5. The TOPSIS component of GAT was applied by integrating the qualitative stakeholder views from GMM+AHP, probabilistic structural fire analysis outcomes and actual costs of the competing options as shown in Figure 7.3. Applying the TOPSIS component of GAT is expected to support the stakeholder’s final decision.

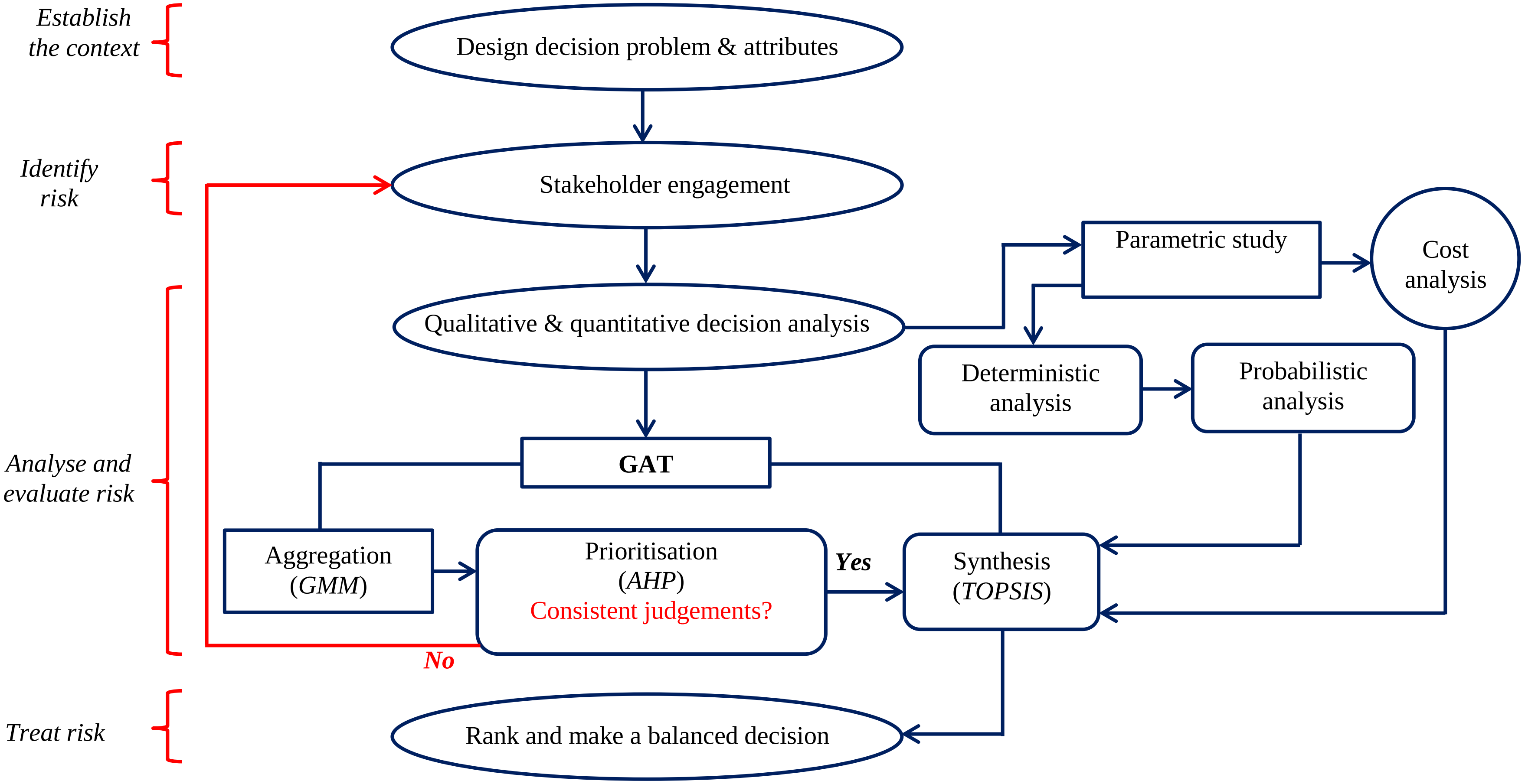


Figure 7.2. Joint risk management and design decision analysis framework.

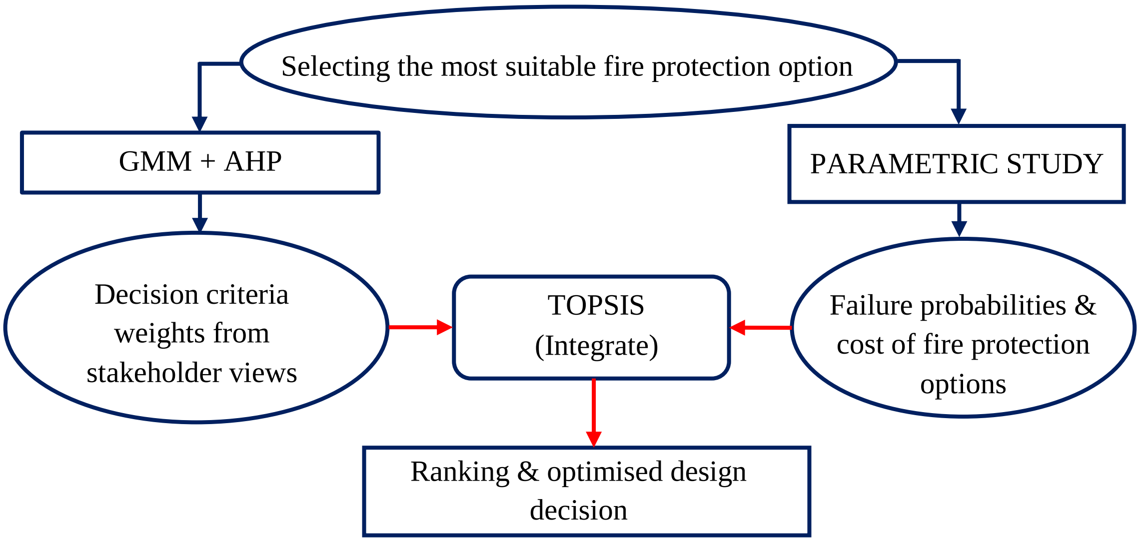


Figure 7.3. Adjusted flow chart for GAT implementation.

7.2.1. Application of GMM+AHP

In the previous study in Chapter 5, the formulated decision goal was *"to select the most suitable fire protection option for steel structures for fully developed fires"*, this is also considered in this chapter. The fire design stakeholders' benefits decision attributes and analytic breakdown were represented by the hierarchical tree shown in Figure 5.5.

The revised goal rating document (i.e. used in Chapter 5) having a fundamental reciprocal scale (Saaty, 1980) and the decision attributes (key criteria, sub-criteria) and options shown in Figure 5.5 were set out in the form of matrices. The document was used to extract paired judgements from 36 fire design stakeholders within the 12 stakeholder categories listed in Section 0. The stakeholders were experienced and chartered professionals within the building and fire industry in New Zealand. The stakeholders were considered as having equal influence in design decision-making, although it may be argued that some stakeholder opinions may carry more weight than others in practice. The key and sub-decision criteria levels in Figure 5.5 present a breakdown of the benefits criteria priority scores from the aggregation and prioritisation of the multiple stakeholder judgements, given the application of GMM+AHP. The qualitative costs criteria priority scores of the stakeholders are available from the cost hierarchical tree (Figure 5.6). Costs are considered as qualitative criteria and used in the decision analysis. The values at the options' level of Figure 5.5 and Figure 5.6 are respectively the benefits and costs performance scores of the competing fire protection options investigated in Chapter 5. They were used in the final synthesis and ranking of the options based on the qualitative benefits-costs ratio. The ranking showed that there was a stronger preference for concrete encasement of steel (CES) as the fire design stakeholders were considered equally important and unweighted, which may not be in keeping with the consensus in structural fire design.

Nevertheless, there was clarity in the transparent and complete use of AHP in solving the structural fire protection decision problem. In comparison to previous applications of AHP in fire safety decision-making in the literature (Shields and Silcock, 1986; Hansen, 1999; Yan *et al*. 2015), the work in Chapter 5 engaged a larger number of decision-makers (i.e. stakeholders). Also, the work in Chapter 5 seamlessly aggregated their stakeholder judgements, checked the consistency of stakeholder judgements and carried out the final synthesis via distributive and ideal modes (Saaty, 1994). However, the results were limited in terms of having equal numbers of stakeholders from all 12 categories. This could give way to skewed expert judgements. In many practical scenarios, most stakeholders may lean toward certain decision criteria, thereby causing a skewed overall decision. For instance, considering only the judgements from building consent authorities, fire service personnel, fire engineers, environmental professionals and end-users, may significantly increase the priority scores of safety sub-criteria, given their goal or interests are mainly within the ‘safety’ design criterion. This invariably affects the ranking of the competing fire protection options, resulting in a skewed decision. The different influences of stakeholder categories in many design decisions would need to be accounted for. As an example, in real design projects, it is likely that the client or architect may have the highest decision-making responsibility compared to other stakeholders. To address potential data skewness in the sample set previously used in Chapter 5 for the structural fire decision analysis, ten additional stakeholders were engaged. These were four *building consent authority* staff, two *building owners*, two *end-users* and two *building services professionals* in the ‘*others*’ fire design stakeholder category. Hence, the priority scores of benefits and costs criteria used in assessing competing fire protection options from aggregated paired judgements of 46 fire design stakeholders with GMM+AHP were considered here.

7.2.2. Parametric study

To further address possible skewness of the stakeholder views on the competing options as well as the inherent property/parameter uncertainties (Melchers, 1987) in achieving optimal structural fire design decision-making, a parametric study is proposed. These types of uncertainties associated with structural fire design have been explained in Table 2.2. The parametric study entails assessing variations in structural fire design parameters deterministically and probabilistically. In this context, the competing fire protection options are assessed as potential applications to representative structural members of a steel-framed building in fire conditions. The thermal response of protected steel members is determined based on variations of the passive fire protection thicknesses. Alternatively, the option to use a larger unprotected member is also considered. The steel temperatures are then used to assess the mechanical response of the member in standard fire condition in the strength domain. The relevant parameters in the study are further defined as probabilistic distributions toward uncertainty evaluation. The idea is to generate the failure probabilities of the steel structures in standard fire within a time horizon when protected by the competing options or designed to be unprotected.

For instance, consider a resistance or capacity domain analysis based on fire limit state. From a reliability perspective (Section 2.2.4), structural failure occurs when the resistance safety margin is less than or equal to zero (Wong, 1999), i.e.

$$R_m = R_c - R_d \leq 0 \qquad 7.1$$

Where R_m is the resistance safety margin, R_c is the resistance capacity and R_d is the resistance demand. The probability of failure (P_f) given post-flashover fires is the probability of the resistance safety margin being less than or equal to zero, i.e.

$$P_f = P(R_m \leq 0) = P(R_c - R_d \leq 0) \qquad 7.2$$

Therefore, in an uncertainty evaluation, the key outputs can be defined using Equation 7.1 and 7.2 considering a normal distribution of the intended outcomes. Zhang *et al.* (2013) suggest that failure probability can be predicted by simulation from:

$$P_f = \frac{n(R_m \leq 0)}{N} \qquad 7.3$$

Where n is the number of simulations for which $R_m \leq 0$; and N is the number of iterations (*i.e. the number of times the repetitive set of probabilistic analysis are performed in a simulation*).

The costs of the fire protection options are also evaluated and integrated into the decision analysis with the failure probabilities and stakeholder views for an optimum design decision using the TOPSIS component of GAT.

7.3. Structural Fire Design Decision Analysis

7.3.1. Deterministic analysis

A simply supported steel beam (section: 406×178×54UB; length: 15 m) was considered for the structural fire deterministic analysis with a desired fire resistance rating (FRR) of 60 min. All other criteria follow previous analyses.

The beam moment demand in fire ($M_{fi,ED}$) was determined as 107.70 kNm. By applying the Eurocode approach (BSI, 2005a), a critical temperature was calculated as 659 °C. For the determination of member temperatures in fire, an analysis was carried out whereby the relevant thermal properties of unprotected steel and passive fire protection materials were used as input parameters in the 'lumped mass' step-by-step technique of Eurocode 3 part 1.2. The thermal property values of the passive fire protection material were taken from the range of values published in the literature (Wang *et al*. 2013; Kodur, 2014; Buchanan and Abu, 2017) as shown in Table 7.1.

Table 7.1. Thermal properties of fire protection options for deterministic analysis (Wang *et al*. 2013; Kodur, 2014; Buchanan and Abu, 2017)

Passive fire protection option	**Density, ρ_i (kg/m^3)**	**Thermal conductivity, k_i (W/m.K)**	**Specific heat, c_i (J/kg.K)**
High density vermiculate plaster (*SCM*)	550	0.12	1200
Fibre calcium silicate board (*BST*)	600	0.15	1200
Normal weight encased concrete (*CES*)	2300	1.60	1000
Intumescent coating (*ITC*)	1300	-	1000

To satisfy the design requirement, the thicknesses of the fire protection materials were varied such that steel temperatures were limited to 620°C (ASFP, 2014) at 60 min for each competing passive fire protection as shown in Figure 7.4.

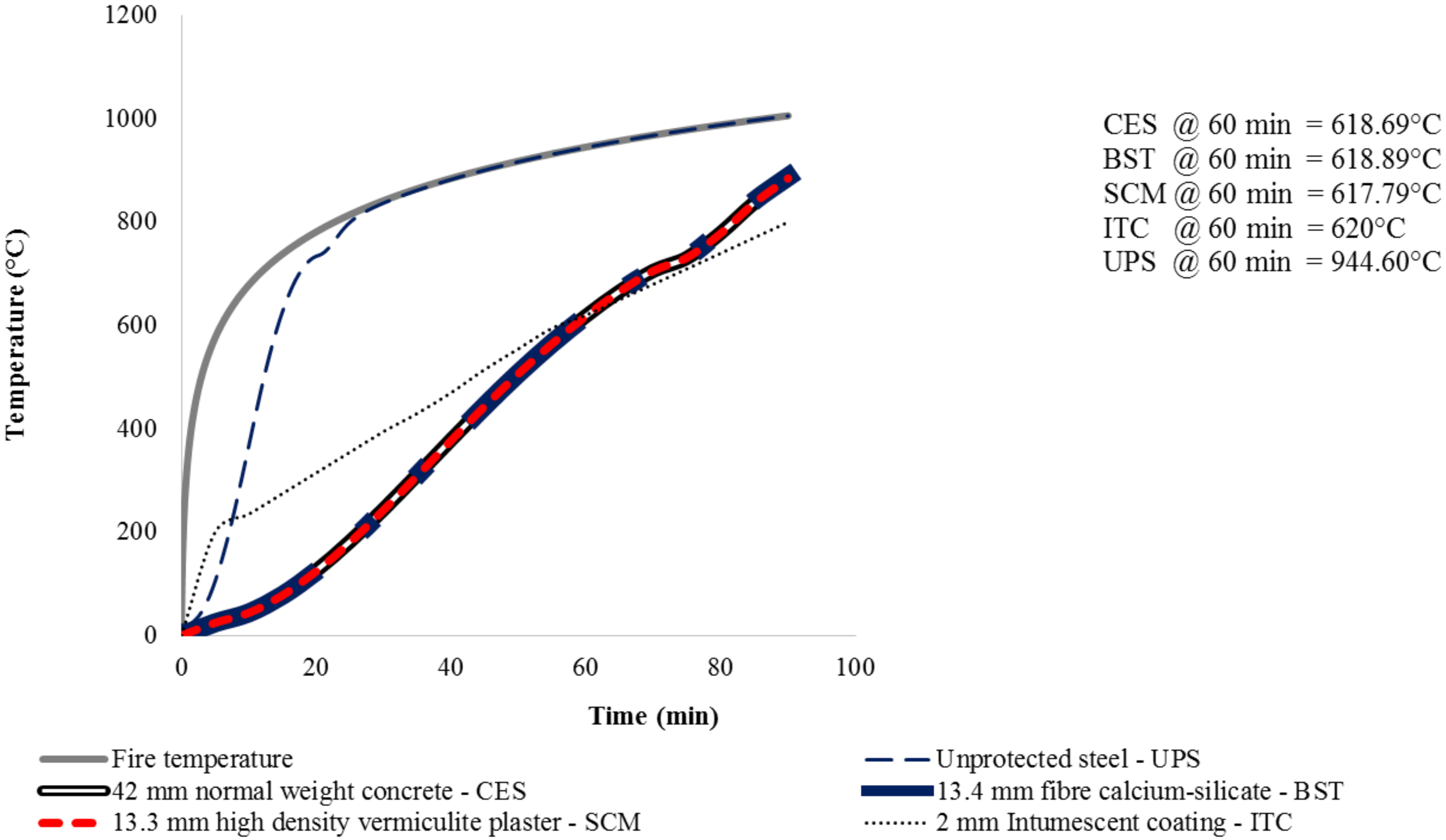
The steel temperatures from the thermal analysis were used for the fire limit state mechanical analysis of the beam section by calculation in the strength domain as detailed in Eurocode 3 part 1.2 (BSI, 2005a). Here the steel temperatures obtained from applying the fire protection materials were used to determine the reduction factor for the yield strength of steel. Then, given plastic section modulus of the nominal beam, the moment capacity, $M_{fi,\Theta,RD}$ of the beam in standard fire was calculated. Figure 7.5 shows the moment capacities of the steel member in fire when protected with the competing options. As expected the unprotected steel failed although this may not be the case in a system design of a steel-framed building with possible load redistribution in fire conditions.

In this study, a larger steel beam section, 838×292×194UB was selected to replace the failed unprotected beam initially used in the analysis. Reapplying the deterministic process, the moment capacity in fire conditions for the new beam section was determined as 113 kNm at 60 min of exposure to the standard fire, which is greater than 108 kNm (the beam moment demand). The deterministic analysis manual calculations for the mechanical response of the steel beam in fire are presented in Appendix 3.

Thermal analysis of intumescent coated steel

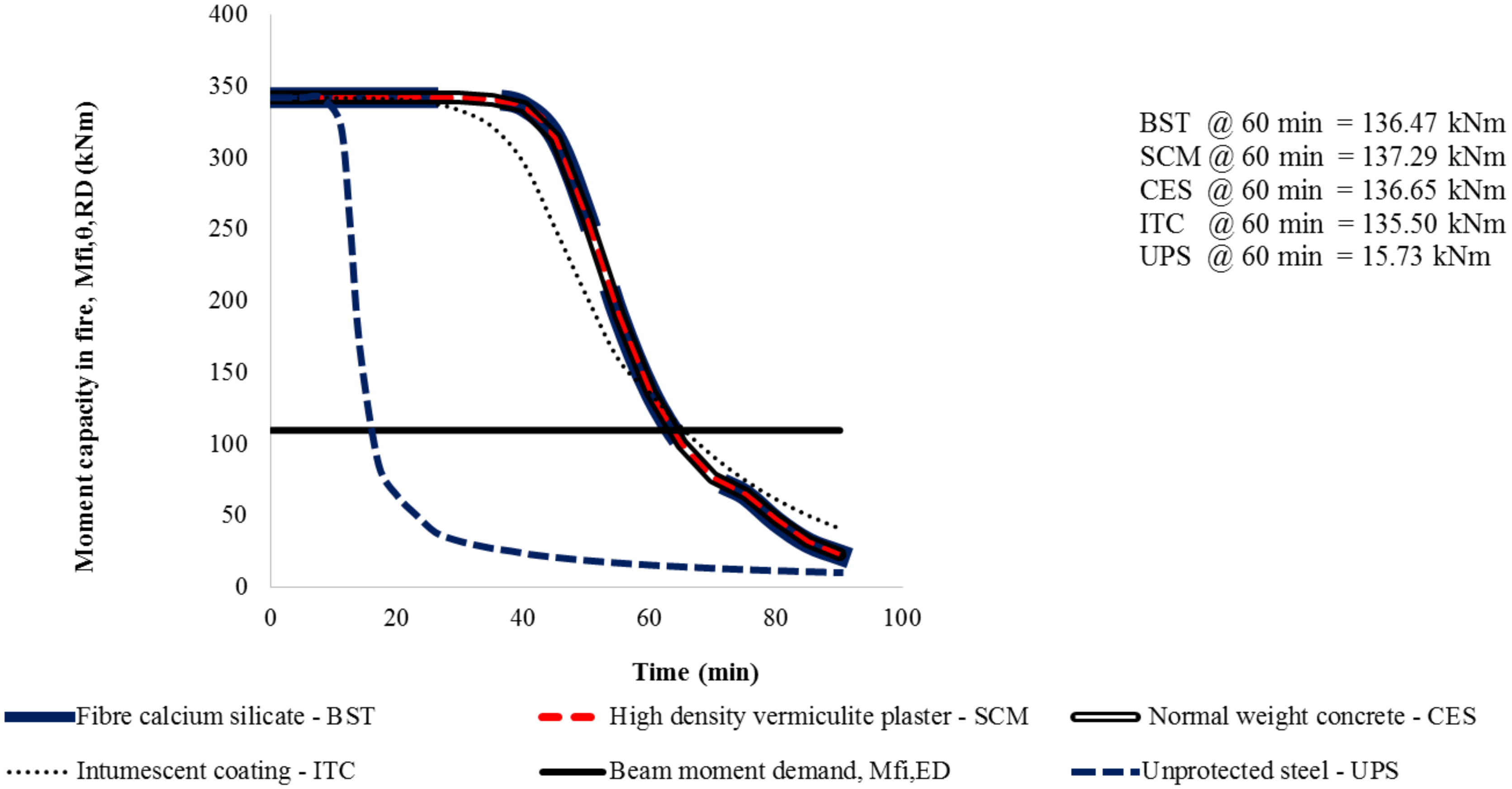
As mentioned earlier in Section 2.2.3 and shown in Table 7.1, the thermal conductivity, k_i of intumescent coating was not found in the literature. This study assumed that in fire conditions, steel temperature could rapidly increase to around 200 °C prior to intumescence then gradually increase linearly to the critical temperature as shown in Figure 7.4. Therefore, two thermal conductivities for intumescent coating were determined as effective thermal conductivity (*i.e. the conducted heat per initial material thickness per unit degree temperature*) and apparent thermal conductivity (*i.e. the conducted heat per expanded material thickness per unit degree temperature*) (Wang *et al*. 2013). By assuming the standard fire exposure and the initial thickness of the intumescent coating (2 mm), an effective thermal conductivity was determined as 0.25 W/m.K using the calculation method detailed in BS EN 13381-8:2010; BSI (2010). Hence, apparent thermal conductivities, k_i*, for intumescent coated steel were calculated at time intervals in the thermal analysis to achieve a design temperature of 620 °C at 60 min.

Notably, Wang *et al.* (2013) mentioned that this approach might not apply to other design fires given that intumescence during heating may not be temperature dependent only but also significantly affected by the rate of change in temperature.



CES @ 60 min = 618.69°C
BST @ 60 min = 618.89°C
SCM @ 60 min = 617.79°C
ITC @ 60 min = 620°C
UPS @ 60 min = 944.60°C

Figure 7.4. Thermal response of steel beam protected by materials of varying thicknesses.



BST @ 60 min = 136.47 kNm
SCM @ 60 min = 137.29 kNm
CES @ 60 min = 136.65 kNm
ITC @ 60 min = 135.50 kNm
UPS @ 60 min = 15.73 kNm

Figure 7.5. Steel beam moment capacity in fire versus time.

7.3.2. Probabilistic analysis

The statistical behaviour of uncertain parameters in the deterministic analysis were considered in defining their respective probabilistic distributions. Latin hypercube sampling through the @Risk (Palisade, 2012), add-on macro to a spreadsheet, was used to define the various distributions and carry out uncertainty evaluation by Monte Carlo simulations.

Table 7.2 shows the probabilistic distributions used in the structural fire analysis. The characterisations of uncertain parameters were taken from the literature (Wong, 1999; Iqbal and Harichandran 2010; Guo *et al*. 2013; Zhang *et al*. 2014). For instance, the total loading action on the beam was characterised as an uncertain parameter having a gamma distribution (Iqbal and Harichandran 2010) based on the inherent variabilities of loading actions in fires. Importantly, the probabilistic characterisation of loading action follows the characterisation of the contributing uncertain actions (i.e. dead and imposed loads) as gamma distributions and correlating them to the total load using @RiskCorrmat function. The section factors of steel sections are mostly supplied by steel manufacturers and may slightly differ in values for steel sections of relatively same size. Hence, section factor was considered to have a triangular probabilistic distribution with minimum value of 210 m^{-1}, most likely value (MLV) as 215 m^{-1} and maximum value as 220 m^{-1} for the unprotected steel section. On the other hand, the density of steel was not expected to vary at ambient temperature but may vary at an elevated temperature, so it was assumed to have a shortened normal distribution with 7850 kg/m^3 and 40 kg/m^3 as mean and standard deviation respectively. The height and width of the steel section, the web thickness and root radii were considered as uncertain parameters and characterised to have normal distributions which can account for possible imperfections in the steel section. The probabilistic distributions of uncertain parameters used in assessing applied fire protection materials to the steel element were also defined as shown in Table 7.2. Notably, the thermal conductivity k_i (W/m.K), and specific heat, c_i (J/kg.K) of the different passive fire protection materials were assumed to have a lognormal distribution as described by Iqbal and Harichandran (2010). The thicknesses of the passive fire protection materials were also defined as lognormal distributions to account for their variability in the determined section factors. Furthermore, in Table 7.2, the densities of the fire protection materials were assumed as normally distributed given that there are different proprietary brands of each protection material. To account for this, the minimum, mean, maximum and standard deviation attributes of the normal distribution was considered a suitable characterisation.

Table 7.2. The probabilistic distributions for steel beam structural fire analysis (Wong, 1999; Iqbal and Harichandran, 2010; Guo *et al*. 2013; Zhang *et al*. 2014).

Parameter - ***Steel beam: 406×178×54UB (UPS)***	**Distribution (PDF)**	**Mean or MLV**	**COV**
Steel section factor, Hp/A (m^{-1})	Triangular	215	0.009
Density of steel, ρ_a (kg/m^3)	Normal	7850	0.010
Specific heat of steel, c_a (J/kg.K)	Normal	600	0.050
Total action (load) on beam, $q_{fi,ED}$ (kN/m)	Gamma	3.83	0.121
Plastic section modulus, S (mm^3)	Normal	1.06×10^4	0.100
Yield strength of steel at 20 °C, f_y (MPa or N/mm^2)	Normal	320	0.093
- ***Fibre calcium silicate board (BST)***			
Section factor, Hp/A (m^{-1})	Triangular	169	0.041
Specific heat of insulation, c_i (J/kg.K)	Lognormal	1500	0.100
Thermal conductivity, k_i (W/m.K)	Lognormal	0.18	0.091
Thickness of protection material, d_i (mm)	Lognormal	13.40	0.090
Density of insulation, ρ_i (kg/m^3)	Normal	520	0.100
- ***Normal weight fully encased concrete (CES)***			
Section factor, Hp/A (m^{-1})	Triangular	169	0.041
Specific heat of insulation, c_i (J/kg.K)	Lognormal	1000	0.120
Thermal conductivity, k_i (W/m.K)	Lognormal	1.76	0.085
Thickness of protection material, d_i (mm)	Lognormal	42	0.091
Density of insulation, ρ_i (kg/m^3)	Normal	2000	0.140
- ***Intumescent coating (ITC)***			
Section factor, Hp/A (m^{-1})	Triangular	215	0.010
Specific heat of insulation, c_i (J/kg.K)	Lognormal	1000	0.110
Effective thermal conductivity, k_i* (W/m.K)	Lognormal	0.25	0.100
Thickness of protection material, d_i (mm)	Lognormal	2.00	0.089
Density of insulation, ρ_i (kg/m^3)	Normal	1300	0.094
- ***High-density vermiculate spray (SCM)***			
Section factor, Hp/A (m^{-1})	Triangular	215	0.010
Specific heat of insulation, c_i (J/kg.K)	Lognormal	1200	0.122
Thermal conductivity, k_i (W/m.K)	Lognormal	0.13	0.090
Thickness of protection material, d_i (mm)	Lognormal	13.30	0.092
Density of insulation, ρ_i (kg/m^3)	Normal	400	0.100

Equations 7.1 and 7.2 were employed to define the outputs of interest, R_m in the analysis. While Equation 7.3 was used to predict the failure probabilities (P_f) of the steel member in standard fire at 60 min when protected by the competing fire protected options presented in Table 7.3. The Monte Carlo simulation outputs in this study are based on 100 thousand iterations where a sensitivity check with 1 million iterations did not change the simulation outcomes for the defined outputs of each competing fire protection option applied to the steel member. The failure probabilities were extracted from the cumulative distribution of resistance safety margin, R_m.

To test the sensitivity of the deterministic analysis outcomes on the failure probabilities of the competing options, the calculated critical temperature of the steel beam (i.e. 659°C) was considered. This consideration was also to satisfy the full utilisation of the steel limiting temperature. Given that the steel beam was assumed as being loaded continuously in the standard fire, the utilisations when protected with the different materials were the same. Consequently, in the thermal analysis, the thicknesses of the fire protection options were also varied such that steel temperatures are limited to 659°C at 60 min. The thermal properties in Table 7.1 were also used accordingly in the analysis. The determined steel temperatures were used to calculate the mechanical response of the beam when protected or designed to be unprotected. The uncertain parameters, in this case, were also defined as distributions, and Monte Carlo simulations were carried out. Table 7.4 shows the steel temperatures, moment capacities and failure probabilities achieved from considering full utilisation of the steel beam capacity in standard fire. For the unprotected steel (UPS) option, the calculated critical temperature, 956°C for the larger steel beam (838×292×194UB) was used here.

Comparatively, given the beam moment demand was determined as 107.7 kNm and using the critical temperature (659°C) instead of a design temperature (620°C), the resistance capacities of the protected and unprotected steel beam were inadequate in standard fire condition as shown in Table 7.4. The previously achieved moment capacities using the design fire temperature, 620°C (ASFP, 2014) were within the fire limit state as shown in Figure 7.5. Table 7.4 also shows that the failure probabilities of the steel beam are highly sensitive to the full utilisation of its capacity given the high P_f values achieved from the probabilistic analysis compared to that initially predicted in Table 7.3. Other reliability issues regarding the competing options which include professional factors and adhesiveness (Zhang *et al*. 2014) were not considered here. However, the issues were noted as other uncertain conditions that may affect probabilistic structural fire analysis outcomes. Nevertheless, this study is mainly about the decision analysis/decision-making process and not the results of this parametric study. The failure probabilities achieved in Table 7.3 were integrated into the decision analysis.

The quantitative costs of the competing fire protection options were analysed to predict the actual material cost of protecting the steel beam in fire. This was achieved from a combination of the unit costs, specifications for structural fire protection in Christchurch, New Zealand (Rawlinson and Co., 2013) and size. Given that the available unit costs are associated with ranges of specifications; this study defined the unit costs as probabilistic functions assuming normal distributions. Monte Carlo simulation of 1,000,000 iterations using @Risk was also carried out in this case. The resulting probabilistic mean unit costs were then used to calculate the actual costs shown in Table 7.5.

Table 7.3. Structural failure probabilities in standard fire condition for protected and unprotected steel based on the design temperature.

Fire protection option	Probability of failure, P_f
13.4 mm fibre calcium silicate board (BST)	0.130
42 mm normal weight fully encased concrete (CES)	0.125
2 mm intumescent coating (ITC)	0.149
13.3 mm high-density vermiculite spray (SCM)	0.085
Unprotected steel (UPS)	0.232

Table 7.4. Structural failure probabilities in standard fire condition for protected and unprotected steel based on full limiting temperature utilisation.

Fire protection option	T_s (°C) @ 60 min	$M_{fi,\theta,RD}$ (kNm)	P_f
11.75 mm fibre calcium silicate board (BST)	658.12	105.62	0.365
38.95 mm normal weight fully encased concrete (CES)	658.04	105.68	0.313
1.88 mm intumescent coating (ITC)	658.28	105.51	0.371
11.65 mm high density vermiculite spray (SCM)	658.35	105.46	0.370
Unprotected steel (UPS)	956.00	105.10	0.606

The actual costs of full protection of the steel member were calculated based on sizing. Herein, ‘actual costs’ imply the real/tangible cost of the fire protection options derived from probabilistic evaluation of the given range of unit costs and material sizes. For instance, the difference in self-weight between the larger steel beam section, 838×292×194UB and initial beam section, 406×178×54UB was calculated as 140 kg/m. This was multiplied by the beam depth (0.81m) and the probabilistic unit cost of steel in Table 7.5 to determine the actual cost ($589) of the extra steel material that enhanced the beam's fire resistance capacity. For the other fire protection options, the probabilistic unit costs were simply multiplied by the beam length and depth of the steel section. In the case of full concrete encasement of steel, the unit cost was multiplied by the beam length and surface area of the steel section. Importantly, the beam length, depth and surface area were characterised as normal distributions.

Table 7.5. Costs of applying steel structural fire protection, adapted from (Rawlinson, 2013).

Fire protection options	Specifications	Units	Unit costs ($)	Probabilistic unit costs ($)	CoV	Actual Costs ($)
Board system	13-15mm thick (1 hour rating)	m^2	167 - 207	186.99	0.041	1130.35
Concrete encasement	Reinforced concrete	m^3	370	369.77	0.100	8208.89
Sprayed on material	1 hour rating; 0 - 230 Hp/A; 13 - 15 mm thick	m^2	17 - 17.90	17.84	0.031	107.84
Intumescent coating	1 hour rating; 201-280 Hp/A; 4-sided	m^2	169	169	0.050	1021.61
Unprotected steel	-	kg	5.10 - 5.20	5.2	0.100	589

7.3.3. Synthesis and optimisation via TOPSIS

This Chapter applied the GAT approach as shown in Figure 7.3, aiming to synthesise and optimise the structural fire design decision-making process. It is noteworthy that a typical GAT process will engage the decision-makers to elicit their views at the beginning of the project based on a defined decision goal, criteria and options as earlier mentioned. In this Chapter, the aggregated judgements on the competing fire protection options from 46 stakeholders given the benefits and costs sub-decision criteria set out in Figure 5.5 and Figure 5.6 respectively were used. This satisfied the implementation of the GMM+AHP component of the GAT process. The mathematical steps (Equations 3.6 - 3.10) in TOPSIS earlier explained in Section 3.1.5 (*Step 1* - *Step 5*) were then applied to integrate the qualitative stakeholder views and the quantitative parametric study outcomes.

To construct the design decision matrix, the five fire protection options investigated were placed at the left end column, sixteen benefits sub-criteria (Figure 5.5) and six costs sub-criteria (Figure 5.6) were considered as qualitative design decision criteria and placed at the top row of the design decision matrix. The determined costs (Table 7.5) and failure probabilities in applying the competing fire protection options to the steel member (Table 7.3) were considered as quantitative design decision criteria and denoted as fire protection costs (FPOC) and fire protection failure probability (FPFP) respectively. The costs and failure probability criteria were also placed at the top row of the design decision matrix as shown in Table 7.6. This implies that the values in decision matrix are priority scores of the conflictual design decision criteria used in assessing the competing fire protection options.

The qualitative benefits and costs priority scores entered in the design decision matrix (Table 7.6) are outcomes from GMM+AHP aggregation and prioritisation of Category ‘C’ unweighted stakeholder paired individual judgements (*AHP*-*Step 2*). The Category ‘C’ paired judgements entail comparing the competing options against each other with respect to each qualitative variable (sub-decision criterion) and the decision goal. The judgements were aggregated with GMM and prioritised with AHP and their priority scores were then entered into the decision matrix. Equation 3.6 was then used to normalise the design decision matrix to transform it to non-dimensional criteria and allow for comparison of the design decision criteria. Using Equation 3.7, the normalised design decision matrix was weighted by multiplying each element in the matrix by their associated weight. Table 7.7 shows the weights of decision attributes used in this analysis; the weights for each cluster in Table 7.7 sum up to unity. These weights were obtained from Categories ‘A’ and ‘B’ stakeholder paired judgements on the decision criteria and options (Section 3.1.1.1). The paired judgements were aggregated with the GMM and prioritised using *AHP*-*Step 4*to derive their weights as described in Section 3.1.1.1. The normalised elements under FPOC and FPFP design decision attributes are weighted with the fire protection options’ weights in Table 7.7.

The ideal and negative ideal solutions are determined by selecting the maximum and minimum values in each column of the weighted design decision matrix respectively. In this context, the minimum values in the FPOC and FPFP columns were considered as the ideal solutions; while the maximum values were the negative ideal solutions. Equations 3.8 and 3.9 were used to calculate the separation measures for each decision option from the ideal and negative ideal solutions respectively. In completing the TOPSIS-synthesis of GAT, Equation 3.10 was applied to predict the relative closeness of each competing option to the ideal solution which systematically ranks the steel structural fire protection options as shown in Figure 7.6.

At the completion of structural fire design decision analysis using the GAT process, board systems (*BST*) ranked best with C_i* value of 0.644. This is a scenario where the fire design stakeholders were considered equally important and unweighted. From Figure 7.6, the ranking order for the unweighted stakeholder scenario is thus: *Board systems (BST)*, Sprayed on cement-based material (*SCM), Intumescent coatings (ITC), Unprotected steel (UPS),* and Concrete encasement of steel (*CES)*. Here *CES* is inferior to other options compared to the previous study in Chapter 5 whereas the small differences between the *BST* and *SCM* mean there is very little to decide between the most suitable options. The unweighted stakeholder scenario thereby highlights the effect of a combination of unweighted stakeholders and integration of quantitative decision criteria in the process. The unweighted scenario may not be the case, as previously noted, in practice, different fire design stakeholders may have a greater or lesser influence on decisions made in a project and may need to be weighted.

Given that this result is based on the expanded data set of 46 stakeholders, this study also considered the views of 36 unweighted stakeholders used in Chapter 5 and then reapplied the TOPSIS aspect of GAT. In this case, the benefits and costs criteria priority scores from aggregated and prioritised unweighted fire design stakeholder judgements via GMM+AHP; and the outcomes of the parametric study in this Chapter were integrated using TOPSIS. The ranking order achieved is *BST, CES, ITC, SCM* and *UPS*; this shows an alteration to the ranking order achieved with the expanded sample set albeit *BST* retained its top-ranked position. Notably, *CES* is the second-ranked option which could be attributed to its competitive or very high qualitative benefits priority scores stemming from the stakeholders' paired judgements in the previous study (Chapter 5).

Table 7.6. Structural fire design decision matrix.

	FRA	SFR	PF1	CDD	FFO	FSC	MA	ES	EC	BA	HC	ASI	BRA	BUF	HS	PF2	CA	BC	PM	MMU	MSC	FRM	FPOC	FPFP
ITC	0.212	0.161	0.170	0.231	0.203	0.106	0.227	0.244	0.171	0.340	0.198	0.207	0.228	0.246	0.149	0.147	0.234	0.168	0.190	0.241	0.185	0.150	$1,022	0.149
BST	0.201	0.262	0.247	0.172	0.176	0.304	0.147	0.131	0.190	0.139	0.236	0.214	0.225	0.209	0.187	0.266	0.159	0.275	0.220	0.081	0.190	0.283	$1,130	0.130
CES	0.209	0.316	0.336	0.187	0.211	0.407	0.164	0.123	0.215	0.125	0.236	0.250	0.257	0.206	0.215	0.339	0.119	0.294	0.251	0.079	0.198	0.320	$8,209	0.125
SCM	0.189	0.147	0.105	0.137	0.198	0.106	0.114	0.151	0.176	0.078	0.154	0.182	0.175	0.170	0.116	0.137	0.220	0.133	0.189	0.219	0.203	0.150	$108	0.085
UPS	0.189	0.114	0.142	0.273	0.211	0.076	0.349	0.352	0.247	0.318	0.176	0.147	0.115	0.169	0.333	0.110	0.267	0.130	0.151	0.380	0.225	0.097	$589	0.232

Table 7.7. Weights of structural fire design decision attributes

Benefits sub-criteria																**Costs-sub criteria**						**Fire protection options**				
FRA	SFR	PF1	CDD	FFO	FSC	MA	ES	EAC	BA	HC	ASI	BRA	BUF	HS	PF2	CA	BC	PM	MMU	MSC	FRM	ITC	BST	CES	SCM	UPS
0.070	0.130	0.040	0.090	0.070	0.080	0.060	0.060	0.120	0.020	0.020	0.030	0.080	0.050	0.050	0.030	0.312	0.195	0.139	0.124	0.093	0.137	0.233	0.228	0.244	0.149	0.146

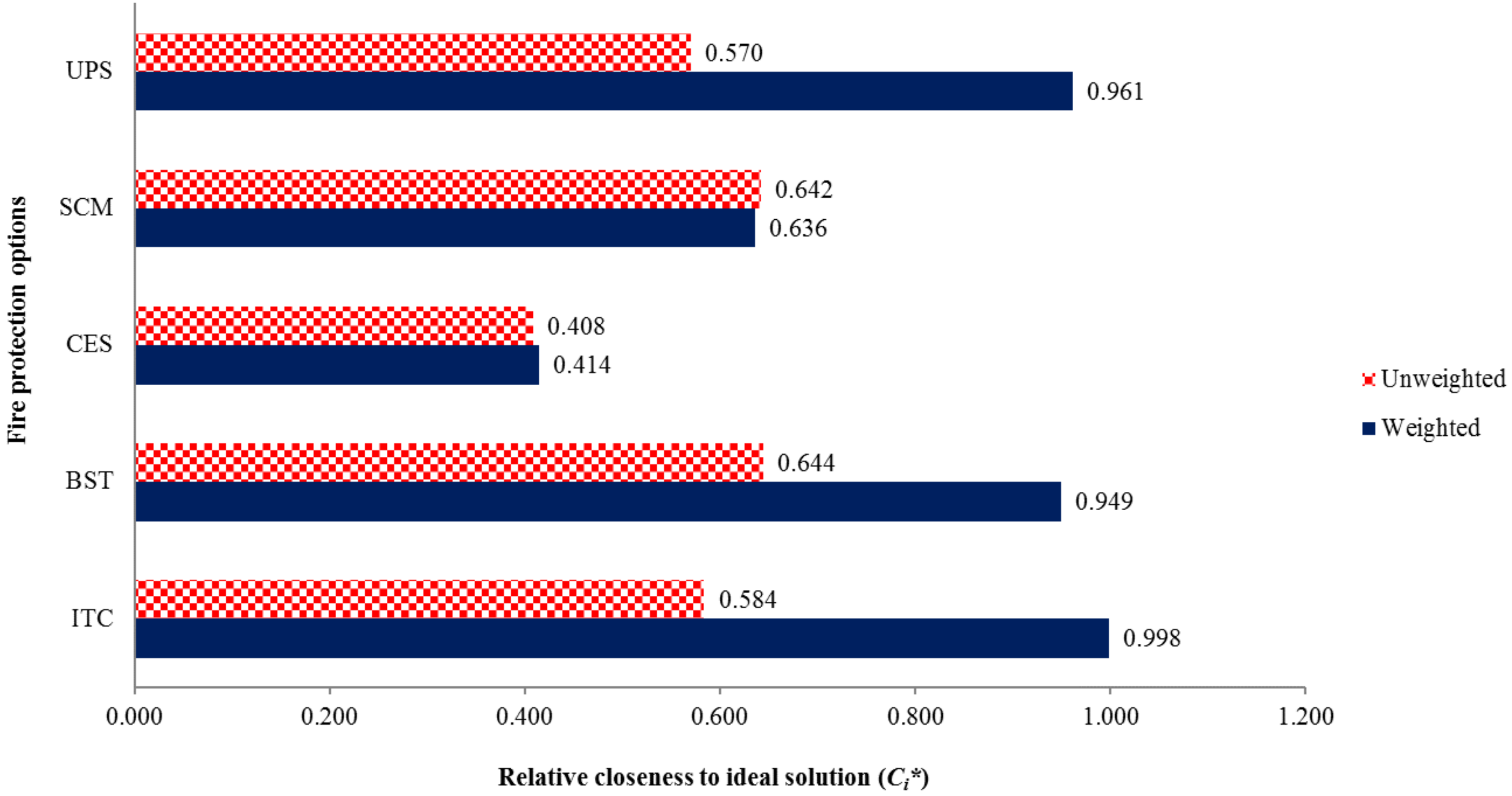


Figure 7.6. Ranking of steel structural fire protection decision-making options

As a form of sensitivity analysis, the possible influence of the different fire design stakeholder in the decision-making process was considered in this Chapter by weighting the stakeholder categories. There are different ways of weighting the participant-stakeholders or decision-makers in the process as discussed earlier in Chapter 3. For instance, the stakeholders can elect a 'super-decision-maker' among them to assign stakeholder weights if they come together in one room to participate in the structural fire design decision-making process. Another way is that the stakeholders can weight each other using the Eigenvalue method after a pairwise comparison of every participant-stakeholder (Section 3.2.1). These stakeholder weights are then applied to aggregate the individual stakeholder judgments using GMM (Forman and Peniwati, 1998) as earlier mentioned. Here the professional fees (CEEC, 2016) of the various fire design stakeholders were considered as a measure of their level of influence on the decision-making and were normalised to generate the stakeholders' weights listed earlier in Chapter 6. The PCA-approach was not considered in deriving the stakeholder weights because it does reflect the potential stakeholder hierarchy in a design decision-making process as mentioned earlier in Chapter 6. The determined stakeholder weights (w_k) add up to unity and were taken to be:

Architects (0.212); building owners (0.183); structural engineers (0.183); others {e.g. building services} (0.125); fire engineers (0.111); environmental professionals (0.073); building insurers (0.037); building contractors (0.029); end-users (0.018); manufacturers/suppliers (0.015); building consent authorities (0.007); and fire service personnel (0.007).

These derived weights were applied in the GMM-aggregation stage of the GAT process. Therefore, reapplying the rest of the GAT process produces the weighted stakeholder scenario ranking of the fire protection options also presented in Figure 7.6. The stakeholder weighting process must not be misconstrued with weighting priority scores or elements in a normalised decision matrix in the GAT process. The procedures used for stakeholder and criteria priority score weightings are different and applied at different stages. The stakeholder weighting is done early in the process and the weights applied at the GMM stage; while weighting the elements of the normalised decision matrix is carried out later in the TOPSIS stage of GAT.

In the weighted stakeholder scenario, it was observed that the ranking order changed significantly, whereby intumescent coating (*ITC*) became the top-ranked fire protection option. The ranking order in this scenario is thus: *ITC*, *UPS*, *BST*, *SCM*, and CES. It can also be observed that board systems (*BST*) and sprayed on material (*SCM*) are now the third and fourth-ranked options when the fire design stakeholders are weighted, due to the influence weights of the participant-stakeholders, e.g. architects and some participant-engineers. It is also interesting to see the performance of unprotected steel (*UPS*) which has become the second-ranked option in the weighted scenario, thereby showing competitiveness given the current drive in the structures and fire design industry toward optimising structural fire design and leaving steel structures unprotected.

A comparison of the ranking orders achieved based on unweighted stakeholder scenarios in Chapters 5, 6 and 7 indicate that the implementation of different MCDA techniques produced different results. For instance, the top and bottom-ranked options from the implementation of GMM+AHP and GMM+ANP were CES and SCM; and UPS and BST respectively as shown in Table 6.7. In the case of the unweighted stakeholder scenario using GAT, BST and CES were the top and bottom-ranked options as shown in Figure 7.6. These results may be attributed to the improved process/technique in each case as well as the formulation and analysis of the design decision problems which was based on a general structural fire design perspective.

7.4. Discussion

In comparing the synthesis results in this Chapter with previous application of the GMM+AHP for assessing and ranking the competing fire protection options based only on elicited fire design stakeholder judgements (Chapter 5) there are some significant differences. In the previous study, concrete encasement of steel (*CES*) was the top-ranked option in the unweighted scenario from a qualitative benefits-costs consideration as earlier mentioned. Here, using the expanded sample set of 46 stakeholders; it is observed that *CES* is the least-ranked option in the unweighted and weighted stakeholder scenarios. This is attributed to weighting and addressing the skewed stakeholder views by an improved sample set, carrying-out a parametric study and integrating its outcomes, given the probable safety-leaning opinions of the participant-stakeholders. The consideration of quantitative cost implications in selecting an applied fire protection option to the analysed representative steel member is an appropriate approach to put the design decision-making process in a realistic economic context regardless of the generalised formulation of this study. This invariably produced a ranking-order, which is considerably in tune with the consensus in structural fire design than the previous study. The integration of failure probabilities from the structural fire analysis as well as fire protection costs using the TOPSIS component of GAT and considered respectively as quantitative benefit and costs criteria in the process improved the synthesis results. The results achieved herein support an optimised stakeholders' final design decision, thereby mitigating parameter and design decision uncertainties (Table 2.2).

The choice of the best fire protection option is dependent on the stakeholders' risk tolerance regarding how benefits or costs outweighs each other and influences their decision. GAT is designed to support or guide fire design stakeholders to make optimised or cost-effective design decisions and not to make the decision for the stakeholders. Importantly, the technique/process is best suited for conceptual/formulated design decision stages involving multiple stakeholders, decision attributes and options and not the technical/detailed design phases of a design project.

Regardless of the general formulation of the structural fire decision problem and attributes, the GAT process is dynamic; it can be reapplied in a structural fire system design decision-making of a specific steel building. In such context, the decision goal, criteria and design options will be based mainly on the realistic design of the steel building, specific stakeholders involved in the design project and their jurisdiction. This implies that the stakeholders will produce different judgements and priorities and will have different weights based on their dominant influence in the project. The deterministic and probabilistic analysis outcomes will also be different. Hence, the ranking order achieved by using GAT in structural system design will differ but will reflect the realistic contributions of the stakeholders' views and analytic outcomes from the design process.

7.5. Conclusion

This Chapter has successfully demonstrated the viability and applicability of a hybrid multi-criteria decision analysis technique, referred to as GAT, in optimising structural fire design decision-making processes. The use of a single element or member design here is for simplicity in demonstrating the GAT process for optimum design decision-making.

The GMM component of GAT aggregated the individual judgements from multiple fire design stakeholders which managed the limitation of not having the stakeholders in one place at one time to apply the process. However, in practice, the normalisation of professional fees may not be an acceptable measure for stakeholder influence in design decision-making processes. A more acceptable method of weighting stakeholders which allows the stakeholders to weight themselves and the use of Eigenvalue or geometric mean to derive their weights has been trailed in the next chapter.

The AHP component in GAT supported the generation of stakeholder priority scores or weights of the conflictual design decision criteria under safety, economic, environmental and societal considerations as extracted from Chapter 5.

The design assumptions and analysis were kept simple to ensure that the potential benefits of GAT application in design decision-making is not lost in a complex structural fire analysis. However, there is need for more critical assessment of the competing options in the future to account for other design uncertainties (Table 2.2) and reliability issues, e.g. ‘stickability’, profession errors etc., which may alter the ranking results achieved in this study.

The capability of GAT in integrating design decision criteria from qualitative and quantitative benefits-costs perspectives through the ability of TOPSIS to provide seamless normalisation and account for multidimensionality in the process is novel in terms of combining fire design stakeholder views and actual outcomes from a structural fire analysis. Although there has been several applications of AHP+TOPSIS to solve complex decision problems in other fields, the adjoining decision-makers’ judgement aggregation component, GMM, has not been explored. Therefore, GAT’s novelty is in its method and application in the fire safety engineering, which is also worthy of further investigation. Notably, an application of GAT in the structural fire design decision analysis for a specific/realistic steel portal framed building is a subject of the next Chapter. The rankings of the competing fire protection options achieved in this study reflect the effect of the conflictual design decision criteria, from the unweighted and weighted stakeholder judgements or expert opinion as well as the transparency employed in the analytic process. Therefore, this hybrid technique is proposed for optimising structural fire design decision-making of buildings.

8. A VIRTUAL CASE STUDY OF DESIGN DECISION-MAKING FOR A STEEL PORTAL-FRAMED BUILDING IN FIRE USING A HYBRID MCDA TECHNIQUE

8.1. Introduction

In this Chapter, the hybrid MCDA technique, GMM+AHP+TOPSIS (GAT) developed in Chapter 7 is applied to a virtual building. The previous chapter applied GAT to generic steel-framed buildings toward optimising the design decision-making process given multiple stakeholder goals and inherent design uncertainties. In this study, four chartered/experienced stakeholders under two different scenarios: as individuals and as a group, to assess how the ranking of competing fire protection options may be influenced when a specific building is considered.

Stakeholder views on the building's structural fire design decision attributes were extracted to determine qualitative criteria priorities/weights with respect to selecting a suitable applied fire protection option. Fire protection costs and structural fire resistance were numerically and probabilistically assessed with reference to the design of one of the building's columns. Stakeholder qualitative priorities and quantitative analyses outcomes were then integrated and synthesised through GAT according to the proposed framework described in Chapter 7 (Figure 7.2).

8.2. Virtual Case Study

Steel portal frames are typical single-storey framed buildings known to be economical and efficient due to their rapid fabrication, low-cost, simple erection and ease of maintenance. They comprise of pitched or horizontal rafters and columns joined by moment-resisting connections (SCI, 2016). Steel portal frames may also consist of haunches (Figure 8.1) or deepened rafters which increase the structure's resistance to lateral and vertical actions. The rigidity and stiffness of connections and structural members respectively also contribute to portal-framed buildings' ability to resist vertical and lateral loads.

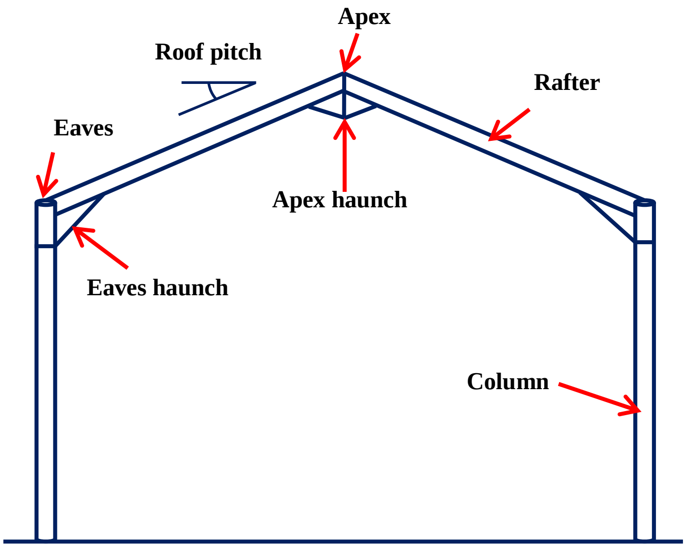


Figure 8.1. A typical symmetrical single-bay pitched portal frame (SCI, 2016).

In fully developed fires, the roofs typically collapse as they usually do not have applied fire protection, giving way to rapid fire growth and spread (Buchanan and Abu, 2017). Depending on the roofing materials used (e.g. the inclusion of plastic skylights), there are scenarios of roof venting whereby the heat in the building is vented into the atmosphere and may aid the structural members to remain relatively cool in fires. However, the issues with this portal-framed building in fire conditions include construction near property boundaries and the possibility of outward collapse during fire-fighting operations. Nonetheless, different fire protection and design options have been suggested in the literature for these buildings. These include passive fire protection of steel columns (SCI, 2016), fire-resistant boundary walls to control fire spread and unprotecting the steel members given an alternative design (O'Meagher *et al*. 1992; Buchanan and Abu, 2017).

There is a concern in New Zealand for the stability of external walls after a fire event. They are expected to remain standing. In most countries around the world, it is appropriate for external walls to collapse inwards in a severe fire event. However, in New Zealand, the design standards require walls to resist collapse inwards and outwards (MBIE, 2016), to primarily ensure that firefighters and Urban Search and Rescue (USAR) can confidently go into buildings to find survivors either after a fire or natural hazard (e.g. earthquakes). This design requirement has been recently criticised in the New Zealand building industry and is currently the subject of on-going consultation for the next iteration of the design standards.

Hence, to meet this requirement for portal-framed buildings, two design options are mainly considered, which are either:

- The external walls are nominally tied to the columns, and the columns are checked for stability in fires (irrespective of the effects of the haunches) so that the deformation of the walls can follow the behaviour of the columns; or
- A cantilever base is designed at the bottom of the external walls so that if the portal frames collapse in fires, the walls can stay in place. This is considered as an expensive option.

Following any of these considerations, the portal frames can be designed for structural adequacy of the column legs to act as restraints against the inward and outward collapse of their potential external walls given internal fire exposure.

The virtual case study building is a specific portal framed building adapted from Bong (2005). The building is a single bay duo-pitch portal frame with regular eaves and haunches but without internal columns. The external columns are steel I-sections without bracing as shown in Figure 8.2. The floor area of the building is 1200 m^2; other details of the building dimensions are also shown in Figure 8.2.

The building use is typical of industrial buildings which may not be compartmentalised and could be in an industrial area in Christchurch, New Zealand. The case study building is assumed to be designed by architects, fire and structural engineers for stability, insulation and integrity in a post-flashover fire. This is on the premise that there are no sprinklers or immediate intervention by the fire service. The life safety concern is mainly on the safety of fire-fighters. Connections are not shown in Figure 8.2 as structural fire analysis of connections is beyond the scope of this research.

For consistency, the four passive fire protection options assessed in Chapters 5, 6 and 7 are considered here as the applied fire protection options to the steel members of the portal framed building. The competing options are *board systems (BST), intumescent coatings or paints (ITC), concrete encasement of steel (CES), sprayed on cement-based material (SCM)* and alternatively the use of *unprotected steel*. The main task is to carry out a structural fire design decision analysis using GAT to achieve suitable stakeholder decision for adequate fire protection of the building’s representative critical element (i.e. column leg) (Figure 8.2).

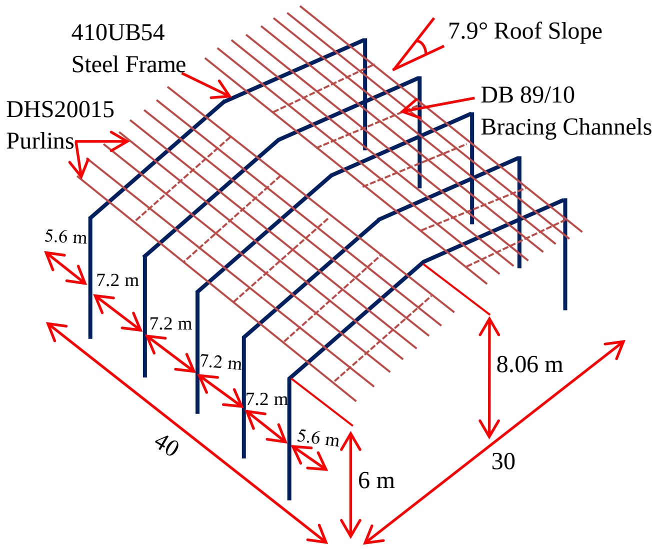


Figure 8.2. Case study steel portal-framed building (Bong, 2005).

8.2.1. Case study decision attributes

For this virtual case study, the Joint risk management and design decision analysis framework proposed earlier (Figure 7.2) is applied here to guide the decision-making process. The goal is *"to select the most suitable fire protection option for structural fire design of a steel portal-framed building for fully developed fires"*. The formulated key decision criteria and sub-criteria were adapted from the ones used in Chapter 5. The key decision criteria are *economy, safety, environmental* and *societal* as shown in Table 5.1.

Given the virtual building (Figure 8.2), the design decision-sub criteria from Table 5.1 were revised to suit for the purpose by removing sub-criteria that may be insignificant to the design. For instance, the sub-criteria, *building use and features* (*BUF*) was not considered as the use of the case study building was defined for industrial purpose. *Human comfort* (*HC*) was considered as trivial given the use of the building and occupants/end-users relaxed feeling may not significantly influence stakeholder decision-making. The sub-criteria *fire spread beyond compartment (FSC)* was revised to *fire spread beyond building (FSB)* to account for fire protection of steel portal frames constructed near adjacent properties and boundaries. The competing fire protections options have been presented earlier in Section 8.2. These options were considered on the premise of either protecting or unprotecting the primary structural members of the steel portal framed building (Figure 8.2).

8.2.2. Structural fire design stakeholder engagement

Prior to the case study stakeholder engagement, a goal rating document (shown in Appendix 4) was developed to assist in eliciting stakeholder views on the decision attributes. The goal rating document consisted of the fundamental reciprocal scale (Table 3.2), the paired judgement question (Section 0) and matrices representing Categories A, B and C paired comparison judgements.

For this virtual case study, the nominated fire design stakeholders (decision-makers) were one of each of these stakeholder categories: *building consent authority (BCA), fire engineer (FE), fire service personnel (FSP)* and *structural engineer (SE).* These stakeholders were chartered professionals actively practicing in the fire industry in New Zealand. The specifics of who is considered a chartered stakeholder in the New Zealand context and the process to attain chartered status has been explained in Section 5.1. Importantly, the participant-stakeholders did not play any roles other than what they do professionally; i.e. they were engaged based on their current/active profession e.g. the fire engineer is an actively practicing Engineering New Zealand chartered professional fire engineer (CPEng) with over 15 years professional experience, etc.

The stakeholders were brought together in one room to participate in the design decision-making process. Ideally, this research would have preferred to engage chartered professionals representing each of the 12-nominated fire design stakeholder categories listed in Chapters 5, 6 and 7. However, this was not possible due to geographical location, different and busy time/work schedules among chartered professionals in the industry. Nevertheless, the number and expertise of the participant-stakeholders were considered adequate to demonstrate the applicability of GAT to the virtual case study building.

The experience and expert judgements from the stakeholders provided suitable qualitative data for the analysis as well as transparency of the process. The multi-disciplinary stakeholders involved entailed that the GMM component of GAT could be used to aggregate judgements considering the weighted stakeholder scenario. In this case, the weighted stakeholder scenario meant the stakeholders were engaged individually, hence their influence level on the design decision-making process were weighted at the GMM stage. On the other hand, the stakeholders acted as a group agreeing to harmonised paired judgements, hence their influence level was considered equally important i.e. unweighted stakeholder scenario.

8.2.2.1 Stakeholder weighting and paired judgements

During the engagement, the participants were asked to pairwise compare the fire design stakeholder categories they represent regarding their influence level on the structural fire design decision-making process for the case study building. This was to support the weighted stakeholder scenario decision analysis. Table 8.1 shows the outcome of weighting the stakeholder paired judgements using '*the mean of normalised row values'* procedure which has been demonstrated earlier in (*AHP*-Step 4).

Table 8.1. Structural fire design stakeholder weights

Fire design stakeholders	BCA	FE	FSP	SE	**Weights**
BCA	1	1/3	1/2	1/3	0.10
FE	3	1	2	1	0.35
FSP	2	1/2	1	1/2	0.20
SE	3	1	2	1	0.35

This method of stakeholders weighting each other to derive their weights has been explained in Section 3.2.1. It ensures that the stakeholders agree on their weights or influences in the process unlike the method employed in Chapter 7 whereby stakeholder weights were derived from the normalisation of stakeholders' professional fees. In Chapter 7, the derived stakeholder weights for BCA, FE, FSP and SE were *0.007, 0.111, 0.007* and *0.183* respectively.

This presented SE as having the highest influence in the general steel-framed building design decision-making process. However, this may not be the case when a specific steel-framed building is considered as shown in Table 8.1. Here, FE and SE have the same and highest weights/influence implying that the chartered stakeholders agree that FE and SE have the same influence level in the structural fire design of a steel portal-framed building. This may be different in a case of a multi-story steel building if a building owner and/or an architect had been involved in the decision-making process. In any case, the stakeholder weighting was expected to reflect influence levels of participant-stakeholders in the design decision-making process as adjudged by them. The ability of stakeholders to weight themselves in the process is considered as a more acceptable method of deriving their influences when they are acting as a group and willing to work together for the common good of achieving a suitable decision (Forman and Peniwati, 1998).

Following the stakeholder weighting, the participants were given a copy of the goal rating document and asked to pairwise compare the design decision attributes according to the intensity of their feelings. Table 8.2 shows the individual judgements of the participant-stakeholders on Category B paired comparison for the societal sub-criteria. The judgement matrices for the safety, environmental and economic criteria are shown in Appendix 5.

Table 8.2. Judgement matrices on societal sub-criteria from participant-stakeholders

Building consent authority (BCA)	BA	BRA	HS	PF2
BA	1	1/8	1/8	1/8
BRA	8	1	1	1
HS	8	1	1	1
PF2	8	1	1	1

Fire engineer (FE)	BA	BRA	HS	PF2
BA	1	1/9	1/9	1
BRA	9	1	1	9
HS	9	1	1	9
PF2	1	1/9	1/9	1

Fire service personnel (FSP)	BA	BRA	HS	PF2
BA	1	1/3	1/4	1/5
BRA	3	1	1/2	1/3
HS	4	2	1	1/2
PF2	5	3	2	1

Structural engineer (SE)	BA	BRA	HS	PF2
BA	1	1/7	1/7	1
BRA	7	1	1	7
HS	7	1	1	7
PF2	1	1/7	1/7	1

The judgement matrix set-up and procedure for pairwise comparison judgement has been explained in AHP-Step 2 and Step 3. From the individual paired judgements in Table 8.2, it can be inferred that the stakeholders have varying views on the sub-decision criteria with respect to societal criteria and the decision goal except *building aesthetics (BA)*. For instance, BCA, FE and SE rated *building aesthetics (BA)* as vastly inferior to *building regulation approval (BRA)* and *health and safety (HS)* with 8, 9 and 7 respectively. Here FSP has a different judgement with 3 and 4 ratings for *BRA* and *HS* respectively. The majority judgement on *BA* may be attributed to the type of building and its proposed use. In this case, the stakeholders consider aesthetics as less important in the structural fire design decision-making of a steel portal-framed building. Other individual judgements shown in Table 8.2 indicate the divergent views of fire design stakeholders given a specific or realistic steel building. Notably, other categories of individual judgement matrices not shown here followed the same pattern of varying stakeholder views which require analysis. The successful collation of paired stakeholder judgements and their weights from the engagement process completed the implementation of step 1 of the GAT method as guided by the framework (Figure 7.2).

8.2.3. Qualitative analysis

8.2.3.1. Aggregation and prioritisation of design decision attributes

The qualitative analysis employed herein entails the aggregation and prioritisation of all categories of paired judgements using GMM and AHP components of GAT. For this case study, GMM (Equation 3.11) was applied to aggregate the stakeholder individual paired judgements to obtain group judgement matrices. In this case, the stakeholder weights in Table 8.1 were used to represent individual stakeholder influences in applying Equation 3.11. Hence, the aggregated matrices were achieved by raising each matrix to the power of their associated stakeholder weight (α_p) and calculated their product. Table 8.3 (a) shows the aggregated judgement matrix from the stakeholder individual judgements in Table 8.2, making Table 8.3 (a) a group or consensus judgement of the four participant-stakeholders on qualitative societal design decision considerations for the steel portal-framed building.

The AHP-prioritisation procedure (*AHP-Step 4*) was then applied to derive the initial weights of all considered decision attributes in the process. Table 8.3 (a) also shows the initial weights of the societal sub-criteria, and health and safety (HS) has the highest weight, 0.43. This means that HS is the most crucial design decision criteria to the stakeholders with respect to societal consideration for the structural fire protection of the portal framed building. In keeping with the GAT process (Figure 7.1), consistency checks (Section 5.2.3.2) were carried out for all aggregated/group judgment matrices, and they were within the 0.10

limit such that the consistency ratio for the group judgement in Table 8.3 (a) was found to be 0.0012.

Table 8.3 (b) shows the group judgement matrix from the aggregation of stakeholder individual judgements on the key decision criteria of this case study. Given that AHP-prioritisation evaluates decision criteria hierarchically as explained in Chapter 4, the sub-criteria initial weights were normalised by multiplying them by their parent key criteria. The normalised weights were then used in the synthesis stage of the GAT process. Table 8.3 (c) shows the normalised weights of the societal sub-criteria group judgement matrix of Table 8.3 (a).

Table 8.3. Group judgement matrices and weights

(a)	BA	BRA	HS	PF2	Initial weights
BA	1.00	0.15	0.14	0.58	0.06
BRA	6.55	1.00	0.87	3.39	0.40
HS	6.93	1.15	1.00	3.67	0.43
PF2	1.72	0.30	0.27	1.00	0.11

(b)	Economy	Environmental	Safety	Societal	Weights
Economy	1.00	2.01	0.59	0.10	0.24
Environmental	0.50	1.00	0.27	0.55	0.12
Safety	1.68	3.72	1.00	2.16	0.43
Societal	0.91	1.83	0.46	1.00	0.21

(c)	BA	BRA	HS	PF2	Initial weights	Normalised weights
BA	1.00	0.15	0.14	0.58	0.06	0.01
BRA	6.55	1.00	0.87	3.39	0.40	0.08
HS	6.93	1.15	1.00	3.67	0.43	0.09
PF2	1.72	0.30	0.27	1.00	0.11	0.03

In this case, the initial weights were multiplied by the weight of societal criteria, i.e. 0.21 in Table 8.3 (b). Note that the normalised weights in Table 8.3 (c) add up to 0.21 which is the weight of societal criterion in Table 8.3 (b); the weights in Table 8.3 (b) add up to unity which represents the hierarchical prioritisation order of the AHP as described in Section 3.1.1.1.

The AHP-prioritisation component of GAT was also implemented to derive the priority scores of the sub-decision criteria for each competing option with respect to the design decision goal (i.e. from Category C paired judgements). Table 8.4 shows the group judgement matrix and priority scores of health and safety (HS) for each fire protection option considered in this case study.

Table 8.4. Group judgement matrix and qualitative priority scores of HS for synthesis

Health and Safety (HS)	BST	CES	ITC	SCM	UPS	Priority scores
BST	1.00	1.07	0.99	1.75	0.40	0.173
CES	0.94	1.00	0.93	1.64	0.39	0.163
ITC	1.01	1.07	1.00	1.76	0.46	0.176
SCM	0.57	0.61	0.57	1.00	0.30	0.101
UPS	2.52	2.57	2.15	3.38	1.00	0.387

The priority scores in Table 8.4 also show that the participant-stakeholders judged unprotected steel (UPS) as having the highest priority when considering the influence of health and safety (HS) with respect to the design decision goal. This can be attributed to the stakeholders' perceived opportunity of using UPS in meeting the design requirement without applying any passive fire protection material to the steel structures. This also implies that potential installation and whole-of-life safety risks are reduced as defined for HS in Table 5.1.

Notably, these priority scores are qualitative and first entries into the decision matrix during the synthesis stage of the GAT process. The completion of the GMM-aggregation and AHP-prioritisation concluded the implementation of GMM+AHP phases of the GAT process.

8.2.4. Quantitative analysis

The quantitative analysis in this case study was achieved through a parametric study as shown in the framework (Figure 7.2). This included deterministic and probabilistic structural fire analysis as well as a cost analysis to critically assess the competing fire protection options for management of design uncertainties in the process. The outcomes of the parametric study were integrated as priority scores of failure probabilities at 60 min of exposure to standard fire and fire protection option cost criteria into the GAT process. As earlier mentioned, this integration is feasible given that GAT has the capability of transforming multidimensional elements toward complete synthesis and ranking of options. The following sub-sections detail how these were achieved.

8.2.4.1.Deterministic and probabilistic structural fire analysis

The collapse of steel portal framed buildings in most cases occurs when a part or the global structure is engulfed in fully developed fires. This type of building is also subject to collapse due to rapid heating of parts of the structure against colder parts of the building; the collapse of unprotected steel portal frames is mainly actuated by buckling. On this basis and following Equation 7.1, structural failure was defined in this case study as the loss of load carrying capacity of one of the columns. For this reason, a single element analysis was considered to investigate the loss of stability of one of the columns. For the general structural fire design decision-making case described in Chapter 7, the investigation was on a simply supported steel beam. The competing fire protection options in this virtual case study are investigated with reference to the effects of the applied fire protection on the resistance of a steel column.

In addition, following the New Zealand design requirement for portal-framed buildings explained in Section 8.2, the structural fire analysis of the critical element (column leg) was considered. On another hand, this study considered the experience and design assumptions of the participant-stakeholders in New Zealand given that their paired judgements were incorporated in the structural fire design decision-making process. Importantly, an analysis of this nature also allows for consistency between Chapters 7 and 8 for easy comparison.

The column section of the portal frame was chosen as 410UB54, as shown in Figure 8.2. The column length (L) is 6 m and considered as fixed at both ends, hence the buckling length in fire (L_{fi}) was taken as $0.7L$, following New Zealand Steel Structures Standard (NZS3404: Part 1:1997). The steel column section's yield strength, f_y is 320 N/mm^2. The column was analysed to the standard fire according to Eurocode 3 Part 1.2 (BSI, 2005a) with a desired fire resistance rating (FRR) of 60 min. Recent research has shown that the structural collapse of an unprotected steel portal frame spanning 36 m may occur at 39 min based on standard fire exposure (Lou *et al*. 2017).

Firstly, the temperature development in the column section was found. The target of the thermal analysis was to limit the column's temperature to a design temperature of 550°C

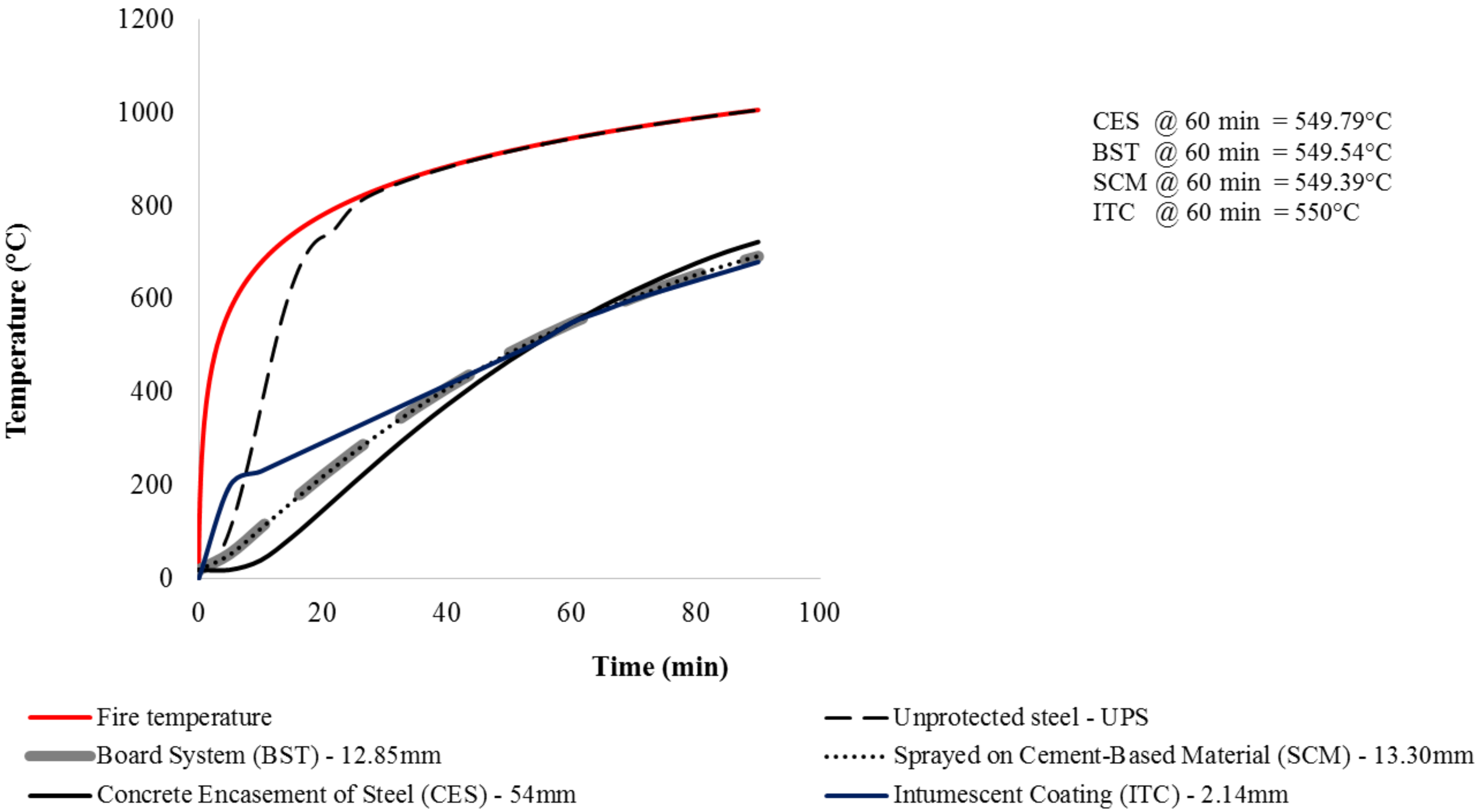
(ASFP, 2014) at 60 min by applying sufficient thicknesses of each of the competing fire protection options. Therefore, the thermal properties (Table 7.1) of the unprotected steel column and the four passive fire protection options were considered as input parameters in the Eurocode 'lumped mass' method (Buchanan and Abu, 2017) to carry-out thermal analysis. The thermal analysis calculation was carried out in a spreadsheet and the resulting steel column temperatures are shown in Figure 8.3. The column temperatures determined its mechanical response in fire by calculation in the strength domain.

The Eurocode calculation in the strength domain is considered here given that the New Zealand design standard is based on empirical equations derived from standard fire tests, which only account for the reduction in yield stress but not the elastic modulus. Hence the current New Zealand method does not appropriately account for buckling effects due to loss of stiffness and strength in fire as mentioned in Section 2.2.1.2.

In this study, the steel column was considered as axially loaded, which buckled at elevated temperature. Hence, the target was to ensure that the axial load on the column ($N_{fi,D}$) was less than the buckling resistance ($N_{b,fi,t,RD}$) throughout the exposure to the standard fire. To achieve this, $N_{fi,D}$ was calculated as 245 kN from the permanent and variable actions on the column, as shown in Appendix 4. Then the steel temperatures from the application of the competing fire protection materials were used to determine the reduction factors for yield strength and elastic modulus of the steel column, which in turn helped to determine the buckling resistance of the column throughout the fire, following Eurocode 3 Part 1.2. Figure 8.4 shows the buckling resistance of the steel column (fixed at both ends) in standard fire when protected by each of the fire protection options.

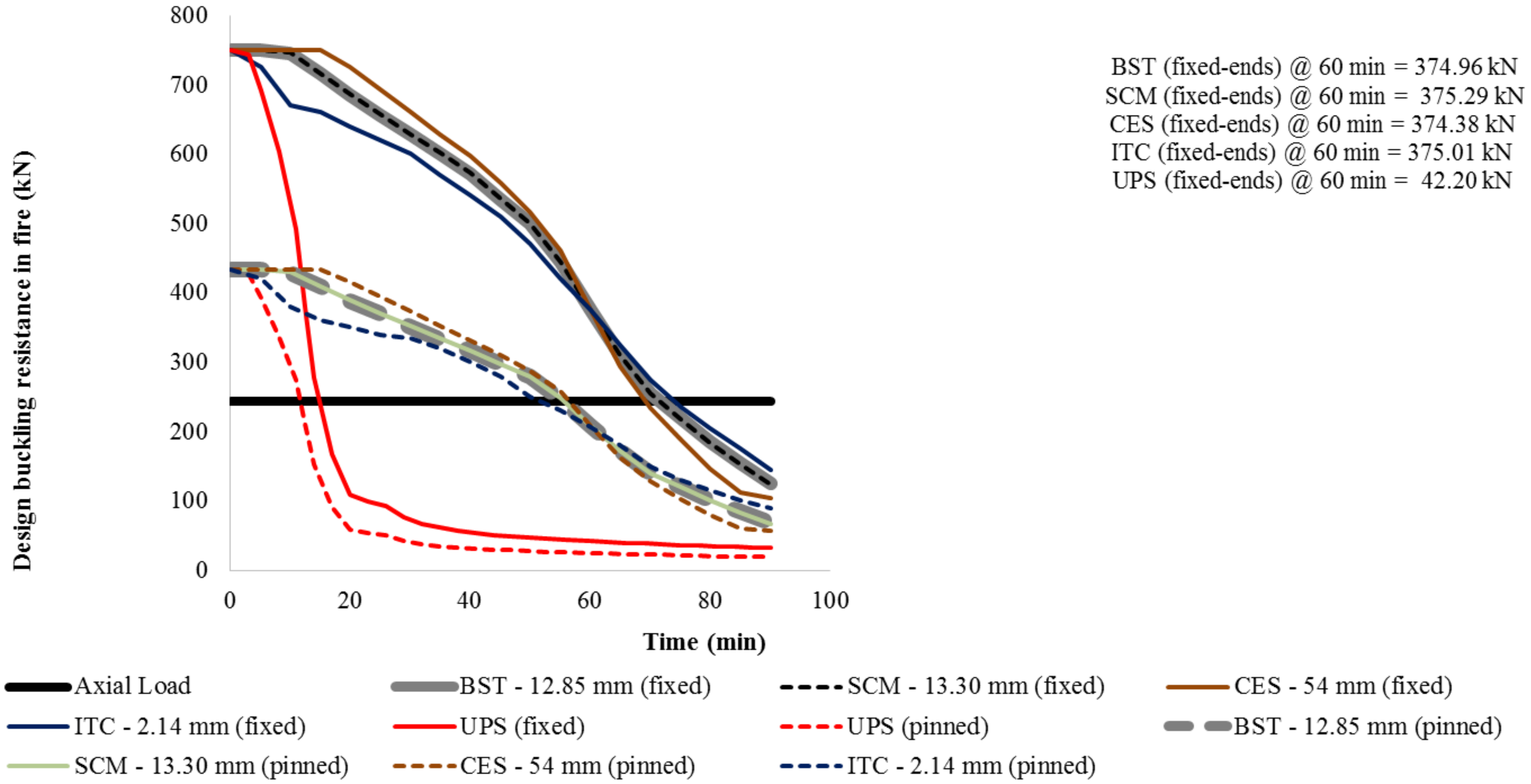
As expected, the unprotected steel column failed at 16 min. A larger steel section, 533×312×182UB was then selected to replace the failed unprotected member. The deterministic structural analysis process was reapplied for the new section. At 60 min exposure to the standard fire, the design buckling resistance was calculated as 252.49 kN which is greater than 245 kN (axial load).

In this deterministic structural fire analysis, the column member's level of resistance was further investigated considering pinned-end conditions. In this case, the column's buckling length in fire (L_{fi}) was taken as unity (i.e. 1.0 L). Figure 8.4 also shows the buckling resistance of the column member when protected and unprotected considering pinned-end conditions.



CES @ 60 min = 549.79°C
BST @ 60 min = 549.54°C
SCM @ 60 min = 549.39°C
ITC @ 60 min = 550°C

Figure 8.3. Thermal response of column member protected by materials of varying thicknesses.



BST (fixed-ends) @ 60 min = 374.96 kN
SCM (fixed-ends) @ 60 min = 375.29 kN
CES (fixed-ends) @ 60 min = 374.38 kN
ITC (fixed-ends) @ 60 min = 375.01 kN
UPS (fixed-ends) @ 60 min = 42.20 kN

Figure 8.4. Steel column buckling resistance in fire vs time

In comparison to the steel column's buckling resistances given fixed-end conditions, the pinned-ends analysis scenario indicates that the column buckles in fire condition regardless of being protected or unprotected. The larger steel section (533×312×182UB) was selected and analysed as well, but it also failed to meet the fire limit state design criteria (i.e. $N_{b,fi,t,RD}$ = 194.63 kN < 245 kN). Therefore, the numerical outcomes from the pinned-ends scenario were not considered for further analysis in this virtual case study.

The probabilistic structural fire analysis followed the same procedure as in Chapter 7. In this case, the column member having met the fire limit state criteria given fixed-end conditions is considered for probabilistic analysis. The essence was to evaluate inherent design parameter/property uncertainties as part of the critical assessment of the competing fire protection options. A summary of potential uncertainties in structural fire design is presented in Table 2.2. The uncertain input parameters in the deterministic analysis were firstly defined as probabilistic distributions. Latin hypercube sampling and Monte Carlo simulation was then carried out using @Risk software (Palisade, 2012). The statistical behaviour of the considered uncertain input parameters was extracted from the literature as explained in Section 7.3.3 and presented in Table 7.2. The mean or most likely values in Table 7.2 are also used here. Notably, the effective length of the column, the axial load on the column, the column's cross-sectional area and radius of gyration were assumed as lognormal, gamma, normal and triangular distributions respectively. The design buckling resistance of each fire protection material applied to the portal frame's column member was defined as risk outputs based on Equations 7.1 and 7.2. Monte Carlo simulations of 10,000 iterations were then carried out to predict the probability of failure (P_f) at 60 min of exposure to the standard fire for each defined output.

At the end of the simulation, P_f was extracted from the cumulative frequency distribution of the resistance safety margin using Equation 7.3. The failure probabilities of the portal frame column member fire-protected with the competing options are shown in Table 8.5.The values in Table 8.5 were taken as the quantitative fire protection failure probability (FPFP) criteria scores for the synthesis phase of this study as shown in the framework (Figure 7.2).

The deterministic and probabilistic structural fire analysis were realised in a spreadsheet albeit the deterministic manual calculations are also shown in Appendix 4. The Eurocode calculation method for structural fire analysis of a compression (column) member was written in an MS-Excel spreadsheet and @Risk software used as an add-on macro to evaluate parameter and design uncertainties (Table 2.2) through probabilistic functions.

Table 8.5. Case study structural failure probabilities in standard fire condition

Fire protection option	Probability of failure, P_f
Board system (BST)	0.054
Concrete encasement of steel (CES)	0.031
Intumescent coating (ITC)	0.119
Sprayed on cement-based material (SCM)	0.053
Unprotected steel (UPS)	0.168

8.2.4.2.Fire protection options' cost analysis

The fire protection costs presented in Table 7.5 were used here. However, the cost difference between the original column section and the larger steel was recalculated. As explained in Section 7.3.1, the fire protection materials' unit costs (i.e. probabilistic unit costs in this case study) were multiplied by the steel column section length and depth to achieve their actual costs. In the case of unprotected steel, the difference between the self-weight of the initial steel column section (410UB54) and the replacement (533×315×182UB) was determined as 199.40 kg/m. This was then multiplied by the column depth, 0.92 m and probabilistic unit cost in Table 7.5.

The achieved actual costs were then taken as the quantitative fire protection options costs (FPOC) criteria scores for the synthesis phase of this study as shown in the framework (Figure 7.2).

8.2.5. Integration, synthesis and ranking

Following the framework (Figure 7.2), the GAT process as applied in Chapter 7 entails that the priority scores achieved in the design decision analysis are synthesised and ranked toward suitable decision-making. In this case study, the aim was to achieve an optimised structural fire design decision, which would also involve the integration of the qualitative and quantitative priority scores for synthesis. The synthesis followed the TOPSIS-approach (*Step 1* - *Step 5*) which is a component of the GAT process shown in Figure 7.1.

The design decision matrix was constructed to include the qualitative benefits-costs priority scores from Section 8.2.3, the quantitative FPFP and FPOC priority scores from Section 8.2.4 as shown in Table 8.6. The competing fire protection options were placed in the first left column, while the qualitative and quantitative design decision elements were placed on the top row of the matrix. Equation 3.6 was used to normalise the design decision matrix to manage multi-dimensionality and allow for assessment of the competing options across all elements. This case study used the derived weights of decision elements shown in Table 8.7 to weight the normalised decision matrix based on Equation 3.7. The derived weights were achieved from AHP-weighting of 'Category A and B' aggregated paired judgements as earlier explained in Chapter 7. Importantly, the fire protection option weights in Table 8.7 were derived from the 'Category A' AHP-weighting of aggregated judgements of 50 fire design stakeholders engaged in the entire research. These obtained option weights were from a general case of structural fire design decision analysis on the same competing options investigated herein. This was considered useful in weighting the normalised priority scores of FPOC and FPFP to manage stakeholder bias or skewed preference on a particular option in this virtual case study. The normalised and weighted case study design decision matrices are shown in Appendix 5.

The next phase of the process was to extract the ideal and negative ideal solutions as explained in (TOPSIS-*Step 5* and Section 7.3.3). Here the maximum and minimum values in each column of the weighted matrix were extracted as the hypothesised ideal and negative ideal solutions respectively. For FPOC and FPFP, their minimum values were considered better (i.e. ideal solution), and the maximum values were considered worse (i.e. negative ideal solution) as shown in Appendix 5.

Then Equations 3.8 and 3.9 were applied to evaluate the separation of the elements in the weighted matrix from the ideal and negative ideal solution. This is also shown in Appendix 5. To complete the process, Equation 3.10 was used to calculate the closeness of the associated competing options' preference scores to the ideal solution, i.e. nearness to unity. This automatically ranks the fire protection options for decision-making as shown in Figure 8.5 under the legend, *weighted stakeholder scenario (portal frame building).* As mentioned earlier, the weighted stakeholder scenario of this case study implies that the stakeholders were individually engaged in one room and weighted. This is to observe how the fire protection options' ranking order may change when a specific building is considered as well as to account for stakeholder influence levels in the aggregation of their judgements.

The fire protection options' ranking order under the case study weighted stakeholder scenario (Figure 8.5) is as follows*: unprotected steel (UPS), board systems (BST), intumescent coatings (ITC), sprayed on cement-based material (SCM), concrete encasement of steel (CES)*. Hence, from the GAT-synthesis and ranking outcome, unprotected steel with the score, 0.797 has the highest relative closeness to unity. This may be taken as the ideal or best fire protection option for the steel portal framed-building (Figure 8.2) based on the weighted stakeholder scenario.

During the case study stakeholder engagement, averages of stakeholder paired judgements on the structural fire design decision attributes for the steel portal framed building was calculated. The participant-stakeholders were then encouraged to discuss averaged judgement matrices to agree as consensus group judgements for each category of pairwise comparison matrices. In this case, the stakeholders were considered as acting as a group and equally important in terms of their influence or weights to carry-out the structural fire design decision analysis. The GAT process was then reapplied in conjunction with the design decision analysis framework (Figure 7.2). The qualitative and quantitative priority scores were integrated into the decision matrix shown in Table 8.8 (a) and weighted with the decision elements' derived weights shown in Table 8.8 (b).

It is noteworthy that, the quantitative scores from the deterministic and probabilistic analyses were used as initially achieved; however, the qualitative benefits-costs priority scores were different given the unweighted stakeholder scenario being investigated. This is because the qualitative scores stem from stakeholder expert judgements, while the quantitative scores are outcomes from a probabilistic structural fire and cost analyses. Having completed the GAT-synthesis, the competing fire protection options were re-ranked as also shown in Figure 8.5. The ranking order in the *unweighted stakeholder scenario (portal frame building)* is as follows: *unprotected steel (UPS), sprayed on cement-based material (SCM), intumescent coatings (ITC), board systems (BST), concrete encasement of steel (CES)*.

Here the ranking order is altered compared to the weighted scenario previously analysed albeit UPS retains its place as the top-ranked option for the fire protection of the case study building.

Table 8.6. Case study design decision matrix (*Weighted stakeholder scenario*).

	CA	BC	MMU	ES	EAC	SFR	PF1	FFO	FSB	MA	BA	BRA	HS	PF2	FPOC	FPFP
BST	0.283	0.207	0.075	0.128	0.246	0.200	0.262	0.228	0.290	0.188	0.251	0.200	0.173	0.196	$ 1,130.35	0.054
CES	0.073	0.207	0.069	0.135	0.253	0.200	0.319	0.250	0.300	0.220	0.166	0.200	0.163	0.170	$ 8,208.89	0.031
ITC	0.190	0.307	0.260	0.156	0.100	0.200	0.154	0.179	0.148	0.225	0.192	0.200	0.176	0.350	$ 1,021.61	0.119
SCM	0.086	0.176	0.182	0.128	0.170	0.200	0.085	0.172	0.136	0.126	0.072	0.200	0.101	0.191	$ 107.84	0.053
UPS	0.368	0.104	0.414	0.453	0.231	0.200	0.181	0.172	0.125	0.242	0.319	0.200	0.387	0.093	$ 589.00	0.168

Table 8.7. Weights of case study design decision elements

Costs-sub criteria			**Benefits-sub criteria**										**Fire protection options**				
CA	BC	MMU	ES	EAC	SFR	PF1	FFO	FSB	MA	BA	BRA	HS	PF2	BST	CES	ITC	SCM	UPS
0.564	0.112	0.324	0.037	0.115	0.094	0.106	0.113	0.116	0.145	0.017	0.109	0.118	0.030	0.228	0.244	0.233	0.149	0.146

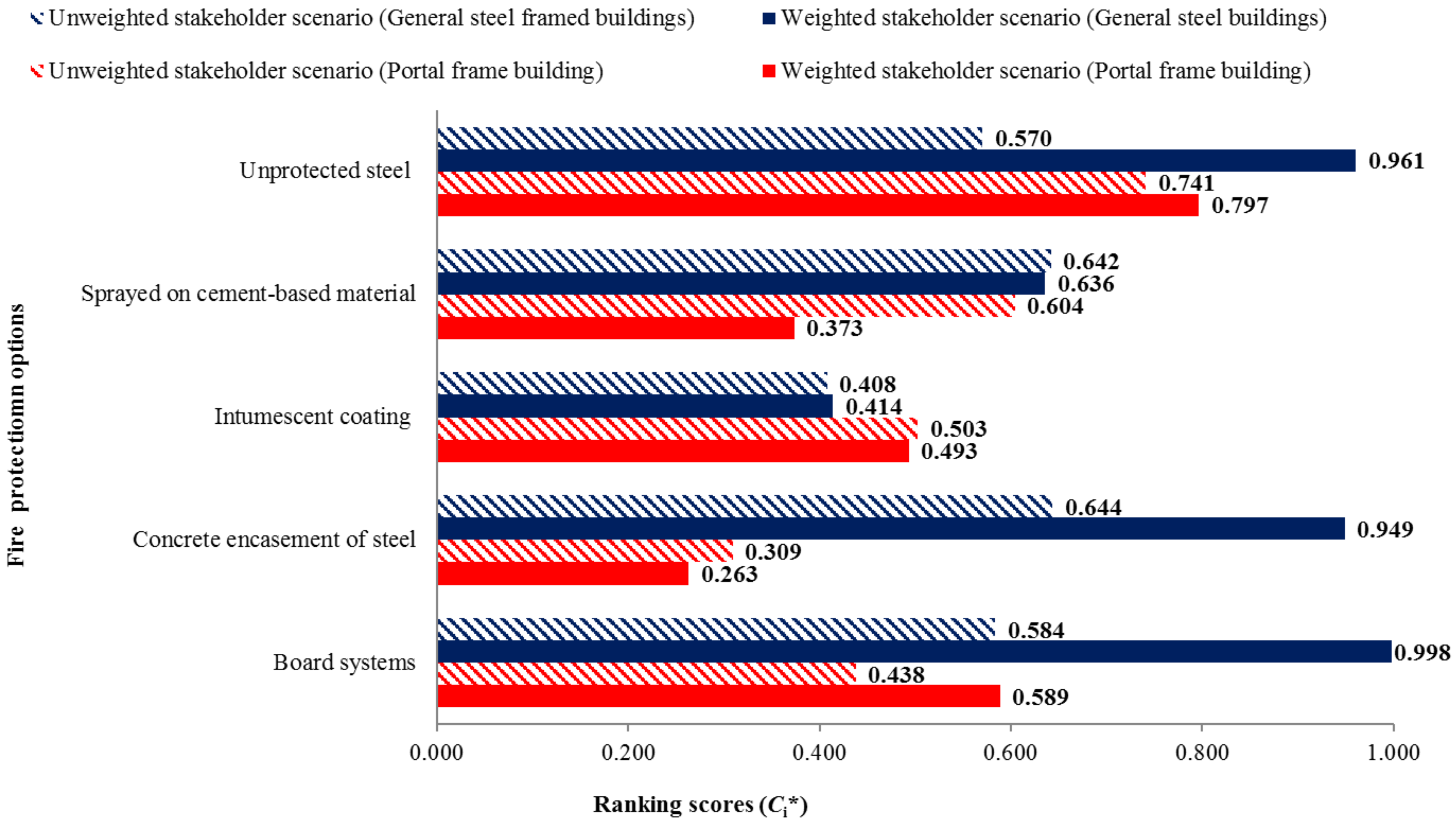


Figure 8.5. Ranks of competing fire protection options from different design decision scenarios.

Table 8.8. Stakeholder unweighted scenario – (a) design decision matrix and (b) weights of decision elements

(a)

	CA	BC	MMU	ES	EAC	SFR	PF1	FFO	FSB	MA	BA	BRA	HS	PF2	FPOC	FPFP
BST	0.124	0.188	0.096	0.096	0.167	0.200	0.231	0.320	0.323	0.052	0.149	0.200	0.143	0.163	$ 1,130.35	0.054
CES	0.048	0.341	0.037	0.189	0.167	0.200	0.425	0.413	0.430	0.052	0.213	0.200	0.252	0.427	$ 8,208.89	0.031
ITC	0.244	0.188	0.204	0.096	0.167	0.200	0.151	0.113	0.082	0.265	0.213	0.200	0.143	0.163	$ 1,021.61	0.119
SCM	0.292	0.188	0.204	0.096	0.167	0.200	0.041	0.113	0.082	0.194	0.034	0.200	0.077	0.163	$ 107.84	0.053
UPS	0.292	0.097	0.458	0.522	0.333	0.200	0.151	0.041	0.082	0.438	0.391	0.200	0.385	0.084	$ 589.00	0.168

(b)

Costs-sub criteria			**Benefits-sub criteria**										**Fire protection options**				
CA	BC	MMU	ES	EAC	SFR	PF1	FFO	FSB	MA	BA	BRA	HS	PF2	BST	CES	ITC	SCM	UPS
0.657	0.090	0.254	0.021	0.083	0.203	0.058	0.114	0.114	0.114	0.014	0.115	0.115	0.049	0.228	0.244	0.233	0.149	0.146

8.3. Discussion

The rank alterations in Figure 8.5 which show the second-ranked option, BST is ranked fourth; and the fourth-ranked option, SCM is ranked second in the case study weighted, and unweighted stakeholder scenario respectively are because of engaging the stakeholders individually and as a group. It also shows the effect of accounting for stakeholder influence levels in the decision-making process. The top-ranked option, UPS retained its place in both scenarios and can be attributed to its competitiveness across the board irrespective of having the highest probability of failure and relatively less expensive as shown in Table 8.6 and Table 8.8.

In the weighted stakeholder scenario (portal frame building), the design decision matrix showed that UPS had the highest priority scores under *CA, MMU, ES, MA, BA, and HS*, which are 6 out of 14 design decision criteria considered. Also, UPS had the highest priority scores under the same criteria including *EAC* in Table 8.8 (a) for the unweighted stakeholder scenario of this case study. Hence, it can be inferred that the best fire protection option for the case study steel portal framed-building is *unprotected steel (UPS)*. UPS may have been prioritised more than other options by adjudging unprotected system designs of steel-framed buildings as having a capacity of possible redistribution of forces and adequate fire resistance. However, it would be of interest to know the outcome of implementing this process in a system design scenario of a multi-storey steel building.

The ranking order in both scenarios reflects the consensus of structural fire design experts in the fire and building industry in New Zealand. For instance, the third-ranked option in the weighted and unweighted case study scenarios (i.e. ITC) may be attributed to its currently gained popularity in New Zealand. However, it will also be interesting to know the rank of SCM considering a weighted stakeholder scenario in jurisdictions where it is dominantly used as applied fire protection on steel structures, e.g. the USA and UK.

In comparing the results achieved herein to the outcomes of applying GAT in a general case of structural fire design decision analysis (Chapter 7), it can be observed that the top-ranked option and ranking orders are different from the ones achieved in this case study. Figure 8.5 shows, BST as the top-ranked option in both *weighted and unweighted stakeholder scenarios (general steel-framed buildings)* as well as the second-ranked option in the *weighted stakeholder scenario (portal frame building)*. This can be attributed to the popularity of BST and its ready availability for use in New Zealand.

For the case study portal-framed building, UPS is analysed as the best option. This also supports the assertion in Chapter 7 that applying GAT for a specific building's design decision analysis will reflect the stakeholder/s influence and judgements on the considered decision attributes. Importantly, the adaptability of GAT in varying cases to assist fire design stakeholders in approaching balanced design decision-making has been demonstrated.

It is noteworthy that, when the stakeholders were engaged as a group (*i.e. after they had been engaged individually and their initial judgements documented*), a short debate ensued among them. This was mainly due to the portal frame building's potential use/functionality for industrial purpose. The debate gave a quick glimpse of their different goals, preferences, interests and views. The fire engineer merely looking at the portal frame building preferred encasing the steel columns in concrete on the premise that it is the safest. The structural engineer countered with an opinion of unprotecting the building because if the building is well designed there can be redistribution of forces at the fire limit state for structural adequacy and that the worst-case scenario would be that the building burns down having an inward failure mechanism which is considered safe. The structural engineer's view was from the economic and safety perspective. The building consent official opined on mainly meeting the requirements of the building code.

Importantly, the stakeholder debate on protecting or unprotecting the portal-framed building against fires was not different from the general case design decision-making problem discussed in Sections 2.3.1 and 5.2.2.1. Nonetheless, the divergent stakeholder views are based on the conflictual safety, environment and socio-economic factors as well as the need to meet structural fire performance objectives. This might give way to uncertainties and design risks, e.g. structural fire redesign or design changes at different stages of building construction, which may increase costs, cause delays and time overruns. There is, therefore, the need for an integrated design decision analysis to resolve the potential conflicts in stakeholder views and mitigate the accompanying risks, which GAT and its associated implementation framework are developed to address.

8.4. Conclusion

A steel portal framed-building was considered for this research case study because of its effective worldwide use as industrial buildings, warehouses and the need to seamlessly demonstrate the application of the hybrid-MCDA technique, GAT, for broader understanding. However, the test of the GAT process on a multi-storey or other steel framed buildings is useful for future work, given that the results achieved in this Chapter were greatly influenced by the building type and its use.

The joint risk and decision-making framework (Figure 7.2) used in this study are considered useful in guiding the practical use of GAT through stakeholder engagement, qualitative and quantitative analyses, synthesis and ranking. The different phases of the framework are related to different phases of the risk management process presented in the international risk management standard (AS/NZS 31000:2009). This serves as a general and transparent background of GAT development and implementation.

The fire design stakeholders engaged in the virtual case study are considered sufficient to demonstrate the GAT process. However, the participation and expert opinions from other traditional fire design stakeholders such as *architects; building owners* and *contractors* may change the results achieved in this case study. Importantly, the top-ranked fire protection option, UPS had the closest preference score to unity and was considerably competitive across the aggregated and prioritised judgements of the participant-stakeholders.

The essence of the quantitative analysis is to serve as a critical assessment of the competing options toward mitigating design risks and uncertainties and not relying on only expert judgements in design decision-making scenarios. The consideration of a representative column member of the steel portal frame in the quantitative structural fire analysis is to ensure that the general GAT process is not obscured in some complex structural system analysis. Notably, the consideration of the steel portal frame as a structural assembly through plastic or elastic analysis as well as verification of its structural members under bending and axial compression can produce failure probabilities that may affect the final ranking of the options. Nonetheless, the capability of GAT is explored through the integration of quantitative analysis outcomes by normalising multi-dimensional design decision elements to approach a cost-effective and balanced decision.

Therefore, there is a potential of applying GAT in structural fire design decision analysis for fire protection systems. In such scenario, the framework used here can be applied to extract qualitative stakeholder judgements and integrate with failure and costs probabilities from advanced computer-based structural fire analysis of the competing fire protection systems. The application of GAT, in this virtual case, will reflect the influence and judgements of the stakeholders involved in the process, and priority levels of the conflictual design decision criteria on the competing options (systems).

There is also a potential of integrating qualitative priority scores stemming from paired stakeholder judgements of interdependent design decision attributes and quantitative scores in the GAT process. This would mean that the Analytic Network Process (ANP) studied in Chapter 6 replaces the AHP component of GAT to account for possible influences/interdependences among conflictual design decision criteria. This can also be explored in future studies, thereby enhancing the viability of GAT as a hybrid decision analysis technique for complex design decision-making in a structural fire design environment.

9. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Interdisciplinary collaboration in the design of buildings will typically entail the coming together of knowledgeable stakeholders from multiple disciplines committed to achieving a sufficiently safe, useable building through different approaches. This is exemplified in the performance-based structural fire design of buildings where the collaborating design stakeholders flexibly apply engineered solutions to meet design objectives. However, conflicting goals, available time and methods to achieve suitable consensus and balanced decisions among stakeholders impede such collaboration. Pertinently, the endpoint of establishing a common ground among stakeholders is ‘decision-making’, and the ‘analysis’ of the stakeholder conflicting goals plays a central role in such decision-making.

Given the research problem and objectives in Chapter 1, this work has studied and applied various decision-making techniques to balance fire design stakeholder goals through a pilot study, general cases and a specific design case study. This Chapter summarises the findings of the research and presents its conclusions and recommendations. The limitations encountered during this work and areas for future work are also highlighted.

9.1. Research Summary and Conclusions

As earlier mentioned in Section 1.1, given conflicting factors (e.g. safety, environmental, socio-economic, among others), human beings usually make judgments based on their knowledge, experience or outcomes of costs-benefits/risk analysis. The case of stakeholder decision-making in structural fire design is not different especially as they are from multiple disciplines, diverse backgrounds and are operating in a flexible design environment. This has been demonstrated and proven through the different stakeholder paired judgement matrices even among individuals of the same fire design stakeholder category as shown in Chapters 4 to 8. Hence, the adaptive use of multi-criteria decision analysis (MCDA) in deriving fire design stakeholders’ weights, integrating qualitative and quantitative analysis outcomes toward achieving cost-effective structural fire designs helps to harmonise decisions.

9.1.1. Balancing fire design stakeholder goals using AHP

The Analytic Hierarchy Process (AHP) adjudged as the most widely used MCDA technique in the literature, has been sufficiently tested in a pilot study, group decision-making and hybridised application via GAT. This research confirms that AHP supports structured stakeholder engagement through its 'fundamental paired judgement question' for top-down hierarchically modelled decision problems and reciprocal judgement scale. The AHP-weighting procedure explained in Chapter 3 is very useful in prioritising conflictual design decision attributes and checking the consistency of fire design stakeholder judgements. The priority scores from AHP application can aid stakeholders to understand the importance levels of design decision criteria earlier in the decision-making process as illustrated in Chapter 5. AHP-prioritisation is valuable in ascertaining how stakeholder priorities may differ owning to varying jurisdictional environments as illustrated in Figure 5.3. The criteria weights or priority scores obtained through AHP can support simple cluster analysis to understand synergies among stakeholders of same categories but of different responsibility hierarchy as illustrated in Figure 5.4. Succinctly, the AHP-prioritisation proves a valuable and adaptable aspect of the technique. The syntheses aspects of AHP are also considered useful mainly for qualitative design decision-making scenarios given independent decision criteria. The application of the entire AHP procedure in balancing stakeholder goals for a general case of protecting steel structures in fire (Chapter 5) produced a ranking order of having concrete encasement (CES) as top-ranked. This may not be in tune with the consensus of steel structural fire design and can be attributed to unequal participant-stakeholders for each category, non-consideration of dependencies among decision attributes, inherent parameter and design uncertainties.

9.1.2. Balancing fire design stakeholder goals using ANP

The Analytic Network Process (ANP) is a more logical and a generalisation of the AHP. Given the successful application of ANP to the research problem in Chapter 6, it can be inferred that AHP is a sub-set of ANP. The ANP goes beyond the hierarchical modelling of independent decision attributes to consider dependent/interdependent decision attributes of a given decision problem. Notably, ANP uses the AHP-pairwise comparison judgment and reciprocal scale with a modification of the AHP-fundamental question reflecting the consideration of 'influence' among the decision attributes. ANP also employs the same criteria weighting or prioritisation procedure to generate priority scores for synthesis and ranking. This implies that given a structural fire design decision problem, conflictual design decision elements can be modelled as networks under hierarchies of decision components and control criteria. The design decision problem can be analysed within *benefits, opportunities, costs and risks* perspectives or merits, which is one of the major advantages of using ANP. However, ANP is a complex MCDA technique especially when dealing with large interdependent decision attributes and may require advanced computer software. In structural fire design decision-making process, the challenge will be to identify and determine suitable dependencies/interdependencies/interactions between decision elements as well as competing design options. The interactions among design decision attributes used in Chapter 6 were painstakingly formulated from a general perspective, which may be different and far-reaching in the fire design of a specific steel building. This may exclusively need the involvement of chartered and highly experienced fire design stakeholders. Also, ANP-synthesis accommodates qualitative decision attributes, but may not be favourably suitable for integrating quantitative structural fire analysis outcomes to balance stakeholder goals fully. This is due to the multi-dimensional nature of deterministic and probabilistic structural fire analysis outcomes which will require transformation to non-dimensional values to complete the assessment of the competing design options. As it stands, the ANP is most suitable for only qualitative design decision analysis in balancing fire design stakeholder goals. In Chapter 6, the ranking order achieved using the ANP in a general case qualitative structural fire design decision analysis reflects the influences of the considered elements' dependencies and stakeholder judgements. Notably, in using AHP, concrete encasement of steel and board systems were the best two ranked options owing to the safety-leaning views of participant-stakeholders regardless of the high costs of concrete and board options as opined by the interviewed stakeholders. However, when ANP was implemented considering possible design decision criteria, dependences and interdependences, the ranking order achieved with AHP were altered. With ANP-implementation, unprotected steel and intumescent coatings were the best two options which conform to current consensus of structural fire design of steel buildings as opined by some of the interviewees. The outcomes from the application of ANP highlight the advantages and disadvantages of the decision analysis techniques.

9.1.3. Group decision-making using GMM

In a group decision-making problem which is the case of this research, the aggregation of individual judgements or priorities of the fire design stakeholders is highly essential. The intention is to achieve suitable consensus among multidisciplinary stakeholders involved in a typical structural fire design decision-making. The weighted or unweighted geometric mean method (W/GMM) studied and applied in this work is viable as it seamlessly weights, and aggregates paired judgements retaining their consistencies. W/GMM is also very useful as stakeholders may not necessarily need to be together in one room at the same time for the decision analysis process. W/GMM is designed as an adjoining component to AHP/ANP to account for decision-making scenarios involving multiple decision-makers (e.g. fire design stakeholders). Although there have been different criticism on the suitability of W/GMM as discussed in Chapter 3, it has remained the accepted or state-of-the-art method of achieving stakeholder consensus judgements/priorities in group decision-making. Notably, Chapter 6 demonstrated that the traditional W/GMM remains a more viable weighting and aggregation method compared to the recently published *principal components analysis-weighted geometric mean method* (PCA-WGMM). The PCA-WGMM method assumes that the variances of stakeholder judgements are inversely proportional to their weights and it uses these weights to aggregate individual judgements per category of paired comparisons. However, this work has shown that the principal components analysis (PCA) assumption may not hold in a typical fire design stakeholder decision-making, given that stakeholder influence levels in the design process may be implicitly known. The application of PCA procedure to 42 stakeholder judgement sample-set produced unreasonable stakeholder weights compared to those achieved from the general rule of weighted geometric mean method (WGMM) application presented in Chapter 3. A worked example of applying GMM+AHP to a different group decision-making problem is concisely presented in Appendix 6. The worked example highlights the viability of GMM+AHP in achieving group judgement consistency following the aggregation of individual judgements and seamless ranking of the competing options. Furthermore, in using W/GMM, stakeholder weightings should be applied when stakeholders are engaged individually or as a group and don’t agree to harmonise their judgments. Stakeholder weightings should not be applied if the participant-stakeholders consider themselves as equally important and agree to harmonise their individual judgements as demonstrated in Chapter 8.

9.1.4. Balancing fire design stakeholder goals using TOPSIS

To effectively balance the goals of fire design stakeholders toward suitable/cost-effective design decision-making, there must be deliberate effort to evaluate design uncertainties through critical assessment of competing design options. This entails the consideration and analysis of stakeholders’ qualitative expert judgements and carrying out probabilistic structural fire analysis. The Technique for Order of Preference and Similarity to Ideal Solution (TOPSIS) has been investigated and applied in this research (Chapter 7) as a viable and adaptable MCDA technique for the integration of qualitative judgements and quantitative analysis outcomes. However, TOPSIS does not have a procedure for generating its own criteria priority scores entered in its decision matrix and weights used in its synthesis phase. In many complex decision-making problems, it is suitably applied in conjunction with other technique/s forming a hybrid technique to solve the problem as applied in Chapter 7.

9.1.5. Balancing fire design stakeholder goals using a hybrid MCDA technique, GAT

To achieve the research objectives, this work developed a hybrid decision analysis technique that implements **G**MM+**A**HP+**T**OPSIS and known as GAT. The GAT development considers the three key phases of stakeholder decision analysis which balances their goals through *judgement aggregation* (GMM), *criteria prioritisation* (AHP), *synthesis and ranking* (TOPSIS). This ensures that the viable and adaptable strengths of GAT-components summarised above are explored to balance stakeholder goals toward cost-effective design decisions for better steel buildings. Notably, GAT has been developed here as an adaptable technique for solving complex decision problems including other disciplines. Hence, for thorough implementation of GAT in a structural fire design environment, this work developed an associated framework to guide its application as proposed in Chapter 7 and used in Chapter 8. Importantly, the framework which implements GAT can be adapted to assess competing system design options for specific buildings in fires, given qualitative stakeholder judgements. In such case, the outcomes from advanced computer-based system analysis can be included as failure probabilities in the design decision matrix and normalised for the completion of GAT-synthesis.

9.1.6. Other Conclusions

The research objectives were achieved given the successful development of a risk-based structural fire design decision-making process and the GAT tool for balancing multiple fire design stakeholder goals. This research also concludes that:

- The GAT process applies to complex decision problems involving multiple stakeholders (decision-makers), ‘independent’ qualitative and quantitative decision attributes and options only. It is best suited for conceptual/formulated design phases and not the technical/detailed phases of a design project.

- GAT in its current state cannot account for possible interdependencies in complex design decision problems.
- The GAT tool is commercially viable given its potential scalability/adaptability for use in other disciplines. However, the user must elicit the relevant stakeholder expert judgements and ensure judgement consistencies at the AHP-prioritisation stage to access the full benefits of the tool.
- Stakeholders' weights impact the ranking outcomes from GAT in group decision-making scenarios; hence, sensitivity analysis is encouraged.
- Given the TOPSIS component of GAT, the validation of ranking outcomes from GAT may be tested with other hybrid MCDA techniques, e.g. GMM+AHP+VIKOR if available as mentioned earlier in Section 3.1.6.
- Importantly, GAT is developed to support stakeholders to make informed decisions and not to force decisions on stakeholders.

9.2. Research Recommendations

The framework (Figure 7.2), which implemented GAT in the virtual case study design decision-making (Chapter 8) is recommended to the building and fire industry. The framework can best be described as '*a stakeholder decision-making procedure for structural fire design*'. The procedure will help to solve complex design decision-making problems especially at conceptual and formulated design phases involving multiple stakeholders, conflictual decision criteria and competing design options. The recommended procedure has been developed from the joint implementation of risk management and optimised multi-criteria decision analysis processes. This is based on thorough research and its transparent application in general and specific design decision-making case studies (Chapters 7 and 8). The procedure follows the international risk management standard (AS/NZS 31000:2009) and can be adapted to other design decision-making scenarios.

Furthermore, fifty chartered and experienced New Zealand stakeholders were engaged in the general structural fire design decision-making case. This produced sufficient *option weights* for GAT-synthesis of the competing applied fire protection options on steel structures in Chapters 7 and 8. Therefore, the derived '*option weights'* (Table 8.7) may be used by New Zealand structural and fire engineers for weighting of the associated fire protection options at conceptual stages of steel structural fire design decision-making processes that involve the same decision attributes investigated here. The '*option weights'* can also support pilot studies and conceptual steel structural fire design decision-making involving the associated fire protection options in other jurisdictions in scenarios of unavailable weighting data.

9.2.1. Research Limitations and future work

This research broadens the knowledge required in enhancing risk-informed structural fire design decision-making. The incorporation of stakeholder goals and the risk-based decision-making procedure proposed by this project also complements the recent efforts of Ministry of Business Innovation and Employment in improving fire safety in New Zealand.

The design decision attributes used in this work were formulated from a general structural fire design perspective and adapted in the virtual case study of a steel portal-framed building. The decision attributes for other building types may be different and should be investigated before the design decision-making process. Notably, for multi-storey or other specific steel buildings, some decision attributes can be adapted from this work, but care must be taken to ensure that precise conflictual criteria associated with the building in context are considered. For instance, in a structural fire system design for a specific steel building, the decision attributes for assessing the competing fire protection options may include *adhesiveness*, *durability*. In view of improving the stakeholder decision-making process and GAT developed in this research project, future researchers are encouraged to consider the design processes of specific building projects to understand how the process may be applied in reality.

The ranks of fire protection options achieved for the virtual case study building (Figure 8.2) was limited to the building type, the assessed design decision attributes and the New Zealand design philosophy/requirements. In other jurisdictions, e.g. the UK, the ranking order in the virtual case study may be influenced by the existent structural fire design principles for steel portal frames which allow for inward collapse of structures in fires as worst-case scenarios. Hence, the fire protection of the portal frame may follow a system analysis and design. The ranking order in Chapter 8 could be different if a multi-storey hospital building were investigated. In such case, the stakeholder judgements and analysis outcomes may be influenced by building occupancy, fire spread, human comfort and the associated structural failure mechanisms distinct from a portal-framed building. Therefore, the application of the developed hybrid technique and structural fire design decision-making procedure (Chapter 8) to other buildings is useful for future work. Also, the characterisation of uncertain inputs in the probabilistic analysis (Chapters 7 and 8) accounted for parameter and design decision uncertainties only. The consideration of other inherent structural fire design uncertainties, e.g. design fires, estimation and human error etc., (Table 2.2) may affect the outcomes of the decision analysis which could be compared to the ranking results achieved in this project. These uncertainties should also be considered in the future to enhance the fire design stakeholder decision-making process/technique for realistic building projects.

In this research, passive fire protection options were mainly investigated; future researchers are encouraged to test the risk-based stakeholder decision-making procedure on design decision analysis involving active fire protection systems.

The fire design stakeholder engagement was structured to elicit as many divergent views as possible to ensure no stakeholder goal is ignored. However, the number of stakeholders was unequal across the 12 stakeholder categories nominated for this work. This is due to the very busy work schedules and geographical locations of chartered stakeholders. More expert judgements from architects, building owners, contractors and insurers may enhance judgement priorities and weights used in assessing fire protection options in the design decision-making processes. The extraction of more stakeholder views from other jurisdictions should be considered in the future to compare with the results achieved in this work. This would mean that GAT is tested in several jurisdiction-specific stakeholder judgements and design decision analysis.

The stakeholder weightings considered here was on their influence/importance in the design decision-making process given the participant stakeholders were chartered/experienced in New Zealand. In practice, not all projects will involve very experienced/chartered stakeholders. Hence, this research recommends that, stakeholder knowledge/experience may be weighted where practicable e.g. using Cooke’s classical method (Section 3.2). This can account for decision uncertainties in scenarios where the level of technical know-how of designers could affect design decision-making processes.

The structural fire design decision analysis using GAT is recommended for further research by considering dependent and interdependent decision attributes whereby AHP is replaced by ANP to generate the qualitative priority scores toward GAT-synthesis. This was not explored in this research due to time limitation.

The quantitative cost analysis of the competing fire protection options in Chapters 7 and 8 was limited to the determination of actual costs by sizing and probabilistic distributions. The consideration of insurance and maintenance costs of the fire protection options may have changed the outcomes of the decision analyses. However, access to maintenance costs from building or fire protection contractors and current insurance data (e.g. discount factors) from insurance organisations were not possible. Passive fire protection maintenance costs were difficult to obtain due to commercial restrictions. The competition in the insurance industry has made premiums to be considered on an actuarial and historical basis limited to occupancy (e.g. high-rise buildings), losses, and of little or no difference for steel or reinforced concrete buildings. Therefore, insurance data are mostly commercial with caveats on non-disclosure and if available may not include the level of detail required to assess the fire protection options as applied herein. Nonetheless, in the future, the availability of insurance discount factors and maintenance costs can support net present value (NPV)-cost analysis for the competing design options and its outcomes integrated into the GAT-synthesis. This can potentially influence final stakeholder decisions as well as enhance the robustness of the developed structural fire design decision-making procedure.

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APPENDIX

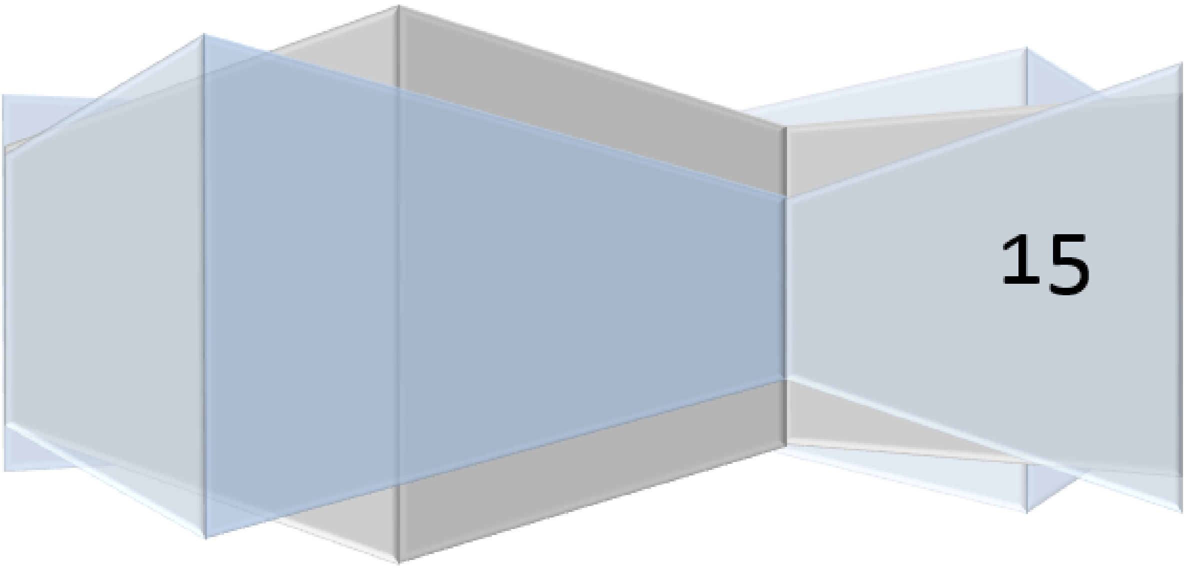
APPENDIX 1: GOAL RATING DOCUMENT USED FOR THE AHP-PILOT STUDY & QUASI-STAKEHOLDER RATING

DEPARTMENT OF CIVIL AND NATURAL RESOURCES ENGINEERING
UNIVERSITY OF CANTERBURY, CHRISTCHURCH
NEW ZEALAND

IDENTIFICATION AND EXTRACTION OF STAKEHOLDER GOALS IN STEEL STRUCTURAL FIRE DESIGN

GOAL-RATING DOCUMENT FOR FIRE DESIGN STAKEHOLDER ENGAGEMENT

OBINNA U. AKAA, Ph.D. CANDIDATE



DEPARTMENT OF CIVIL AND NATURAL RESOURCES ENGINEERING

IDENTIFICATION AND EXTRACTION OF STAKEHOLDER GOALS IN STEEL STRUCTURAL FIRE DESIGN

GOAL RATING DOCUMENT

OBINNA U. AKAA, Ph.D. CANDIDATE

STAKEHOLDER DETAILS

NAME: ……………………………………………………………………………………

POSITION/LEVEL/DESIGNATION: ………………………………E.g. Fire engineer, Architect, Building regulator)

COMPANY/ORGANISATION: …………………………………………CODE: ……………………………………….

9	7	5	3	1	1/3	1/5	1/7	1/9
Extremely more important	*Strongly* more important	*Moderately* more important	*Slightly* more important	*Equally* important	*Slightly* less important	*Moderately* less important	*Strongly* less important	*Extremely* less Important

Fig. 1: Goal-rating scale

GOAL:

To choose the most suitable fire protection option for structural fire design of steel-framed buildings for fully developed fires.

INTERVIEW ACTIVITIES

1. Participatory discussion and goal-rating. Time required is 50mins.
2. Review of rated stakeholder desires. Time required is 10mins.

GOAL-RATING EXERCISE

KEY EXERCISE QUESTIONS:

1. Given a parent element and comparing elements A and B under it, which element has greater influence on the parent element?
2. Given a parent element and comparing elements A and B, which element is influenced more by the parent element?

INDEPENDENCE RATING

Table 1: Rating structural fire design 'benefits' key decision criteria with respect to the goal

GOAL	Safety	Environmental	Societal
Safety	**1**		
Environmental		**1**	
Societal			**1**

TABLE 2: STEEL STRUCTURAL FIRE DESIGN GOALS & RATINGS

	RATINGS								
GOALS (X)	**GOALS (Y)**								
Building cost	*Maintainability*	*Constructability*	*Business continuity*	*Fire spread*	*Clarity in designs*	*Building reg. apprv.*	*Accessibility for ff.*	*Env. Sustainability*	*Human comfort*
	1	1	1	1/3	1	3	1	3	3
Maintainability	*Constructability*	*Business continuity*	*Fire spread*	*Clarity in designs*	*Building reg. apprv.*	*Accessibility for ff.*	*Env. Sustainability*	*Human comfort*	
	1	3	1	1	1	1/3	1	1	
Constructability	*Business continuity*	*Fire spread*	*Clarity in designs*	*Building reg. apprv.*	*Accessibility for ff.*	*Env. Sustainability*	*Human comfort*		
	1	1/3	1	1	1	1	1		
Business continuity	*Fire spread*	*Clarity in designs*	*Building reg. apprv.*	*Accessibility for ff.*	*Env. Sustainability*	*Human comfort*			
	1/5	1	1	1/3	1	1			
Fire spread beyond compartment	*Clarity in designs*	*Building reg. apprv.*	*Accessibility for ff.*	*Env. Sustainability*	*Human comfort*				
	5	1	1	7	5				
Clarity in design details and specifications	*Building reg. apprv.*	*Accessibility for ff.*	*Env. Sustainability*	*Human comfort*					
	1	1	5	5					
Building regulations approval	*Accessibility for ff.*	*Env. Sustainability*	*Human comfort*						
	1/5	1	1						
Accessibility for fire-fighting operations	*Env. Sustainability*	*Human comfort*							
	5	5							
Environmental sustainability	*Human comfort*								
	1/3								

TABLE 3: STEEL STRUCTURAL PASSIVE FIRE PROTECTION OPTIONS & RATINGS

	RATINGS			
OPTIONS (X)	**OPTIONS (Y)**			
Compartmentation	*Intumescent coatings*	*Board systems*	*Concrete encasement*	*Unprotected steel/Alt. design*
	1	1/5	1/3	1
Intumescent coatings	*Board systems*	*Concrete encasement*	*Unprotected steel/Alt. design*	
	1/3	1	1	
Board systems (gypsum, plaster, etc.)	*Concrete encasement*	*Unprotected steel/Alt. design*		
	3	1		
Concrete encasement (full or partial)	*Unprotected steel/Alt. design*			
	1			

TASK 2

Which of the following stakeholder best represents your rating?

List of stakeholders

1. Building owners
2. Architects
3. Building insurers
4. Building contractor
5. Environmental protection agencies
6. Fire service management
7. [✓ Fire protection engineers]
8. Fire operations
9. Building consent authorities
10. Resource consent authorities
11. Manufacturers/suppliers
12. End-users (community)

APPENDIX 2: EXPERT STAKEHOLDER ENGAGEMENT DOCUMENTS

2(a). Human Ethics Approval Letter.

UC
UNIVERSITY OF
CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

HUMAN ETHICS COMMITTEE

Secretary, Lynda Griffioen
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2015/32/LR-PS

19 June 2015

Obinna Akaa
Department of Civil & Natural Resources Engineering
UNIVERSITY OF CANTERBURY

Dear Obinna

Thank you for forwarding to the Human Ethics Committee a copy of the low risk application you have recently made for your research proposal “Balancing stakeholder goals in structural fire design of steel frames buildings”.

I am pleased to advise that this application has been reviewed and I confirm support of the Department’s approval for this project.

Please note that this approval is subject to the incorporation of the amendments you have provided in your email of

With best wishes for your project.

Yours sincerely

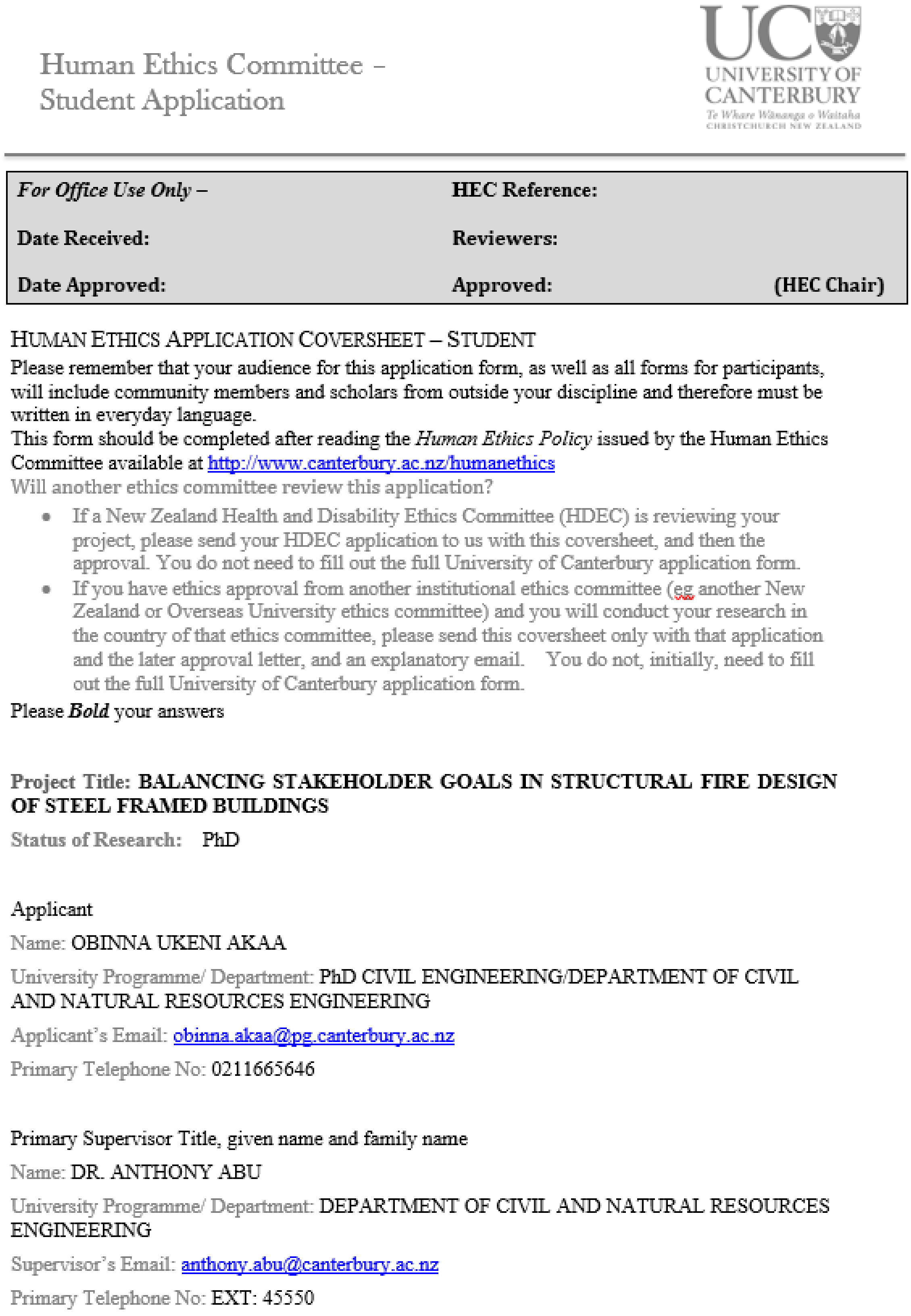
L MacDonald

Lindsey MacDonald
Chair, Human Ethics Committee

University of Canterbury Private Bag 4800, Christchurch 8140, New Zealand. www.canterbury.ac.nz

F E S

2(b). Relevant Details of Human Ethics Application Approval for Research Interviews



Human Ethics Committee –
Student Application

UC
UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

For Office Use Only –	**HEC Reference:**	
Date Received:	**Reviewers:**	
Date Approved:	**Approved:**	**(HEC Chair)**

HUMAN ETHICS APPLICATION COVERSHEET – STUDENT

Please remember that your audience for this application form, as well as all forms for participants, will include community members and scholars from outside your discipline and therefore must be written in everyday language.

This form should be completed after reading the *Human Ethics Policy* issued by the Human Ethics Committee available at http://www.canterbury.ac.nz/humanethics

Will another ethics committee review this application?

- If a New Zealand Health and Disability Ethics Committee (HDEC) is reviewing your project, please send your HDEC application to us with this coversheet, and then the approval. You do not need to fill out the full University of Canterbury application form.
- If you have ethics approval from another institutional ethics committee (eg another New Zealand or Overseas University ethics committee) and you will conduct your research in the country of that ethics committee, please send this coversheet only with that application and the later approval letter, and an explanatory email. You do not, initially, need to fill out the full University of Canterbury application form.

Please ***Bold*** your answers

Project Title: BALANCING STAKEHOLDER GOALS IN STRUCTURAL FIRE DESIGN OF STEEL FRAMED BUILDINGS

Status of Research: PhD

Applicant

Name: OBINNA UKENI AKAA

University Programme/ Department: PhD CIVIL ENGINEERING/DEPARTMENT OF CIVIL AND NATURAL RESOURCES ENGINEERING

Applicant's Email: obinna.akaa@pg.canterbury.ac.nz

Primary Telephone No: 0211665646

Primary Supervisor Title, given name and family name

Name: DR. ANTHONY ABU

University Programme/ Department: DEPARTMENT OF CIVIL AND NATURAL RESOURCES ENGINEERING

Supervisor's Email: anthony.abu@canterbury.ac.nz

Primary Telephone No: EXT: 45550

Other Supervisors

Name: ASSOCIATE PROF. MICHAEL SPEARPOINT

University Programme/ Department: DEPARTMENT OF CIVIL AND NATURAL RESOURCES ENGINEERING

Supervisor's Email: michael.spearpoint@canterbury.ac.nz

Primary Telephone No: EXT: 6237

Name: DR. SONIA GIOVINAZZI

University Programme/ Department: DEPARTMENT OF CIVIL AND NATURAL RESOURCES ENGINEERING

Supervisor's Email: sonia.giovinazzi@canterbury.ac.nz

Primary Telephone No: EXT: 7327

RESEARCHER'S SIGNATURE

I ***[OBINNA UKENI AKAA]*** have considered, the various ethical issues involved in this research, I have discussed this proposal with my supervisor(s), and I will conduct this research within the bounds of any approval given by the Human Ethics Committee of the University of Canterbury.

Signed: ____________________________________ Dated:

Is the approval of this application a necessary pre-requisite for the Dean of Postgraduate Studies to formally accept your PhD proposal? [NO]

SENIOR SUPERVISOR'S SIGNATURE

As the primary supervisor of ***[OBINNA UKENI AKAA]*** research project I, ***DR. ANTHONY ABU*** consider that the design and documentation are of a standard appropriate for a research project carried out in the name of the University of Canterbury.

Signed: ____________________________________ Dated:

LOW RISK PROCESSES (TO BE COMPLETED BY THE PRIMARY SUPERVISOR)

The low risk process for students differs from a full application only in that it is examined solely by the Chair of the Human Ethics Committee. As a result it may be possible to reply to the applicant in 7 days. It is to be signed only by supervisor(s).

Please explain why the research is low risk research low risk, noting the information overleaf
If this section is left blank, the application will be considered a full application.

This project is considered a low risk project because it involves the engagement of fire design stakeholders through participatory interviews (professional discussions) and the completion of a goal-rating document. The questions and discussions shall be centred on the professional views of the participants toward achieving appropriate structural fire design for better buildings.

Therefore, there are no invasive procedures and invasion of privacy, given that participants shall be contacted officially, they shall complete consent forms and shall have the right of withdrawal from the study at any point. The interview will not include personal issues and the personal identities of participants will not be revealed, but they will be presented in publications/PhD thesis according to their respective professional position/designation/level as the case may be.

The fire design stakeholders are adults in their professional capacity and not vulnerable people. This interview has not been carried out elsewhere. Hence, originality is expected from the information that will be gathered.

Data confidentiality shall be highly maintained by coding before storing all the interview information in secured location on the researcher's office computer and university servers.

Signed (Senior/Primary Supervisor only) ______________________________ Dated:

SUBMISSION INSTRUCTIONS.

Please submit ONE electronic file containing all the necessary documents in a PDF format and ONE fully signed hard copy. Exceptions may be made, but must be discussed first with the HEC Secretary. Processing of HEC applications is unable to begin until a hard copy of the application has been received by the Ethics Office.
Electronic copies should be emailed to human-ethics@canterbury.ac.nz. Hard copies should be sent to the Secretary, Human Ethics Committee (Level 5, Matariki South).

28. Is information that identifies participants to be given to any person outside the research team, or if identification of or attribution of comments by participants is sought, please explain how and why. NO

29. Please explain how confidentiality of the participants' identities will be maintained in the treatment and use of the data. e.g., the HEC expects that researchers will attempt to ensure that stored data is separated into identifying data (e.g., consent forms, coding forms), and de-identified (e.g., coded data, de-identified transcripts): typically, this is done by assigning participants a code on the consent form, and using that code on any data, transcripts, etc. Where this is too difficult, please explain why.

Data confidentiality shall be highly maintained by storing all the data in secured location in the researcher's office cabinet, computer and university servers. Each consent form and completed goal-rating document shall be coded with respect to each participant-stakeholder. Therefore, the code assigned to each participant shall be used to identify all documents relating to that participant. The secured password and codes of the interview information shall be known to the research team only.

30. Is an institution (e.g., school, business, etc.) to which participants belong to be named or be able to be identified in the publication or presentation of this project? NO

31. Where will the project be conducted? It is recommended that interviews be conducted in public spaces, not in private homes. *The committee appreciates that in some cases there may be good academic reasons for conducting research in private homes. If you believe this applies to your project, we ask you to provide (a) a concise justification of why research in the home is necessary for your project, what alternative locations were considered, and why they were discounted, and (b) detail how you anticipate and will seek to mitigate potential risks to both participants and researchers when undertaking research in a private home(s).*

Please note: in the case of research involving children, young adults and participants who need particular care, an adult other than the researcher is required to be present.

The interviews shall be conducted in public places such as offices, office lounge, conference hall etc., not in any private home.

RISK

If the answer to any of the following questions is "Yes", please indicate briefly the nature of the risk and what actions you could take, or support mechanisms you could rely on, if a participant should become injured, distressed or offended while taking part in this project. In order to maintain a distinction between the researcher and other roles, support should not be undertaken by researcher. At the very least, a list of support services should be included in the information sheet and also participants made aware of the possibility in the information sheet.

32. Is there any risk to physical well-being? NO

33. Could participation involve mental stress or emotional distress? NO

34. Is there a possibility of causing moral or cultural offence, inadvertently or otherwise? NO

35. Is deception involved at any stage of the project? NO

36. NIL

DATA STORAGE AND FUTURE USE

37. Please provide details of how the data will be securely stored, and how you will separate identifying and non-identifying data. i.e., what steps will be taken to ensure that information given by participants is safe and protected? All storage facilities including electronic equipment should be in rooms that can be locked. All data should be stored in password-protected files and, where on computers, the computers should be password protected. Data should be backed up or stored on the University servers. If you intend to store the data in cloud services please provide a justification and documentary proof that the data will be secure (e.g., relevant sections of the terms of service of the provider).

All data shall be stored in password-protected files on the researcher's office-computer. This computer is password-secured and locked in room E329 (Civil/Mechanical building) when not in use. The information gathered from the interview shall be backed-up in password-protected university servers.

38. Who, apart from the researcher and their supervisor (where applicable) will have authorised access to the data? Research Assistants and transcribers need their own confidentiality forms and their participation needs to be made known to participants.

Nobody shall have access to the stored data except the research team i.e. the researcher, primary and co-supervisors.

39. What will happen to the raw data at the end of the project? Standard HEC principles are that data from research projects will be kept safely and then destroyed as follows:

At the completion of an Honours or similar project
After 5 years for an MA
After 10 years for a PhD or staff research

This form should be completed after reading the *Human Ethics Policy* issued by the Human Ethics Committee available at http://www.canterbury.ac.nz/humanethics

Please discuss and justify any variations to these guidelines that your project requires (for instance, if the data is to be kept permanently).
This information should be contained in all information sheets and consent forms.

On completion of the PhD research, the interview data shall be stored by the primary supervisor on the university password-secured computer for ten years and then destroyed.

40. What plans do you have for the publication of the data? Please note, and include in your information sheets, that Masters thesis and PhDs are public documents available via the UC library database. Also, participants should be offered summary of results.

The information from this research project shall be used in the publication of technical/conference paper, journals and PHD thesis. The researcher shall offer the participants the summary of results at the end of the research work.

41. Please describe plans for future use of the data beyond those already described above.

NIL

2(c). Stakeholder Information Sheet and Consent Form

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Department: Civil and Natural Resources Engineering

Telephone: +6433642987 Ext. 7317
Email: obinna.akaa@pg.canterbury.ac.nz
Date: ____________________________

Research title: Balancing stakeholder goals in structural fire design of steel framed buildings
Information Sheet for gathering stakeholder opinions on passive fire protection options

My name is Obinna Ukeni Akaa, a PhD candidate (researcher) at the University of Canterbury.

You are invited to participate in the research project as titled above; the purpose of this research is to create a tool that balances the goals of stakeholders in order to optimize decisions for the design of steel framed buildings for fully developed fires.

In designing a steel framed building, there are many fire protection options available in meeting structural fire performance. Different fire design stakeholders have different opinions about which approach is most appropriate. Therefore, there is need to identify, extract and balance the divergent desires of the different stakeholders in order to optimize decisions for design of steel framed buildings for fully developed fires.

Your involvement in this research will be:

1. Participatory discussion (interview) on your views and preferences regarding protection of steel structures in fully developed fires. This will be done in 50 minutes.
2. Review of your rated desires at the end of the interview. This will be done in 10 minutes.

You may receive a copy of the research project results by contacting the researcher at the conclusion of the project.

Participation is voluntary and you have the right to withdraw at any stage without penalty. If you withdraw, I will remove information relating to you, provided the project is not at publication stage (i.e. between completion of data analysis and write-up).

The result of the project may be published and you may be assured of the complete confidentiality of data gathered in this interview: your identity will not be made public without your prior consent. To ensure anonymity and confidentiality, the researcher shall use general or official terms representing the position/designation/category of participants e.g. fire engineer, building owner, architect etc., in any of his publications. All data shall be stored in the researcher's password-secured computer, university servers and locked university office cabinet; the passwords/information shall be known and accessed by the researcher and his supervisor only. Data gathered will be stored for ten years, after the completion of the PhD degree and then destroyed. A thesis is a public document and will be available through the UC Library.

The project is being carried out as part of a Doctor of Philosophy research by Obinna Ukeni Akaa under the supervision of Dr. Anthony Abu, who can be contacted at anthony.abu@canterbury.ac.nz. He will be pleased to discuss any concerns you may have about participation in the interview.

The research project has been reviewed and approved by the University of Canterbury Human Ethics Committee, and participants should address any complaints to The Chair, Human Ethics Committee, University of Canterbury, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz).

If you agree to participate in the study, you are asked to complete the consent form and return to the researcher by email: obinna.akaa@pg.canterbury.ac.nz

Obinna Ukeni Akaa.

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Department: Civil and Natural Resources Engineering
Telephone: +6433642987 Ext. 7317
Email: obinna.akaa@pg.canterbury.ac.nz
Date: ___________________________

Research title: Balancing stakeholder goals in structural fire design of steel framed buildings
Consent form for gathering stakeholder opinions on passive fire protection options

I have been given a full explanation of this project and have had the opportunity to ask questions.

I understand what is required of me if I agree to take part in the research.

I understand that participation is voluntary and I may withdraw at any time without penalty. Withdrawal of participation will also include the withdrawal of information I have provided should this remain practically achievable.

I understand that any information or opinions I provide will be kept confidential to the researcher and his supervisor and that any published or reported results will not identify the participants or their institutions. I understand that a thesis is a public document and will be available through the UC Library.

I understand that all data collected for the study will be kept in locked and secured facilities and/or in password protected electronic form and will be destroyed ten years after the completion of the researcher's PhD degree.

I understand that I am able to receive the report on the findings of the study by contacting the researcher at the conclusion of the project.

I understand that I can contact the researcher (Obinna Ukeni Akaa; telephone: +6433642987 Ext. 7317, email: obinna.akaa@pg.canterbury.ac.nz) or supervisor (Dr. Anthony Abu; email: anthony.abu@canterbury.ac.nz) for further information. If I have any complaints, I can contact the Chair of the University of Canterbury Human Ethics Committee, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz).

By signing below, I agree to participate in this research project.

Name (Please print): ………………………………………………….......................

Signature: …………………………………………………………………………

Date: ………………………………………………………………………………

Please return signed copy of this consent form to the researcher by email: obinna.akaa@pg.canterbury.ac.nz

Obinna Ukeni Akaa.

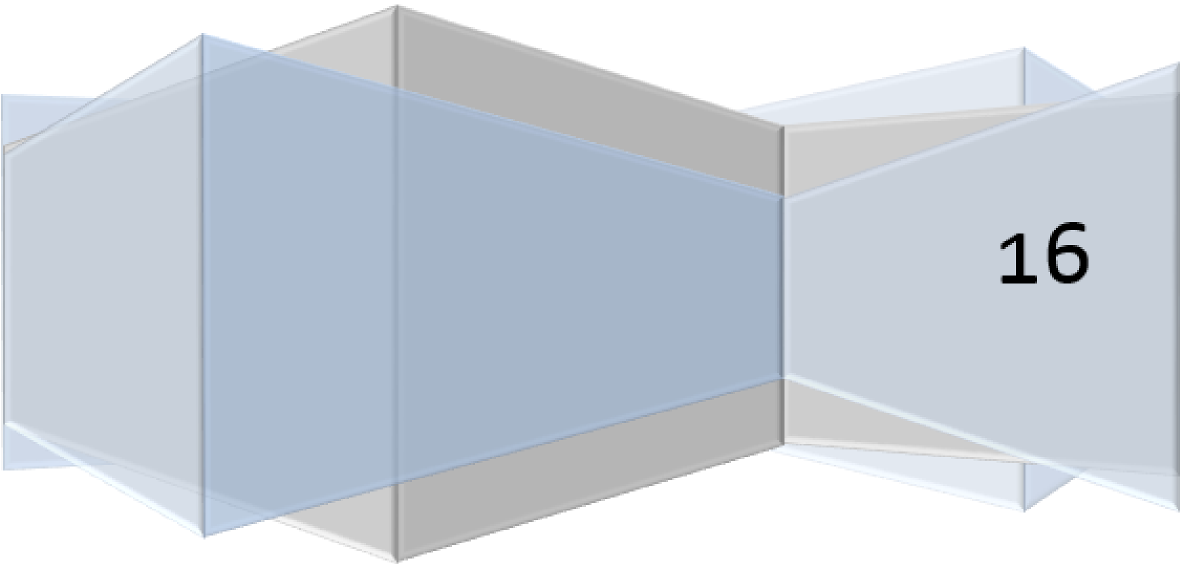
2(d). A Sample of the Revised Goal Rating Document

DEPARTMENT OF CIVIL AND NATURAL RESOURCES ENGINEERING
UNIVERSITY OF CANTERBURY, CHRISTCHURCH
NEW ZEALAND

IDENTIFICATION AND EXTRACTION OF STAKEHOLDER GOALS IN STEEL STRUCTURAL FIRE DESIGN

GOAL-RATING DOCUMENT FOR FIRE DESIGN STAKEHOLDER ENGAGEMENT

OBINNA U. AKAA, Ph.D. CANDIDATE



DEPARTMENT OF CIVIL AND NATURAL RESOURCES ENGINEERING
IDENTIFICATION AND EXTRACTION OF STAKEHOLDER GOALS IN STEEL STRUCTURAL FIRE DESIGN

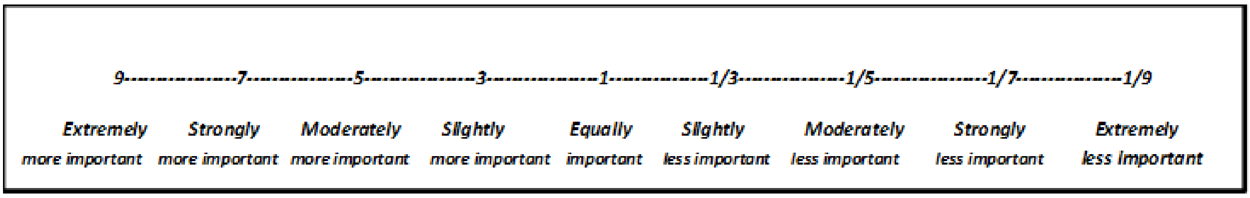
GOAL RATING DOCUMENT
OBINNA U. AKAA, Ph.D. CANDIDATE

STAKEHOLDER DETAILS

NAME: …………………………………………………………

POSITION/LEVEL/DESIGNATION: ………………. (E.g. Fire engineer, Architect, Building regulator)

COMPANY/ORGANISATION: ……………………………………………CODE: ………………………



9	7	5	3	1	1/3	1/5	1/7	1/9
Extremely more important	*Strongly* more important	*Moderately* more important	*Slightly* more important	*Equally* important	*Slightly* less important	*Moderately* less important	*Strongly* less important	*Extremely* less important

Fig. 1: Goal-rating scale

GOAL:

To choose the most suitable fire protection option for structural fire design of steel-framed buildings for fully developed fires.

INTERVIEW ACTIVITIES

1. Participatory discussion and goal-rating. Time required is 50mins.
2. Review of rated stakeholder desires. Time required is 10mins.

GOAL-RATING EXERCISE

KEY EXERCISE QUESTIONS:

1. *Compare (criteria or element A) and (criteria or element B) with respect to selecting the most suitable passive fire protection on steel elements for fully developed fires.*

   i.e. Given a parent element and comparing elements A and B under it, which element has greater influence on the parent element?

2. *Given a critical element (criterion, sub-criterion) and comparing elements X (criterion, sub-criterion) and Y (criterion, sub-criterion) under it, which element has more influence on the critical element?*

   i.e. Given a critical element and comparing elements A and B, which element is influenced more by the critical element?

INDEPENDENCE RATING

Table 1: Rating structural fire design ‘benefits’ key decision criteria with respect to the goal

GOAL	Safety	Environmental	Societal
Safety	**1**		
Environmental		**1**	
Societal			**1**

Table 2: Rating structural fire design key decision criteria with respect to the goal

GOAL	Economy	Safety	Environmental	Societal
Economy	**1**			
Safety		**1**		
Environmental			**1**	
Societal				**1**

Table 3: Rating steel structural passive fire protection options with respect to the goal

GOAL	ITC	BS	CET	SCM	US
Intumescent coatings (ITC)	**1**				
Board systems (gypsum, plaster etc.) (BS)		**1**			
Concrete encasement of steel (full or partial) (CET)			**1**		
Sprayed on cement-based material (SCM)				**1**	
Unprotected steel (US)					**1**

Table 4: Rating 'costs' sub-decision criteria against each other with respect to their parent criteria (economy)

ECONOMY	CA	BC	PM	MMU	MSC	FRM
Constructability (CA)	**1**					
Business continuity (BC)		**1**				
Profit-making (PM)			**1**			
Minimum material use (MMU)				**1**		
Maintaining supply chain (MSC)					**1**	
Financial risk mgt. & loss prevention (FRM)						**1**

Table 5: Rating 'benefits 'sub-decision criteria against each other with respect to their parent criteria (safety)

SAFETY	FRA	SFR	PBR1	CCD	EFF	FSBC	MA
Fire risk assessment (FRA)	**1**						
Structural fire resistance (SFR)		**1**					
Pre-fire building resilience (PBR1)			**1**				
Clarity in design details & specifications (CDD)				**1**			
Fire-fighting operations (EFF)					**1**		
Fire spread beyond compartment (FSBC)						**1**	
Maintainability (MA)							**1**

Table 6: Rating 'benefits' sub-decision criteria against each other with respect to their parent criteria (environmental)

ENVIRONMENTAL	ES	EAHC
Environmental sustainability (ES)	**1**	
Environmental act/HSNO compliance (EAHC)		**1**

Table 7: Rating ‘benefits’ sub-decision criteria against each other with respect to their parent criteria (societal)

SOCIETAL	BA	HC	ASID	BRA	BUF	HS	PBR2
Building aesthetics (BA)	**1**						
Human comfort (HC)		**1**					
All stakeholder involvement in design (ASID)			**1**				
Building regulation approval (BRA)				**1**			
Building use and features (BUF)					**1**		
Health & safety (HS)						**1**	
Post-fire building resilience (PBR2)							**1**

INNER DEPENDENCE RATING

Table 8: Rating sub-decision criteria against each other, given their influence on constructability (inner dependence) with respect to ‘costs’ control criteria

MAINTAINING SUPPLY CHAIN	CA	PM
Constructability (CA)	**1**	
Profit-making (PM)		**1**

Table 9: Rating sub-decision criteria against each other, given their influence on constructability (inner dependence) with respect to ‘costs’ control criteria

PROFIT-MAKING	CA	BC	MMU	FRM
Constructability (CA)	**1**			
Business continuity (BC)		**1**		
Minimum material use (MMU)			**1**	
Financial risk management & loss prevention (FRM)				**1**

Table 10: Rating sub-decision criteria against each other, given their influence on constructability (inner dependence) with respect to ‘costs’ control criteria

FINANCIAL RISK MANAGEMENT & LOSS PREVENTION	BC	MMU
Business continuity (BC)	**1**	
Minimum material use (MMU)		**1**

Table 11: Rating sub-decision criteria against each other, given their influence on structural fire resistance (inner dependence) with respect to ‘benefits’ control criteria

STRUCTURAL FIRE RESISTANCE	FRA	PBR1	CCD	EFF	FSBC	MA
Fire risk assessment (FRA)	**1**					
Pre-fire building resilience (PBR1)		**1**				
Clarity in design details & specifications (CDD)			**1**			
Fire-fighting operations (EFF)				**1**		
Fire spread beyond compartment (FSBC)					**1**	
Maintainability (MA)						**1**

Table 12: Rating sub-decision criteria against each other, given their influence on clarity on design details & specs. (inner dependence) with respect to ‘benefits’ control criteria

CLARITY IN DESIGN DETAILS AND SPECIFICATIONS	FRA	EFF	FSBC
Fire risk assessment (FRA)	**1**		
Fire-fighting operations (EFF)		**1**	
Fire spread beyond compartment (FSBC)			**1**

Table 13: Rating sub-decision criteria against each other, given their influence on fire spread beyond compartment (inner dependence) with respect to ‘benefits’ control criteria

FIRE SPREAD BEYOND COMPARTMENT	SFR	PB R1	CDD	EFF
Structural fire resistance (SFR)	**1**			
Pre-fire building resilience (PBR1)		**1**		
Clarity in design details and specifications (CDD)			**1**	
Fire-fighting operations (EFF)				**1**

Table 14: Rating sub-decision criteria against each other, given their influence on fire risk assessment (inner dependence) with respect to ‘benefits’ control criteria

FIRE RISK ASSESSMENT	CDD	PBR1	FSBC
Clarity in design details and specifications (CDD)	**1**		
Pre-fire building resilience (PBR1)		**1**	
Fire spread beyond compartment (FSBC)			**1**

Table 15: Rating sub-decision criteria against each other, given their influence on pre-fire building resilience (inner dependence) with respect to ‘benefits’ control criteria

PRE-FIRE BUILDING RESILIENCE	SFR	CDD
Structural fire resistance (SFR)	**1**	
Clarity in design details and specifications (CDD)		**1**

Table 16: Rating sub-decision criteria against each other, given their influence on effects of fire-fighting operations (inner dependence) with respect to ‘benefits’ control criteria

FIRE-FIGHTING OPERATIONS	FRA	SFR	PBR1	CDD	FSBC	MA
Fire risk assessment (FRA)	**1**					
Structural fire resistance (SFR)		**1**				
Clarity in design details and specifications (CDD)			**1**			
Pre-fire building resilience (PBR1)				**1**		
Fire spread beyond compartment (FSBC)					**1**	
Maintainability (MA)						**1**

Table 17: Rating sub-decision criteria against each other, given their influence on human comfort (inner dependence) with respect to 'benefits' control criteria

HUMAN COMFORT	BA	ASID	PBR2
Building aesthetics (BA)	**1**		
All stakeholder involvement in design (ASID)		**1**	
Health and safety (HS)			**1**

Table 18: Rating sub-decision criteria against each other, given their influence on building regulation approval (inner dependence) with respect to 'benefits' control criteria

BUILDING REGULATION APPROVAL	ASID	HC	PBR2
All stakeholder involvement in design (ASID)	**1**		
Health and safety (HS)		**1**	
Post-fire building resilience (PBR2)			**1**

OUTER DEPENDENCE RATING

Table 19: Rating sub-decision criteria against each other, given their influence on intumescent coatings (outer dependence) with respect to 'cost' control criteria

INTUMESCENT COATINGS	CA	BC	PM	MMU	MSC	FRM
Constructability (CA)	**1**					
Business continuity (BC)		**1**				
Profit-making (PM)			**1**			
Minimum material use (MMU)				**1**		
Maintaining supply chain (MSC)					**1**	
Financial risk mgt. & loss prevention (FRM)						**1**

2(e). Aggregated Judgement Matrices of Online Participants from Other Jurisdictions used in determining the result in Figure 5.3(a) (building regulation approval).

i. 2 Australian Fire Engineers

SOCIETAL	BA	HC	ASID	BRA	BUF	HS	PF2	*Priority Scores*
Building aesthetics (BA)	1.0000	0.5774	0.6325	0.6547	0.3536	0.4472	0.8944	0.0839
Human comfort (HC)	1.7321	1.0000	0.8165	0.7746	0.5000	0.5774	1.1547	0.1179
All stakeholder involvement in design (ASID)	1.5811	1.2247	1.0000	0.8165	0.8165	0.7071	1.7321	0.1454
Building regulation approval (BRA)	1.5274	1.2909	1.2247	1.0000	1.0000	1.0000	2.4495	0.1756
Building use and features (BUF)	2.8284	2.0000	1.2247	1.0000	1.0000	1.0000	1.5811	0.1918
Health & safety (HS)	2.2361	1.7321	1.4142	0.9999	1.0000	1.0000	2.0000	0.1918
Post-fire building resilience (PF2)	1.1180	0.8660	0.5773	0.4082	0.6325	0.5000	1.0000	0.0936

ii. 1 American Fire Engineer

SOCIETAL	BA	HC	ASID	BRA	BUF	HS	PF2	*Priority Scores*
Building aesthetics (BA)	1.0000	0.2000	0.3333	0.2000	0.3333	0.2000	3.0000	0.0460
Human comfort (HC)	5.0000	1.0000	3.0000	1.0000	3.0000	1.0000	7.0000	0.2439
All stakeholder involvement in design (ASID)	3.0000	0.3333	1.0000	0.3333	1.0000	0.3333	5.0000	0.0986
Building regulation approval (BRA)	5.0000	1.0000	3.0000	1.0000	3.0000	1.0000	7.0000	0.2439
Building use and features (BUF)	3.0000	0.3333	1.0000	0.3333	1.0000	0.3333	5.0000	0.0986
Health & safety (HS)	5.0000	1.0000	3.0000	1.0000	3.0000	1.0000	7.0000	0.2439
Post-fire building resilience (PF2)	0.3333	0.1429	0.2000	0.1429	0.2000	0.1429	1.0000	0.0251

iii. 2 British (UK) Fire Engineers

SOCIETAL	BA	HC	ASID	BRA	BUF	HS	PF2	*Priority Scores*
Building aesthetics (BA)	1.0000	1.0000	0.4472	0.3333	0.5774	0.5774	1.0000	0.0858
Human comfort (HC)	0.9999	1.0000	0.3333	0.4472	0.7746	0.5774	1.0000	0.0894
All stakeholder involvement in design (ASID)	2.2361	3.0000	1.0000	1.0000	1.2910	1.7321	2.2361	0.2176
Building regulation approval (BRA)	3.0000	2.2361	0.9999	1.0000	1.7321	1.7321	3.0000	0.2366
Building use and features (BUF)	1.7321	1.2909	0.7746	0.5773	1.0000	1.0000	1.7321	0.1424
Health & safety (HS)	1.7321	1.7321	0.5773	0.5773	0.9999	1.0000	1.7321	0.1424
Post-fire building resilience (PF2)	1.0000	0.9999	0.4472	0.3333	0.5773	0.5773	1.0000	0.0858

iv. 1 Iranian Structural Engineer

SOCIETAL	BA	HC	ASID	BRA	BUF	HS	PBR2	***Priority Scores***
Building aesthetics (BA)	1.0000	0.1666	2.0000	0.1428	0.1428	0.1250	0.1428	0.0281
Human comfort (HC)	6.0000	1.0000	7.0000	0.5000	0.5000	0.3333	0.5000	0.1106
All stakeholder involvement in design (ASID)	0.5000	0.1428	1.0000	0.1250	0.1250	0.1111	0.1250	0.0210
Building regulation approval (BRA)	7.0000	2.0000	8.0000	1.0000	1.0000	0.5000	1.0000	0.1814
Building use and features (BUF)	7.0000	2.0000	8.0000	1.0000	1.0000	0.5000	1.0000	0.1814
Health & safety (HS)	8.0000	3.0000	9.0000	2.0000	2.0000	1.0000	2.0000	0.2961
Post-fire building resilience (PF2)	7.0000	2.0000	8.0000	1.0000	1.0000	0.5000	1.0000	0.1814

v. 4 Nigerian Structural Engineers

SOCIETAL	BA	HC	ASID	BRA	BUF	HS	PF2	***Priority Scores***
Building aesthetics (BA)	1.0000	0.5411	1.3161	0.3861	0.5411	0.3124	1.0648	0.0823
Human comfort (HC)	1.8481	1.0000	2.9428	1.0000	1.0000	0.6687	1.9680	0.1676
All stakeholder involvement in design (ASID)	0.7598	0.3398	1.0000	0.3398	0.3398	0.2272	0.6687	0.0585
Building regulation approval (BRA)	2.5900	1.0000	2.9428	1.0000	1.1583	0.5081	1.9680	0.1727
Building use and features (BUF)	1.8481	1.0000	2.9428	0.8633	1.0000	0.5774	2.2361	0.1636
Health & safety (HS)	3.2011	1.4953	4.4006	1.9680	1.7321	1.0000	2.9428	0.2718
Post-fire building resilience (PF2)	0.9391	0.5081	1.4953	0.5081	0.4472	0.3398	1.0000	0.0836

vi. 7 New Zealand Fire Engineers

SOCIETAL	BA	HC	ASID	BRA	BUF	HS	PF2	***Priority Scores***
Building aesthetics (BA)	1.0000	2.0534	0.4917	0.2998	0.4428	1.5742	1.7311	0.0957
Human comfort (HC)	0.6765	1.0000	0.1959	0.1338	0.1765	0.3608	0.6377	0.0393
All stakeholder involvement in design (ASID)	2.0332	5.1046	1.0000	0.2676	0.5533	1.7768	2.5870	0.1461
Building regulation approval (BRA)	3.3352	7.4709	3.7365	1.0000	2.5766	5.0691	4.1587	0.3738
Building use and features (BUF)	2.2580	5.6650	1.8069	0.3881	1.0000	1.7310	4.0966	0.2000
Health & safety (HS)	0.6351	2.7716	0.5628	0.1972	0.5776	1.0000	1.2774	0.0838
Post-fire building resilience (PF2)	0.5776	1.5680	0.3865	0.2404	0.2441	0.7828	1.0000	0.0612

vii. 3 New Zealand Structural Engineers

SOCIETAL	BA	HC	ASID	BRA	BUF	HS	PF2	***Priority Scores***
Building aesthetics (BA)	1.0000	1.1005	1.9999	0.2877	0.3293	0.5000	0.6299	0.0799
Human comfort (HC)	0.9086	1.0000	1.5182	0.2646	0.2500	0.2645	0.3969	0.0607
All stakeholder involvement in design (ASID)	0.5000	0.6586	1.0000	0.1908	0.1734	0.2646	0.2752	0.0425
Building regulation approval (BRA)	3.4756	3.7793	5.2406	1.0000	1.0000	1.5873	1.5873	0.2465
Building use and features (BUF)	3.0363	3.9994	5.7680	1.0000	1.0000	1.6509	1.9128	0.2552
Health & safety (HS)	1.9998	3.7793	3.7793	0.6300	0.6057	1.0000	1.4937	0.1758
Post-fire building resilience (PF2)	1.5871	2.5196	3.6338	0.6300	0.5227	0.6695	1.0000	0.1393

viii. Summary of Normalised Priority Scores of Building Regulation Approval used in Plotting Figure 5.3(a)

A. Fire Engineers

Jurisdiction	**Priority Scores**	**Normalised Scores**
Australia	0.1756	0.1705
USA	0.2439	0.2295
UK	0.2366	0.2297
New Zealand	0.3738	0.3630

B. Structural Engineers

Jurisdiction	Priority Scores	Normalised Scores
Iran	0.1814	0.3021
Nigeria	0.1727	0.2875
New Zealand	0.2465	0.4104

APPENDIX 3: DETERMINISTIC MANUAL CALCULATIONS – BEAM RESPONSE IN FIRE

CALCULATION SHEET	**TITLE:** Deterministic manual calculations – Structural response in fire **DATE:** 27/03/2017		REFERENCE
	MADE BY: O.U. AKAA	**CHECKED BY:** A.K. ABU	

1.0. INTRODUCTION

This is a structural fire analysis calculation for a simply supported nominal restrained steel beam (Length: 15 m; Section: 406×178×54UB)

Eurocodes 0, 1, 3, 3-1-2 and accompanying annex standards were the basic guide for the derivation of characteristic loads, loading combinations and mechanical analysis of the steel beam in fire condition.

The design fire had been chosen as standard fire (ISO 834). By applying the Eurocode approach (Eurocode 3 part 1.2), a critical temperature is calculated as 659 °C. The thermal analysis was carried out on spreadsheets and variation of thicknesses of different applied fire protection products on steel structures were also considered to achieve the best fit thicknesses and maximum temperature of 620 °C in the individual members for a fire resistant rating of 60 min.

The steel temperatures from the thermal analysis were used in the mechanical analysis of the steel beam based on fire limit state in the strength or capacity domain.

CALCULATION SHEET	**TITLE:** Deterministic manual calculations – Structural response in fire **DATE:** 27/03/2017		REFERENCE
	MADE BY: O.U. AKAA	**CHECKED BY:** A.K. ABU	

1.1. Design Data

Given the proposed or trial steel section, 406×178×54UB, an initial preliminary sizing of members had been carried out in cold or ambient temperature design condition.

Steel beam properties:

Length of beam, l = 15 m

Depth of beam, h = 403 mm

Width of beam, b = 178 mm

Flange thickness, t_f = 10.90 mm

Web thickness, t_w = 7.6 mm

Second moment of area about the z-z axis, I_z = 1.02 mm^4

Warping constant, I_w = 394 mm^6

Torsion constant, I_t = 234 mm^4

Plastic section modulus, $W_{pl,y}$ = 1060 mm^3

Area of beam cross-section, A == 6890 mm^2

Yield strength of steel @ 20°C, f_y = 320 N/mm^2

CALCULATION SHEET	**TITLE:** Deterministic manual calculations – Structural response in fire **DATE:** 27/03/2017		REFERENCE
	MADE BY: O.U. AKAA	**CHECKED BY:** A.K. ABU	

2.0. DESIGN OF STEEL BEAM (406 x 178 x 54UB)

2.1. <u>Loading</u>

Self-weight of steel beam, $G_{sw} = 0.53$ kN/m^2

Roofing (roofing sheets, purlins) and services, $G_{roof} = 0.30$ kN/m^2

Total permanent action on steel beam, $G_k = 0.53 + 0.30 = 0.83$ kN/m^2

EN 1991-1-1
Tab 4.4 & 6.10

2.1.1. *<u>Snow Load</u>*

Snow load is determined thus: $Q_S = \mu_1 \times C_e \times C_t \times S_k$

EN 1991-1-3
§ 5.2.2 eq. 5.1

Where:

μ_1 is roof coefficient;

C_e is exposure coefficient, usually taken as 1.0

C_t is thermal coefficient, taken as 1.0

S_k is characteristic value of ground snow load for the relevant altitude.

The roof coefficient depends on the roof pitch needed for snow loading adjustments. Considering the effects of drifted and non-drifted snow load arrangement and given that $\theta = 7.9°$:

Consider $\theta \leq 7.9° \leq 30$, so take $\mu_1 = 0.8$

EN 1991-1-1 §5.3 tab 5.1

Then, $S_k = [0.15 + (0.1Z + 0.05)] + \frac{A-100}{525}$

NZS 3604:2011

Where: Z is zone number in the map; Christchurch is located at Zone 1.

A is altitude of the site; here we take the maximum altitude (m) from AS/NZ standard. A = 350 m

So, $S_k = [0.15 + (\{0.1 \times 1\} + 0.05)] + \frac{350-100}{525} = 0.98$ kN/m^2

Then, $Q_S = 0.8 \times 1 \times 1 \times 0.98 = 0.78$ kN/m^2

Take variable action on the steel beam as $Q_S = Q_k = 0.78$ kN/m^2

2.1.2. *Action on steel beam*

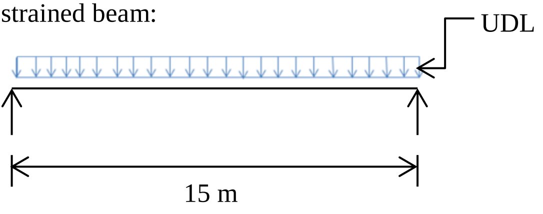
Characteristic value for accidental variable action, $\psi_2 = 0.3$

Total action on the steel beam in fire condition, $q_{fi,ED} = 1.0G_k + 0.3Q_k$

$q_{fi,ED} = [\{(1.0 \times 0.83) + (0.3 \times 0.78)\} \times (0.5 \times 7.2)] = 3.83$ kN/m

2.2. Mechanical Analysis

Consider beam to be a simply supported unrestrained beam:



Beam capacity at 20 °C, $M_{pl,y} = w_{pl,y} \, {f_y}/{\gamma_{M1}}$ = 1060000 × 320 = 339200000 Nmm ≈ 339.2 kNm

CALCULATION SHEET	**TITLE:** Deterministic manual calculations – Structural response in fire **DATE:** 27/03/2017		REFERENCE
	MADE BY: O.U. AKAA	**CHECKED BY:** A.K. ABU	

2.2.1. *Beam moment demand in fire condition*

Design moment demand, $M_{fi,ED} = \frac{q_{fi,ED} \times L^2}{8}$

$M_{fi,ED} = \frac{3.83 \times 15^2}{8}$ = **108 kNm**

2.2.2. *Beam moment resistance in fire condition*

Steel member (unprotected steel beam) temperature @ 60mins FRR = 944.60°C

From thermal analysis

Reduction factor for yield strength of steel at temperature, $k_{y,\theta}$ can be determined by:

$k_{y,\theta} = [0.9674(\frac{T_s - 482}{39.19} + 1)]^{-1/3.833} \leq 1$

Buchanan and Abu (2017)

Where: T_s is the temperature in the steel member.

$k_{y,\theta} = [0.9674(\frac{944.60 - 482}{39.19} + 1)]^{-1/3.833} \leq 1$

$k_{y,\theta} = 0.0464$ < 1

CALCULATION SHEET

TITLE: Deterministic manual calculations – Structural response in fire
DATE: 27/03/2017

MADE BY: O.U. AKAA

CHECKED BY: A.K. ABU

REFERENCE

Steel beam load ratio (degree of utilisation), μ_0

$\mu_0 = M_{fi,ED} / M_{pl,y} = 108 / 339.2 = 0.3184$

Steel beam resistant moment, $M_{b,fi,t,RD}$

$M_{b,fi,t,RD} = k_{y\theta}\gamma_{M_{fi}}M_{pl,y} = 0.0464 \times 1.0 \times 339.2 = 15.73$ kNm

$M_{b,fi,t,RD}$ = **15.73 kNm** Here $M_{b,fi,t,RD}$ < beam moment demand; i.e. **15.73KNm < 108 kNm**

Therefore, unprotected steel beam failed in fire, consider suitable steel section or passive fire protection.

Considering a steel beam section of higher size, 839 x 178 x 194UB:

Critical temperature, $\theta_{a,cr}$ = 956 °C; Steel temperature @ 60 min FRR = 944.46 °C; Beam moment capacity = **113.49 kNm > 108 kNm is OK.**

Buckling capacity of fire protected steel beam

Passive fire protection	**Steel beam temp., T_s (°C) @ 60 min FRR**	**Beam resistance, $M_{b,fi,t,RD}$ (kNm)**	**Remark (if < or > 108 kNm)**
13.4mm fibre-calcium silicate board	618.89	136.47	Ok
13.3mm vermiculite spray (high density)	617.97	137.29	Ok
42mm NW concrete (full encasement)	618.69	136.65	Ok
2mm Fire steel 47-1 intumescent coating	620.00	135.50	Ok

APPENDIX 4: DETERMINISTIC MANUAL CALCULATIONS – CASE STUDY STEEL COLUMN RESPONSE IN FIRE

CALCULATION SHEET	**TITLE:** Deterministic manual calculations – Structural response in fire **DATE:** 27/03/2017		REFERENCE
	MADE BY: O.U. AKAA	**CHECKED BY:** A.K. ABU	

1.0. INTRODUCTION

This is a structural fire analysis calculation for the design of an industrial steel portal frame.

The deterministic analysis herein is based on single element design of a steel building case study (Figure 8.2) adapted from Bong (2005). The results from this work will assist the client to design and develop a steel portal framed building for industrial offices in Christchurch, New Zealand.

Eurocodes 0, 1, 3, 3-1-2 and accompanying annex standards were the basic guide for the derivation of characteristic loads, loading combinations and mechanical analysis of the representative steel column of the portal frame in fire condition.

The design fire had been chosen as standard fire (ISO 834). The thermal analysis were carried out on spreadsheets and variation of thicknesses of different applied fire protection products on steel structures were also considered to achieve the best fit thicknesses and maximum temperature in the individual members for a fire resistant rating of 60 min.

The steel temperatures from the thermal analysis were used in the mechanical analysis of the steel column (leg) based on fire limit state in the strength or capacity domain.

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	MADE BY: O.U. AKAA	**CHECKED BY:** A.K. ABU	

2.0. BUILDING DESCRIPTION

A single bay duo-pitch steel portal frame without internal columns, eaves haunch; the external columns are Steel-I-sections without bracing.

2.1. Building Dimension

The floor area of the building is 1200m^2. See the table below for other details:

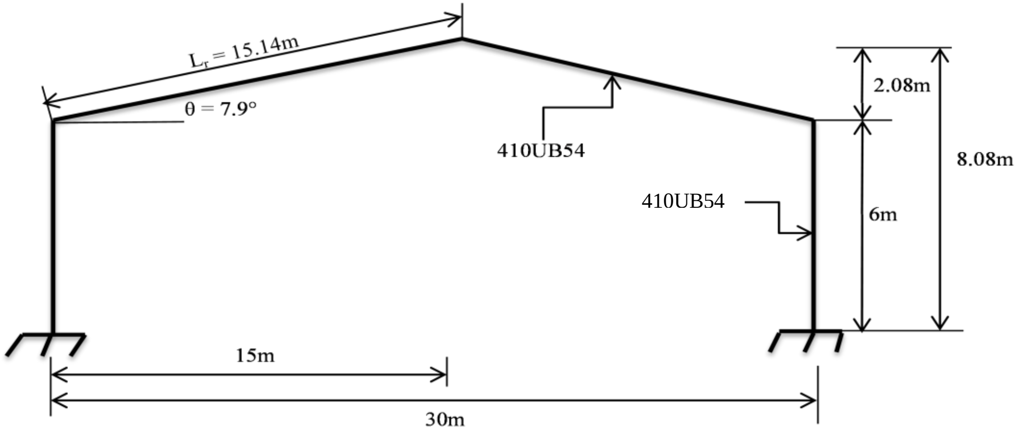
Table 1. Dimension details of the steel portal framed building.

Description	Dimension
Clear span	30m
Internal clear height	6m
Height to frame apex	2.08m
Roof slope	7.9°
Length of building	40m
Frame spacing	7.2m
Space between columns and building ends	2x5.6m
Number of external columns	2x4 columns
Steel beam section (rafter)	AS/NZ 410UB54
Steel column section (leg)	AS/NZ 410UB54

N/B: The choice of clear span and frame spacing had been checked and complies with the required dimensional set out of portal frames in SCI (2016). The beam and column are class 1 hot-rolled steel sections.

CALCULATION SHEET	**TITLE:** Deterministic manual calculations – Structural response in fire **DATE:** 27/03/2017		REFERENCE
	MADE BY: O.U. AKAA	**CHECKED BY:** A.K. ABU	

2.2. Frame Geometry



Using Pythagoras theorem:

Length of rafter, $L_r = \sqrt{2.08^2 + 15^2}$ = 15.14 m or 15140 mm

Steel column (leg) properties:

Depth of column, h = 403 mm

Width of column, b = 178 mm

Flange thickness, t_f = 10.90 mm

Web thickness, t_w = 7.60 mm

Second moment of area about the y-y axis, $I_y = 18.70\ \text{mm}^4$

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Second moment of area about the z-z axis, I_z = 1.02 mm^4

Warping constant, I_w = 394 mm^6

Torsion constant, I_t = 234 mm^4

Plastic section modulus of steel column (y-y axis), $W_{pl,y}$ = 1060 mm^3

Plastic modulus of steel column (z-z axis), $W_{pl,z}$ = 178 mm^3

Radius of gyration (y-y axis), i_y = 165 mm

Radius of gyration (z-z axis), i_z = 385 mm

Area of column cross-section, A = 6890 mm^2

Yield strength of steel @ 20°C, f_y = 320 N/mm^2

3.0. DESIGN OF STEEL COLUMN (410UB54)

3.1. Loading

Self-weight of steel column, $G_{sw} = 0.53$ kN/m → 0.53×6 m = 3.18 kN

Characteristic permanent action on the steel column, G_k = 3.18 kN

3.1.1. *Wind Load*

EN 1991-1-4 Annex A.

a. *Basic value of wind velocity, V_b*

$V_b = (C_{dir} \times C_{season} \times C_{prob}) \times (C_{alt}) \times V_{b,\,map}$

Where: C_{dir} is the direction factor = (1.0) NW

$V_{b,\,map}$ is the fundamental value of basic wind velocity

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$C_{prob} = (\frac{1 - K \times In(1-p)}{1 - K \times In(0.98)})^2$	
Assume design life of New Zealand buildings' is 50 years just same as the UK, then $P = 0.02$ i.e. 1/50. Hence, C_{prob} numerator and denominator cancels out; $C_{prob} = 1$	EN 1991-1-4 § 3.4
But $V_{b0} = V_{b,\ map} \times C_{alt}$.	
For Christchurch, $V_{b,\ map} = 19$ MPh ≈ 8.49 ms^{-1}	google.co.nz
$C_{alt} = 1 + 0.001 \times A$ i.e. for z or $h \leq 10$ m; where A is site altitude	EN 1991-1-4 fig. NA.1 & NA 2a
Here, $z = 8.06$ m; 8.06 m < 10 m	
Altitude (Christchurch), $A = 7$ m	
Then, $C_{alt} = 1 + (0.001 \times 7) = 1.007$	
So, $V_{b0} = 8.49 \times 1.007 = 8.55$ ms^{-1}	
Conservatively, take C_{dir} as 1.0	EN 1991-1-4 Tab NA 1
For C_{season}, we assume a 4-month winter period: June, July, August, September, as worst-case scenario, then $C_{season} = 0.83$	EN 1991-1-4 Tab NA 2
Hence, $V_b = C_{dir} \times C_{season} \times C_{prob} \times V_{b0} = 1.0 \times 0.83 \times 1.0 \times 8.55$	
$V_b = 7.10$ ms^{-1}	
b. *Basic velocity pressure, q_b*	
Basic velocity pressure is determined thus: $q_b = ½ \times \rho_{air} \times V_b^2$	EN 1991-1-4 § 4.5 Eqn. 4.10
The density of air, ρ_{air} is taken as 1.25 kg/m^3	
$q_b = 0.5 \times (1.25 \times 9.81) \times 7.10^2 = 309.08$ kN/m^2	

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c. *Peak pressure, $q_{p\,(z)}$*

Peak pressure is determined thus: $q_{p\,(z)} = [1 + (7 \times I_{v(z)} \times \frac{1}{2}\rho \times V_{m}{}^{2}{}_{(z)}]$

EN 1991-1-4 § 4.5 Eqn. 4.8

Where: $V_{m\,(z)}$ is the mean wind velocity; and

I_v is turbulence intensity.

$V_{m\,(z)} = C_{r\,(z)} \times C_{o\,(z)} \times V_b$

Here, $C_{o\,(z)}$ is orographic factor and $C_{r\,(z)}$ is roughness factor

$C_{r\,(z)} = K_T \times In\left(\frac{Z}{Z_o}\right)$ for $Z_{min} \leq Z \leq Z_{max}$

Where: Z_o is the roughness length; and

K_T is the terrain factor, depending on roughness length, Z_0

EN 1991-1-4 § 4.3.2 Tab 4.1

But, $C_{r\,(z)} = C_{r\,(Zmin)}$ for $Z \leq Z_{min}$

Given z = 8.08m; Z_{min} for the site in Christchurch = 10m, so $Z < Z_{min}$

Terrain factor is determined thus: $K_T = 0.19 \times \left(\frac{Z_0}{Z_{IV}}\right)^{0.07} \approx 0.19 \times \left(\frac{1.0}{1.0}\right)^{0.07} = 0.19$

Note: Z_0 and Terrain IV (Z_{IV}) = 1.0 from Eurocode.

Hence, $C_{r\,(z)} = 0.19 \times In\left(\frac{Z}{Z_o}\right) = 0.19 \times \text{In}\left(\frac{8.08}{1}\right) = 0.19 \times 2.089$

$C_{r\,(z)} = 0.397 \rightarrow C_{r\,(z)} = C_{r\,(Zmin)}$ for $Z < Z_{min}$

EN 1991-1-4 § NA 2.13

Note: Orographic factor, $C_{o\,(z)}$ is not considered in this calculation due to site location in Christchurch. Therefore, $C_{o\,(z)}$ is taken as 1.0.

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Then, mean wind velocity, $V_{m\,(z)} = 0.397 \times 1.0 \times 7.10 = 2.82\ \text{ms}^{-1}$

Turbulence intensity, $I_v = \frac{K_1}{C_{o(z)} \times In(\frac{Z}{Z_0})}$ for $z_{min} \leq Z \leq z_{max}$

EN 1991-1-4 § 4.4 Eqn. 4.7

Where: K_1 is the turbulence factor, recommended as 1.0;

z_{max} is taken as 200 m; recall: h = z = 8.08m → $z < z_{max}$

So, $I_{v\,(z)} = \frac{1}{1 \times In(\frac{8.08}{1})} = 0.48$

Hence, peak velocity pressure, $q_{p\,(z)} = [1 + (7 \times 0.48 \times 0.5 \times 1.25 \times 9.81 \times 2.82^2))]$

$q_{p\,(z)} = 164.83\text{N/m}^2 \approx 0.1648\ \text{kN/m}^2$

$q_{p(z)} = 0.165\ \text{kN/m}^2$

d. *External wind pressure, W_e*

External wind pressure is determined thus: $W_e = q_p \times (Z_e) \times C_{pe}$

EN 1991-1-4 § 5.2 Eqn. 5.1

Where: Z_e is the reference height for the external pressure;

C_{pe} is the pressure coefficient for the external pressure depending on the size of the loaded area.

Recall: Bong (2005) portal frame, loaded area = 30 × 40 = 1200m^2

So; C_{pe} is taken as C_{pe10} as loaded area for the building is > 10m^2

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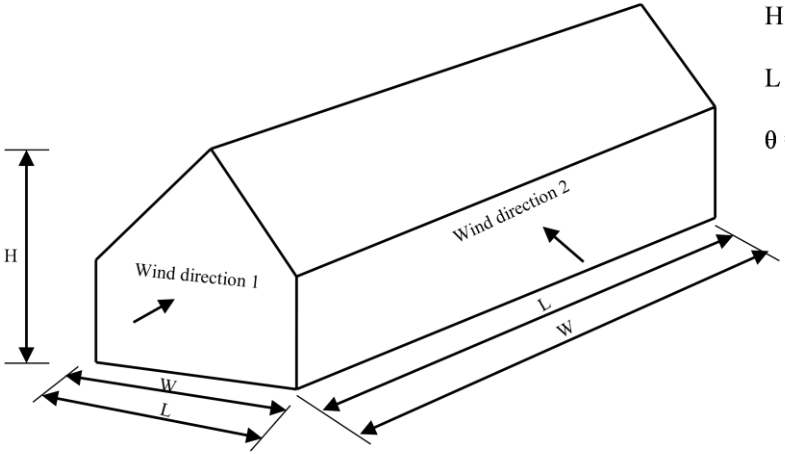

H = h, H = 8.08m

L = 40m = d, W = 30m

θ =7.90°

Here, we consider wind blows in two directions on vertical walls.

EN 1991-1-4 § 7.2

<u>Data for wind direction 1:</u>

H = 8.06 m, b = W b = 30 m; hence, h < b

<u>Data for wind direction 2:</u>

h = 8.06 m, b = L, b = 40 m; hence h < b.

For consider only wind direction 1, given the location of column (leg) being analysed:

$\frac{h}{d} = \frac{8.06}{40} = 0.202$;

EN 1991-1-4
Fig. 4.5

Then, determine e: = min (b or 2h)

e = min (30m or 2 × 8.08m = 16.16m) → e = 16 → e < d

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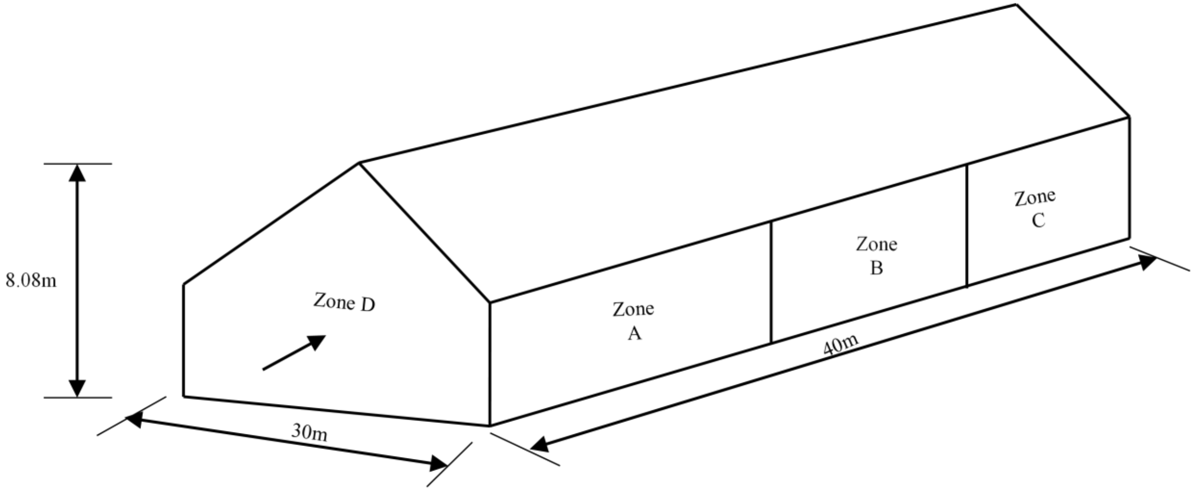
Hence, there will be zones A, B and C on the side wall. Since, 0.202 < 0.25, then values for Cpe10 are:

Cpe10 Zone A = -1.2, Cpe10 Zone B = -0.8, Cpe10 Zone C = -0.5, Cpe10 Zone D = 0.71, Cpe10 Zone E = -0.3.



Given that a representative steel column (leg) a Zone D is being analysed, the determined pressure coefficient for Zone D is used.

Hence, the external (incoming) wind action on the column at Zone D is determined thus:

$W_e = 6890\ \text{m}^2 \times 0.165\ \text{kN/m}^2 \times 0.71 = 807.16\ \text{kN}$

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3.1.2. *Action on steel column (leg)*

Characteristic value for accidental variable action, $\psi_2 = 0.3$

Design effect of actions on the steel column in fire condition, $E_{fi,ED} = 1.0G_k + 0.3Q_k$

$E_{fi,ED} = [(1.0 \times 3.18) + (0.3 \times 807.16)]$

$E_{fi,ED} =$ **245 kN**

3.2. Mechanical Analysis (Fixed-Fixed End Conditions)

Steel member (unprotected steel column) temperature @ 60mins FRR = 940.04°C

From thermal analysis

Reduction factor for yield strength of steel at temperature, $k_{y,\theta}$

Buchanan and Abu (2017)

$$k_{y,\theta} = [0.9674(\frac{T_s - 482}{39.19} + 1)]^{-1/3.833} \leq 1$$

Where: T_s is the temperature in the steel member.

$$k_{y,\theta} = [0.9674(\frac{940.04 - 482}{39.19} + 1)]^{-1/3.833} \leq 1$$

$k_{y,\theta} = 0.052$ < 1

3.2.1. *Capacity of unprotected steel column in fire condition*

The design buckling resistance of column in fire condition, $N_{b,fi,t,RD}$ is determined thus:

EN 1991-1-2 § 4.2.3.2
Eqn. 4.5

$N_{b,fi,tRD} = \chi_{fi} A\, k_{y,\theta}\, f_y / \gamma_{M,fi}$

Where: χ_{fi} is the reduction factor for flexural buckling in the fire design situation;

$k_{y,\theta}$ is the reduction factor for the yield strength of steel at the steel temperature θ_a reached at time, *t*.

Non dimensionless slenderness in ambient temp (buckling about y-y axis), Δ_y

EN 1991-1-1

The non-dimensionless slenderness, $\Delta_y = \frac{\lambda_{cr}}{i}\frac{1}{\pi}\sqrt{\frac{f_y}{E}}$

Where: λ_{cr} is the buckling length in the buckling plane considered and *i* is the radius of gyration about the relevant axis being considered. Here λ_{cr} = 0.7*L* = (0.7 × 6000) = 4200 mm (for fixed end condition).

So, $\Delta_y = \frac{4200}{165} \times \frac{1}{3.142}\sqrt{\frac{320}{210000}}$ = 03162 ≈ 0.316

EN 1991-1-2 § 4.2.3.2
Eqn. 4.7

Normalised slenderness (temperature-based), $\Delta_{y,\theta}$

$$\Delta_{y,\theta} = \Delta[\sqrt{k_{y\theta}/k_{E\theta}}]^{0.5}$$

$k_{E,\theta}$ is the reduction factor for the slope of the linear elastic range. $k_{E,\theta}$ is obtained by linear interpolation from EN 1993-1-2 Table 3.1 using the steel temperature determined from the thermal analysis.

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$k_{E,\theta}$ = $\frac{(940.04-900)\times(0.0450-0.0675)}{(1000-900)}+(0.0675)=0.058$

$$\Delta_{y,\theta}=0.316\times[\sqrt{0.052/0.058}]^{0.5}$$ = 0.298

EN 1991-1-2
§ 4.2.3.2

Imperfection factor, α

$$\alpha=0.65\sqrt{235/f_y}=0.65\sqrt{235/320}$$

So, α = 0.557

EN 1991-1-2
§ 4.2.3.

Value to determine reduction, φ_θ

$$\varphi_\theta=\frac{1}{2}[1+\alpha\Delta_\theta+\Delta_\theta{}^2]=\frac{1}{2}[1+0.557\times0.298+0.298^2]$$

φ_θ = 0.628

Then, reduction factor for flexural buckling in fire design situation, $\chi_{,fi}$ is determined thus:

$$\chi_{fi}=\frac{1}{\varphi_\theta+\sqrt{\varphi_\theta{}^2-\Delta_\theta{}^2}}=\frac{1}{0.628+\sqrt{0.628^2-0.298^2}}=0.848$$

$\chi_{y,fi}$ = 0.848. However, reduction factor for buckling in the z-z direction, $\chi_{z,fi}$ was determined as 0.363. So we take minimum $\chi_{,fi}$ = **0.363**

CALCULATION SHEET	**TITLE:** Deterministic manual calculations – Structural response in fire **DATE:** 27/03/2017		REFERENCE
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Hence, the design buckling resistance of column in fire condition, $N_{b,\,fi,t,RD}$ is thus:

$N_{b,fi,t,RD}$ = 0.363 × 6890 × 0.052 × 320/1 = 41617.805 N

$N_{b,fi,t,RD}$ ≈ **42 kN**

42 kN < 245 kN i.e. $N_{b,fi,t,RD} < E_{fi,ED}$ is not OK.

Therefore, unprotected steel column failed in fire, consider suitable steel section or passive fire protection.

Considering a steel section of higher size, 533 x 312 x 182UB:

Steel temperature @ 60 min FRR = 940.04 °C; Column buckling resistance = **252.49 kN > 245 kN is OK.**

Design buckling resistance of fire protected steel column (leg)

Passive fire protection	**Steel temperature, T_s (°C) @ 60 min FRR**	**Buckling resistance, $N_{b,fi,t,RD}$ (kN)**	**Remark (if < or > 245 kN)**
Fibre-calcium silicate board, BST	549.54	374.96	Ok
Vermiculite spray (high density), SCM	549.39	375.29	Ok
Normal Weight concrete (full encasement), CES	549.79	374.38	Ok
Intumescent coating, ITC	550.00	375.01	Ok

APPENDIX 5: CASE STUDY – FIRE DESIGN STAKEHOLDER ENGAGEMENT DOCUMENTS AND JUDGEMENT MATRICES

DEPARTMENT OF CIVIL AND NATURAL RESOURCES ENGINEERING

IDENTIFICATION AND EXTRACTION OF STAKEHOLDER OPINIONS IN STEEL STRUCTURAL FIRE DESIGN

STAKEHOLDER DETAILS

NAME: ……………………………………………………………………………………

POSITION/LEVEL/DESIGNATION: ………………………………………………… (E.g. Fire engineer)

RESEARCH GOAL:

To select the most suitable fire protection option for structural fire design of a steel portal framed building for fully developed fires.

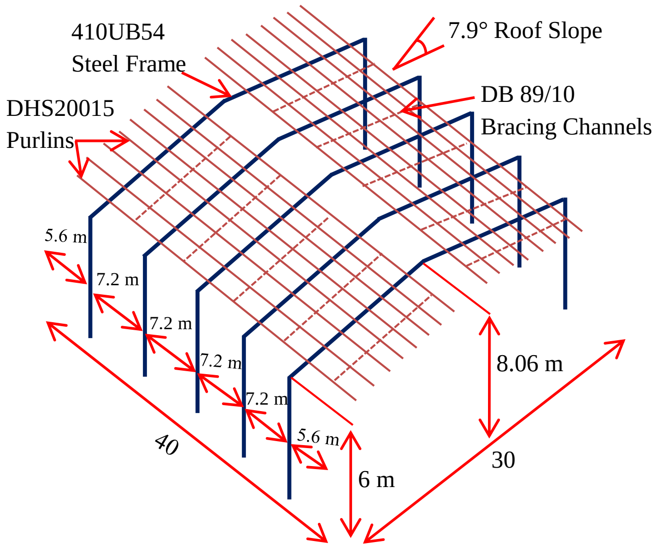


Fig. 1. Case study building – Steel portal frame

9	***7***	***5***	***3***	***1***
Extremely important	***Strongly important***	***Moderately important***	***Slightly important***	***Not significant***

Use 2, 4, 6, and 8 for compromise ratings accordingly

Fig. 2. Goal-rating scale

INITIALS

Fire Design Stakeholder Weighting

Exercise Question 1:

Rate the fire design stakeholders in the table with respect to their influence/importance to structural fire design decision-making.

STRUCTURAL FIRE DESIGN DECISION-MAKING	Rating
Architects	
Building consent authorities	
Fire engineers	
Fire service	
Structural engineers	

INITIALS

Case Study Goal-Rating Exercise

Exercise Question 1:

Rate the criteria with respect to the research goal.

GOAL	Rating
Economy	
Safety	
Environmental	
Societal	

Exercise Question 2:

Given the research goal, rate the criteria in each table with respect to the highlighted parent criterion.

ECONOMY	Rating
Constructability	
Business continuity	
Minimum material use	

SAFETY	Rating
Structural fire resistance	
Pre-fire building resilience	
Fire-fighting operations	
Fire spread beyond building	
Maintainability	

ENVIRONMENTAL	Rating
Environmental sustainability	
Environmental act/HSNO compliance	

SOCIETAL	Rating
Building aesthetics	
Building regulation approval	
Health & safety	
Post-fire building resilience	

INITIALS

Exercise Question 3:

Given the research goal, rate the criteria in each table with respect to their importance to the highlighted criterion.

STRUCTURAL FIRE RESISTANCE	Rating
Pre-fire building resilience	
Fire-fighting operations	
Fire spread beyond building	
Maintainability	

FIRE SPREAD BEYOND BUILDING	Rating
Structural fire resistance	
Pre-fire building resilience	
Fire-fighting operations	

FIRE-FIGHTING OPERATIONS	Rating
Structural fire resistance	
Pre-fire building resilience	
Fire spread beyond building	
Maintainability	

BUILDING REGULATION APPROVAL	Rating
Health and safety	
Post-fire building resilience	

ENVIRONMENTAL SUSTAINABILITY	Rating
Structural fire resistance	
Pre-fire building resilience	
Post-fire building resilience	

MAINTAINABILITY	Rating
Building aesthetics	
Health and safety	
Post-fire building resilience	

BUILDING REGULATION APPROVAL	Rating
Pre-fire building resilience	
Effects on fire-fighting operations	
Maintainability	

FIRE SPREAD BEYOND BUILDING	Rating
Environmental act/HSNO compliance	
Environmental sustainability	

MAINTAINABILITY	Rating
Environmental sustainability	
Environmental act/HSNO compliance	

INITIALS

BUILDING REGULATION APPROVAL	Rating
Environmental sustainability	
Environmental act/HSNO compliance	

Exercise Question 4:

Rate the criteria in each table with respect to their importance to selecting the highlighted fire protection option.

INTUMESCENT COATING	Rating
Constructability	
Business continuity	
Minimum material use	

BOARD SYSTEMS	Rating
Constructability	
Business continuity	
Minimum material use	

CONCRETE ENCASEMENT OF STEEL (PARTIAL OR FULL)	Rating
Constructability	
Business continuity	
Minimum material use	

SPRAYED-ON CEMENT-BASED MATERIAL ON STEEL	Rating
Constructability	
Business continuity	
Minimum material use	

UNPROTECTED STEEL	Rating
Constructability	
Business continuity	
Minimum material use	

INITIALS

Exercise Question 5:

Rate the fire protection option in each table with respect to their importance to the highlighted criterion.

BUSINESS CONTINUITY	Rating
Intumescent coating	
Board systems	
Concrete encasement of steel (full or partial)	
Sprayed on cement-based material	
Unprotected steel	

BUILDING AESTHETICS	Rating
Intumescent coating	
Board systems	
Concrete encasement of steel (full or partial)	
Sprayed on cement-based material	
Unprotected steel	

HEALTH AND SAFETY	Rating
Intumescent coating	
Board systems	
Concrete encasement of steel (full or partial)	
Sprayed on cement-based material	
Unprotected steel	

POST-FIRE BUILDING RESILIENCE	Rating
Intumescent coating	
Board systems	
Concrete encasement of steel (full or partial)	
Sprayed on cement-based material	
Unprotected steel	

ENVIRONMENTAL SUSTAINABILITY	Rating
Intumescent coating	
Board systems	
Concrete encasement of steel (full or partial)	
Sprayed on cement-based material	
Unprotected steel	

ENVIRONMENTAL ACT/HSNO COMPLIANCE	Rating
Intumescent coating	
Board systems	
Concrete encasement of steel (full or partial)	
Sprayed on cement-based material	
Unprotected steel	

Case Study - Fire Design Stakeholder Paired Judgement Matrices:

Stakeholder 1 – Building consent authority (BCA)

Decision Goal	Environmental	Safety	Societal	Priority scores
Environmental	1.0000	0.1111	0.1250	0.0544
Safety	9.0000	1.0000	2.0000	0.5278
Societal	8.0000	0.5000	1.0000	0.4178

Economy	CA	BC	MMU	Priority scores
CA	1.0000	9.0000	9.0000	0.8182
BC	0.1111	1.0000	1.0000	0.0909
MMU	0.1111	1.0000	1.0000	0.0909

Environmental	ES	EAC	Priority scores
ES	1.0000	1.0000	0.5000
EAC	1.0000	1.0000	0.5000

Safety	SFR	PBR1	FFO	FSB	MA	Priority scores
SFR	1.0000	9.0000	5.0000	2.0000	8.0000	0.4071
PBR1	0.1111	1.0000	0.2000	0.1250	0.5000	0.0315
FFO	0.2000	5.0000	1.0000	0.2500	4.0000	0.1702
FSB	0.5000	8.0000	4.0000	1.0000	7.0000	0.3339
MA	0.1250	2.0000	0.2500	0.1429	1.0000	0.0573

Stakeholder 2 – Fire engineer (FE)

Decision Goal	Environmental	Safety	Societal	Priority scores
Environmental	1.0000	0.2000	1.0000	0.1429
Safety	5.0000	1.0000	5.0000	0.7143
Societal	1.0000	0.2000	1.0000	0.1429

Economy	CA	BC	MMU	Priority scores
CA	1.0000	3.0000	1.0000	0.4286
BC	0.3333	1.0000	0.3333	0.1429
MMU	1.0000	3.0000	1.0000	0.4286

Environmental	ES	EAC	Priority scores
ES	1.0000	0.1111	0.1000
EAC	9.0000	1.0000	0.9000

Safety	SFR	PBR1	FFO	FSB	MA	Priority scores
SFR	1.0000	1.0000	0.1429	0.1429	0.3333	0.0479
PBR1	1.0000	1.0000	0.1429	0.1429	0.3333	0.0479
FFO	7.0000	7.0000	1.0000	1.0000	5.0000	0.3843
FSB	7.0000	7.0000	1.0000	1.0000	5.0000	0.3843
MA	3.0000	3.0000	0.2000	0.2000	1.0000	0.1354

Stakeholder 3 – Fire service personnel (FSP)

Decision Goal	Environmental	Safety	Societal	Priority scores
Environmental	1.0000	0.5000	1.0000	0.2500
Safety	2.0000	1.0000	2.0000	0.5000
Societal	1.0000	0.5000	1.0000	0.2500

Economy	CA	BC	MMU	Priority scores
CA	1.0000	5.0000	5.0000	0.7143
BC	0.2000	1.0000	1.0000	0.1429
MMU	0.2000	1.0000	1.0000	0.1429

Environmental	ES	EAC	Priority scores
ES	1.0000	0.5000	0.3333
EAC	2.0000	1.0000	0.6667

Safety	SFR	PBR1	FFO	FSB	MA	Priority scores
SFR	1.0000	3.0000	6.0000	7.0000	3.0000	0.4134
PBR1	0.3333	1.0000	4.0000	5.0000	1.0000	0.2343
FFO	0.1667	0.2500	1.0000	2.0000	0.2500	0.0758
FSB	0.1429	0.2000	0.5000	1.0000	0.2000	0.0422
MA	0.3333	1.0000	4.0000	5.0000	1.0000	0.2343

Stakeholder 4 – Structural engineer (SE)

Decision Goal	Environmental	Safety	Societal	Priority scores
Environmental	1.0000	0.3333	0.3333	0.1429
Safety	3.0000	1.0000	1.0000	0.4286
Societal	3.0000	1.0000	1.0000	0.4286

Economy	CA	BC	MMU	Priority scores
CA	1.0000	7.0000	1.0000	0.4667
BC	0.1429	1.0000	0.1429	0.0667
MMU	1.0000	7.0000	1.0000	0.4667

Environmental	ES	EAC	Priority scores
ES	1.0000	0.5000	0.3333
EAC	2.0000	1.0000	0.6667

Safety	SFR	PBR1	FFO	FSB	MA	Priority scores
SFR	1.0000	0.2000	1.0000	1.0000	0.2000	0.0769
PBR1	5.0000	1.0000	5.0000	5.0000	1.0000	0.3846
FFO	1.0000	0.2000	1.0000	1.0000	0.2000	0.0769
FSB	1.0000	0.2000	1.0000	1.0000	0.2000	0.0769
MA	5.0000	1.0000	5.0000	5.0000	1.0000	0.3846

Case Study - Weighted Stakeholder Scenario Gat-Synthesis

(a) Normalised design decision matrix

	CA	BC	MMU	ES	EAC	SFR	PF1	FFO	FSB	MA	BA	BRA	HS	PF2	FPOC	FPFP
BST	0.550	0.440	0.141	0.241	0.528	0.447	0.541	0.503	0.605	0.411	0.519	0.447	0.348	0.404	0.135	0.244
CES	0.141	0.440	0.130	0.256	0.543	0.447	0.660	0.551	0.625	0.481	0.343	0.447	0.328	0.351	0.981	0.140
ITC	0.370	0.652	0.490	0.294	0.215	0.447	0.318	0.394	0.308	0.492	0.396	0.447	0.354	0.722	0.122	0.537
SCM	0.167	0.374	0.342	0.241	0.365	0.447	0.176	0.379	0.283	0.276	0.149	0.447	0.204	0.394	0.013	0.239
UPS	0.716	0.221	0.779	0.856	0.497	0.447	0.374	0.379	0.261	0.531	0.659	0.447	0.777	0.193	0.070	0.758

(b) Weighted design decision matrix

	CA	BC	MMU	ES	EAC	SFR	PF1	FFO	FSB	MA	BA	BRA	HS	PF2	FPOC	FPFP
BST	0.310	0.049	0.046	0.009	0.061	0.042	0.057	0.057	0.070	0.060	0.009	0.049	0.041	0.012	0.031	0.056
CES	0.080	0.049	0.042	0.009	0.062	0.042	0.070	0.062	0.073	0.070	0.006	0.049	0.039	0.011	0.239	0.034
ITC	0.209	0.073	0.158	0.011	0.025	0.042	0.034	0.045	0.036	0.072	0.007	0.049	0.042	0.022	0.028	0.125
SCM	0.094	0.042	0.111	0.009	0.042	0.042	0.019	0.043	0.033	0.040	0.003	0.049	0.024	0.012	0.002	0.036
UPS	0.404	0.025	0.252	0.031	0.057	0.042	0.040	0.043	0.030	0.077	0.011	0.049	0.092	0.006	0.010	0.111

(c) Hypothesised solution

	CA	BC	MMU	ES	EAC	SFR	PF1	FFO	FSB	MA	BA	BRA	HS	PF2	FPOC	FPFP
IDEAL SOLUTION	0.404	0.073	0.252	0.031	0.062	0.042	0.070	0.062	0.073	0.077	0.011	0.049	0.092	0.022	0.002	0.034
NEGATIVE IDEAL SOLUTION	0.080	0.025	0.042	0.009	0.025	0.042	0.019	0.043	0.030	0.040	0.003	0.049	0.024	0.006	0.239	0.125

(d) Separation from ideal solution

	CA	BC	MMU	ES	EAC	SFR	PF1	FFO	FSB	MA	BA	BRA	HS	PF2	FPOC	FPFP	S_i^*
BST	0.094	0.024	0.206	0.023	0.002	0.000	0.013	0.005	0.002	0.017	0.002	0.000	0.051	0.010	0.029	0.021	0.499
CES	0.324	0.024	0.210	0.022	0.000	0.000	0.000	0.000	0.000	0.007	0.005	0.000	0.053	0.011	0.237	0.000	0.895
ITC	0.195	0.000	0.094	0.021	0.038	0.000	0.036	0.018	0.037	0.006	0.005	0.000	0.050	0.000	0.027	0.091	0.615
SCM	0.310	0.031	0.141	0.023	0.020	0.000	0.051	0.019	0.040	0.037	0.009	0.000	0.068	0.010	0.000	0.002	0.761
UPS	0.000	0.049	0.000	0.000	0.005	0.000	0.030	0.019	0.042	0.000	0.000	0.000	0.000	0.016	0.008	0.077	0.247

(e) Separation from negative ideal solution

	CA	BC	MMU	ES	EAC	SFR	PF1	FFO	FSB	MA	BA	BRA	HS	PF2	FPOC	FPFP	S_i'
BST	0.230	0.025	0.004	0.000	0.036	0.000	0.039	0.014	0.040	0.020	0.006	0.000	0.017	0.006	0.208	0.070	0.715
CES	0.000	0.025	0.000	0.001	0.038	0.000	0.051	0.019	0.042	0.030	0.003	0.000	0.015	0.005	0.000	0.091	0.319
ITC	0.129	0.049	0.116	0.002	0.000	0.000	0.015	0.002	0.006	0.031	0.004	0.000	0.018	0.016	0.211	0.000	0.599
SCM	0.014	0.017	0.069	0.000	0.017	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.006	0.237	0.090	0.453
UPS	0.324	0.000	0.210	0.023	0.032	0.000	0.021	0.000	0.000	0.037	0.009	0.000	0.068	0.000	0.229	0.014	0.967

(f) Closeness to ideal solution (unity)

Fire protection options	S_i^*	S_i'	C_i^*	**Rank**
Board systems (BST)	0.4994	0.7146	*0.5886*	2nd
Concrete encasement of steel (CES)	0.8946	0.3194	*0.2631*	5th
Intumescent coating (ITC)	0.6152	0.5987	*0.4932*	3rd
Sprayed on cement-based material (SCM)	0.7608	0.4532	*0.3733*	4th
Unprotected steel (UPS)	0.2468	0.9671	*0.7967*	1st

APPENDIX 6: WORKED EXAMPLE – GROUP DECISION-MAKING USING GMM+AHP

Consider the group decision-making scenario below:

Decision Goal: "*Choose the most suitable mobile telephone*".

Decision Attributes: *Durability (DB), Economy (EC), and Efficiency (EF).*

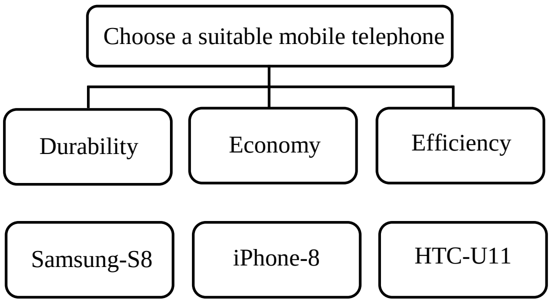
Decision Options: *Samsung-S8 (SS8), iPhone-8 (IP8), HTC-U11 (U11).*

Decision-makers: *2 colleagues having equal weights/influence level in the process*.

Solution

Step 1 – Decision model:

i. Given the decision goal, attributes and options, design a hierarchical tree:



Step 2 – Pairwise comparisons (decision-makers' individual judgements):

i. Given an engagement of the two decision-makers, let the judgement matrices *A* and *B* represent their individual paired judgements on the decision attributes with respect to the goal using Saaty's reciprocal scale Table 3.2.

$$A = \begin{array}{cc} & \begin{array}{ccc} \mathrm{DB} & \mathrm{EC} & \mathrm{EF} \end{array} \\ \begin{array}{c} \mathrm{DB} \\ \mathrm{EC} \\ \mathrm{EF} \end{array} & \begin{pmatrix} 1.00 & 0.25 & 0.33 \\ 4.00 & 1.00 & 2.00 \\ 3.00 & 0.50 & 1.00 \end{pmatrix} \end{array} \qquad B = \begin{array}{cc} & \begin{array}{ccc} \mathrm{DB} & \mathrm{EC} & \mathrm{EF} \end{array} \\ \begin{array}{c} \mathrm{DB} \\ \mathrm{EC} \\ \mathrm{EF} \end{array} & \begin{pmatrix} 1.00 & 0.33 & 6.00 \\ 3.00 & 1.00 & 4.00 \\ 0.17 & 0.25 & 1.00 \end{pmatrix} \end{array}$$

ii. Let matrices C_1, D_1, and E_1, represent the paired judgements on the decision options with respect to *Durability*, *Economy* and *Efficiency* respectively from decision-maker-1 and C_2, D_2 and E_2 for the same qualitative attributes from decision-maker-2:

***Durability* (DB)**

$$C_1 = \begin{array}{cc} & \begin{array}{ccc} \text{SS8} & \text{IP8} & \text{U11} \end{array} \\ \begin{array}{c} \text{SS8} \\ \text{IP8} \\ \text{U11} \end{array} & \begin{pmatrix} 1.00 & 0.50 & 1.00 \\ 2.00 & 1.00 & 2.00 \\ 1.00 & 0.50 & 1.00 \end{pmatrix} \end{array}$$

***Economy* (EC)**

$$D_1 = \begin{array}{cc} & \begin{array}{ccc} \text{SS8} & \text{IP8} & \text{U11} \end{array} \\ \begin{array}{c} \text{SS8} \\ \text{IP8} \\ \text{U11} \end{array} & \begin{pmatrix} 1.00 & 5.00 & 5.00 \\ 0.20 & 1.00 & 1.00 \\ 0.20 & 1.00 & 1.00 \end{pmatrix} \end{array}$$

***Efficiency* (EF)**

$$E_1 = \begin{array}{cc} & \begin{array}{ccc} \text{SS8} & \text{IP8} & \text{U11} \end{array} \\ \begin{array}{c} \text{SS8} \\ \text{IP8} \\ \text{U11} \end{array} & \begin{pmatrix} 1.00 & 1.00 & 5.00 \\ 1.00 & 1.00 & 5.00 \\ 0.20 & 0.20 & 1.00 \end{pmatrix} \end{array}$$

***Durability* (DB)**

$$C_2 = \begin{array}{cc} & \begin{array}{ccc} \text{SS8} & \text{IP8} & \text{U11} \end{array} \\ \begin{array}{c} \text{SS8} \\ \text{IP8} \\ \text{U11} \end{array} & \begin{pmatrix} 1.00 & 6.00 & 5.00 \\ 0.17 & 1.00 & 0.50 \\ 0.20 & 2.00 & 1.00 \end{pmatrix} \end{array}$$

***Economy* (EC)**

$$D_2 = \begin{array}{cc} & \begin{array}{ccc} \text{SS8} & \text{IP8} & \text{U11} \end{array} \\ \begin{array}{c} \text{SS8} \\ \text{IP8} \\ \text{U11} \end{array} & \begin{pmatrix} 1.00 & 0.25 & 2.00 \\ 4.00 & 1.00 & 5.00 \\ 0.50 & 0.20 & 1.00 \end{pmatrix} \end{array}$$

***Efficiency* (EF)**

$$E_2 = \begin{array}{cc} & \begin{array}{ccc} \text{SS8} & \text{IP8} & \text{U11} \end{array} \\ \begin{array}{c} \text{SS8} \\ \text{IP8} \\ \text{U11} \end{array} & \begin{pmatrix} 1.00 & 3.00 & 1.00 \\ 0.33 & 1.00 & 0.33 \\ 1.00 & 3.00 & 1.00 \end{pmatrix} \end{array}$$

Step 3 – Judgement matrices & Aggregation of individual judgements:

i. Using Geometric Mean Method (GMM), *matrices A and B*, C_1 *and* C_2, D_1 *and* D_2, E_1 *and* E_2 are aggregated using Equation 3.11 considering the decision-makers as equally important. The calculation for matrices *A* and *B* which results to matrix *AB* is shown here thus:

$$AB = \begin{array}{cc} & \begin{array}{ccc} \text{DB} & \text{EC} & \text{EF} \end{array} \\ \begin{array}{c} \text{DB} \\ \text{EC} \\ \text{EF} \end{array} & \begin{pmatrix} 1.00 \times 1.00 & 0.25 \times 0.33 & 0.33 \times 6.00 \\ 4.00 \times 3.00 & 1.00 \times 1.00 & 2.00 \times 4.00 \\ 3.00 \times 0.17 & 0.50 \times 0.25 & 1.00 \times 1.00 \end{pmatrix}^{\mathbf{0.5}} \end{array} = \begin{array}{cc} & \begin{array}{ccc} \text{DB} & \text{EC} & \text{EF} \end{array} \\ \begin{array}{c} \text{DB} \\ \text{EC} \\ \text{EF} \end{array} & \begin{pmatrix} 1.00 & 0.29 & 1.41 \\ 3.46 & 1.00 & 2.83 \\ 0.71 & 0.35 & 1.00 \end{pmatrix} \end{array}$$

Note the *AB* is raised to the power, 0.5, which represents $1/a_p$ in Equation 3.11 used when decision-makers are considered equally important. There are two decision-makers in this case; hence $a_p = 2$, so that ½ = 0.5. If the decision-makers had unequal weights, Matrices *A* and *B* would have been raised to the powers of their respective decision-maker's weight prior to achieving matrix *AB*.

ii. Matrices C_1 and C_2, D_1 and D_2, E_1 and E_2 are determined using the same approach in Step 2 (i), this resulted to aggregated matrices $C_{1,2}$, $D_{1,2}$ *and* $E_{1,2}$ shown below:

***Durability* (DB)**

$$C_{1,2} = \begin{array}{cc} & \begin{array}{ccc} \text{SS8} & \text{IP8} & \text{U11} \end{array} \\ \begin{array}{c} \text{SS8} \\ \text{IP8} \\ \text{U11} \end{array} & \begin{pmatrix} 1.00 & 1.73 & 2.24 \\ 0.58 & 1.00 & 1.00 \\ 0.45 & 1.00 & 1.00 \end{pmatrix} \end{array}$$

***Economy* (EC)** **_Efficiency_ (EF)**

$$D_{1,2}= \begin{array}{cc} & \begin{array}{ccc} \mathrm{SS8} & \mathrm{IP8} & \mathrm{U11} \end{array} \\ \begin{array}{c} \mathrm{SS8} \\ \mathrm{IP8} \\ \mathrm{U11} \end{array} & \begin{pmatrix} 1.00 & 1.12 & 3.16 \\ 0.89 & 1.00 & 2.24 \\ 0.32 & 0.45 & 1.00 \end{pmatrix} \end{array} \qquad E_{1,2}= \begin{array}{cc} & \begin{array}{ccc} \mathrm{SS8} & \mathrm{IP8} & \mathrm{U11} \end{array} \\ \begin{array}{c} \mathrm{SS8} \\ \mathrm{IP8} \\ \mathrm{U11} \end{array} & \begin{pmatrix} 1.00 & 1.73 & 2.24 \\ 0.57 & 1.00 & 1.28 \\ 0.45 & 0.77 & 1.00 \end{pmatrix} \end{array}$$

Step 4 – Prioritise aggregated judgements and check judgement consistency:

i. Using the *'AHP-mean of normalised row values'* approach, the aggregated matrices are weighted, and judgement consistencies are then checked. Below is the calculation for aggregated matrix *AB* which results to the weights of *Durability (DB_w), Economy (EC_w) and Efficiency (EF_w)*:

$$DB_w = \frac{1.00 + 0.29 + 1.41}{1.00 + 0.29 + 1.41 + 3.46 + 1.00 + 2.83 + 0.71 + 0.35 + 1.00} = 0.22$$

$$EC_w = \frac{3.46 + 1.00 + 2.83}{1.00 + 0.29 + 1.41 + 3.46 + 1.00 + 2.83 + 0.71 + 0.35 + 1.00} = 0.61$$

$$EF_w = \frac{0.71 + 0.35 + 1.00}{1.00 + 0.29 + 1.41 + 3.46 + 1.00 + 2.83 + 0.71 + 0.35 + 1.00} = 0.17$$

The weights of the decision attributes are: Durability = 0.22; Economy = 0.61; Efficiency = 0.17.

The summation of the weights must be equal to unity (i.e. 0.22 + 0.61 + 0.17 = 1.00)

ii. To check the consistency ratio of aggregated judgement matrix, *AB*, the weights, DB_w, EC_w and EF_w are normalised thus:

Durability = (1.00 × 0.22) + (0.29 × 0.61) + (1.41 × 0.17) = 0.64;
Economy = (3.46 × 0.22) + (1.00 × 0.61) + (2.83 × 0.17) = 1.85;
Efficiency = (0.71× 0.22) + (0.35 × 0.61) + (1.00 × 0.17) = 0.54.

The normalised weights for each criterion are

Durability = 0.64/0.22 = 2.91;
Economy = 1.85/0.61 = 3.03;
Efficiency = 0.54/0.17 = 3.18

so that the mean (λ_{max}) is

λ_{max} = (2.91 + 3.03 + 3.18) / 3 = 3.04

The consistency index (*CI*) is found using Equation 3.1,

$CI = (3.04 – 3) / (3 - 1) = 0.02$

and thus, the consistency ratio (*CR*), using Equation 3.2 and Table 3.3, is

$CR = 0.02 / 0.58 = 0.034$.

Given CR, 0.034 < 0.10, the decision-makers' judgements on the decision attributes are consistent.

iii. The AHP-prioritisation of aggregated matrices, $C_{1,2}$, $D_{1,2}$ *and* $E_{1,2}$ followed the same procedure in Steps 2 (i) and (ii). The resulting performance scores and consistency ratios are presented below.

Decision Options	**Performance scores $E_{1,2}$ (Durability)**	**Performance scores $F_{1,2}$ (Economy)**	**Performance scores $G_{1,2}$ (Efficiency)**
Samsung-S8 (SS8)	0.50	0.47	0.50
I Phone-8 (IP8)	0.26	0.37	0.28
HTC-U11 (U11)	0.24	0.16	0.22
CR =	*0.01*	*0.01*	*0.00*

***Step 5 – Synthesis (Distributive mode synthesis)*:**

i. In the distributive synthesis mode, $X_{1\text{-}3}$, the performance scores of the options with respect to the decision attributes are multiplied by the calculated weights of the attributes and added up. The distributive synthesis for this example is shown below:

Distributive synthesis mode

$$X_{1\text{-}3} = \begin{array}{cccc} & \text{SS8} & \text{IP8} & \text{U11} \\ \text{DB} & 0.50 \times 0.22 & 0.26 \times 0.22 & 0.24 \times 0.22 \\ \text{EC} & 0.47 \times 0.61 & 0.37 \times 0.61 & 0.16 \times 0.61 \\ \text{EF} & 0.50 \times 0.17 & 0.28 \times 0.17 & 0.22 \times 0.17 \end{array} = \begin{array}{cccc} & \text{SS8} & \text{IP8} & \text{U11} \\ \text{DB} & 0.11 & 0.06 & 0.05 \\ \text{EC} & 0.29 & 0.23 & 0.10 \\ \text{EF} & 0.09 & 0.05 & 0.04 \end{array}$$

$$\begin{array}{cccc} & \text{SS8} & \text{1P8} & \text{U11} \\ \text{DB} & 0.11 & 0.06 & 0.05 \\ & + & + & + \\ \text{EC} & 0.29 & 0.23 & 0.10 \\ & + & + & + \\ \text{EF} & 0.09 & 0.05 & 0.04 \\ \text{Preference scores =} & \mathbf{0.49} & \mathbf{0.34} & \mathbf{0.19} \end{array}$$

Step 6 – Ranking and decision-making:

i. The preference scores are normalised to achieve the ranking order of the competing options, thus:

Total preference scores = 0.49 (SS8) + 0.34 (IP8) + 0.19 (U11) = 1.02

Normalised score for Samsung-S8 (SS8) = 0.49 ÷ 1.02 = 0.48

Normalised score for iPhone-8 (IP8) = 0.34 ÷ 1.02 = 0.33

Normalised score for HTC-U11 (U11) = 0.19 ÷ 1.02 = 0.19

Note the normalised scores must add to up to unity i.e. 0.48 + 0.33 + 0.19 = 1.00.

The ranks of the competing options and the completed decision model are shown below:

Decision Option	Ranking score	Rank
Samsung-S8 (SS8)	0.48	1st
iPhone-8 (IP8)	0.33	2nd
HTC-U11 (U11)	0.19	3rd

From the group decision analysis using GMM+AHP, 'Samsung-S8' is the top-ranked option.