Politechnika Łódzka

PhD Thesis

A SEMI-QUANTITATIVE METHOD FOR THE EVALUATION OF HOLISTIC FIRE STRATEGIES FOR NON-STANDARD PUBLIC BUILDINGS

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Abstract

The Thesis titled "A semi-quantitative method for the evaluation of holistic fire strategies for non-standard public buildings" reflects the 30 years of the Author's experience in the field of fire safety and protection engineering in the UK, Europe, and internationally. It presents key elements of his research and describes a novel semi-quantitative method for the evaluation of holistic fire strategies for non-standard public buildings. This would incorporate an assessment of fire strategy elements, namely, building management, passive fire protection, fire detection, active fire protection systems, and fire-fighting arrangements. The methodology would be applicable to the design process of both new build projects and existing buildings. It can guide the building process from the concept stages through to the construction phase. It provides a proposal for a uniform global solution for both fire strategy formulation and evaluation. The Thesis is written over seven chapters:

Chapter 1 presents an introduction and asserts that the formulation and verification of fire strategies for buildings in different countries do not follow a consistent approach. Even for a single risk building profile, the output strategy can vary considerably. This belief became the Author's motivation for instigating the research presented in this Thesis. The chapter introduces the subject of fire engineering and the concept of fire strategies and provides a state-of-the-art review. It illustrates how fire engineering is unique as a discipline, although its subject matter is, in fact, a combination of many aspects of engineering, management, technical and social sciences, including civil engineering, chemical engineering, environmental engineering, mechanical engineering, and finally safety science and management science.

Chapter 2 examines the development of fire (safety) regulations over time and demonstrates how contemporary "performance-based" fire engineering solutions are increasingly used in preference to the more traditional prescriptive rules. This is particularly the case for more complex building arrangements such as non-standard public buildings. The chapter introduces the term "fire strategy" and how this has been used and understood in the context of national and international fire standards and regulations. One of the objectives behind this Thesis is to develop a methodology that is global rather than nationally based. An analysis of the national fire regulation requirements for seven countries was undertaken to find out if there were commonalities over a number of areas of fire safety specification. It was found that, in many aspects, there was an implicit agreement, whilst in other areas, there were still noticeable variations in the national approach to fire safety.

Chapter 3 introduces the concept of holistic fire strategies and presents a detailed description. The emphasis of the approach is to improve the consistency of both preparation and evaluation of fire strategies. It also discusses the primary objectives as life safety, property protection, business protection & continuity, and environmental protection. Each of these objectives is further divided into four sub-objectives. This idea and the associated diagram is unique in the field of fire engineering and was originally developed by the Author of this Thesis. It is proposed that every fire strategy should consider all 16 sub-objectives for every building project rather than the one or two objectives currently assessed in many countries. This chapter describes how the novel method enables assessment in terms of the suitability to a specific building protection purpose. Furthermore, the topical

issues of sustainability and the increasing use of building information modelling (BIM) are considered as related to the assurance of building fire safety.

Chapter 4 introduces the concept of fire scenario determination and provides an overview of existing methods used for fire safety and fire risk assessment. A new fire risk assessment method for the adopted fire scenario is proposed here. It is based on an enhanced and novel analysis method of the probability of fire ignition and fire growth. The result of the analysis, and the determination of a Scenario Fire Risk Value, allows the selection of the most adverse fire scenarios for any building profile, which will then be used as a basis for further analysis and evaluation of the fire strategy.

Chapter 5 describes the Author's semi-quantitative index method for fire strategy evaluation. It allows for the detailed scoring of eight separate fire safety measures incorporated into every fire strategy. It is a comparative method, allowing the evaluation of solutions proposed for a building's actual fire strategy risk index ($FSRI_{actual}$), with the expected fire risk index given in a baseline fire strategy ($FSRI_{baseline}$). The presented method of assessing the fire strategy was inspired by the UK fire strategies fundamentals developed by the Author in British Standard PAS 911:2007 in combination with the *Max Gretener* risk assessment index method. The evaluation makes use of a seven-stage process:

1. description of the building,
2. analysis of possible fire scenarios and prediction of the worst case scenario,
3. specification of the baseline fire strategy,
4. preliminary analyses for the assessment of the actual fire strategy,
5. evaluation of the actual fire strategy,
6. presentation of the baseline and actual fire strategies on a fire strategy value grid,
7. calculation and analysis of the actual fire strategy risk indices.

The presented method divides the analysis of eight fire safety factors, covering (1) fire prevention and fire spread limitation - organisation and management; (2) control of ignition sources and combustible materials; (3) fire and smoke spread limitation - passive systems; (4) detection and alarm communication; (5) fire suppression; (6) smoke control and evacuation; (7) maintenance of fire precautions and systems; and (8) fire service intervention.

A questionnaire is utilised to allow a detailed understanding of how each of the factors is relevant to the overall fire strategy. This uses a scoring system with a range from 0 to 25 points for each factor. The actual fire strategy is based upon a detailed consideration of those elements currently provided for the building in question. The baseline strategy can be based upon, for example, local/national fire regulations or, alternatively, make use of the Author's table of default values assigned to individual building's risk profiles (as described in a UK standard BS 9999:2018). A detailed summary of the default baseline values for fire strategies based on building risk profiles is given in Annex D.

Additionally, this chapter presents the Author's self-developed default values of weighting factors for baseline fire strategies, relevant to the risk profiles of the building. A mathematical relationship has been devised to allow the calculation of the fire strategy risk index and to make a final assessment of whether the fire protection measures applied in the assessed building provide the required level of fire protection. The results would help determine whether a fire strategy is fit for purpose or further control measures are required.

The proposed methodology allows for a comparison of different fire strategies for a singular building or, alternatively, of similar strategies for different buildings.

Chapter 6 presents a trial of the methodology for three public buildings. The chosen publicly used buildings have all been developed from their original designated use. In the case of the Polish buildings, these evaluations were used, together with the fire expert reports, for obtaining permits to use non-standard solutions in relation to the requirements of the local regulations. The buildings were:

- The City of Culture EC1 in Łódź (Poland) - originally an industrial facility (a power plant), converted in 2015-19 into a cultural and entertainment centre (ZLIII public building) with non-standard complex architecture, and a multi-storey atrium;
- Hotel Castle in Ryn (Poland) - originally a teutonic castle (14th century), rebuilt in the 1990s into a hotel building (public building ZLV) of a non-standard architecture, with a vast covered courtyard intended for use by large groups of people;
- Chelsea Hospital in London (UK) - originally a shopping centre building, rebuilt into a hospital building in 1992 (ZLII public building), with a non-standard architectural layout due to the multi-storey central parts, open passages (formerly shopping arcades).

For each of the above examples, the seven stage process as described in the presented methodology, was undertaken. It included the selection of the most adverse fire scenario for further analysis (described in Chapter 4) and the calculation of the fire strategy risk index (FSRI) for the baseline and actual conditions (Chapter 5). This chapter also provides the results of the supportive analysis, including CFD simulations of fire development and smoke spread. In each case, the actual and expected fire strategy risk index was calculated.

In the case of the EC1 Centre, the analysis showed that the first approach to the fire strategy was acceptable. However, in the case of the Hotel in Ryn and the Chelsea Hospital, the first evaluation showed the need for adjustments to the actual strategy. Once these had been made, the revised results led to a positive conclusion. Annexes A, B, and C present detailed data for all three buildings.

Chapter 7 provides the summary and conclusions. It is concluded that the proposed technique of a fire scenario risk analysis, and the development of a new, semi-quantitative method for determination of the fire strategy risk index was proved to be a useful tool for the formulation of holistic fire strategies and their subsequent evaluation.

As well as annexes A to C, annex D provides a summary of the score ratings developed to create baseline fire strategies based upon a building’s risk profiles. Annex E presents the details of a computer programme created by the Author for the development of fire strategies in accordance with the proposed methodology. The programme is currently available in Polish because it had been used for evaluation by Polish industry. In the future, it is planned to provide the programme in multiple languages.

Streszczenie

Praca zatytułowana "Półilościowa metoda oceny holistycznych strategii przeciwpożarowych dla niestandardowych budynków użyteczności publicznej" odzwierciedla 30-letnie doświadczenie autora w obszarze inżynierii bezpieczeństwa pożarowego zdobyte na arenie międzynarodowej i przedstawia kluczowe elementy jego badań w ramach nowej półilościowej metody oceny holistycznych strategii przeciwpożarowych dla niestandardowych budynków użyteczności publicznej. Metoda ta uwzględnia środki organizacyjne, elementy pasywnej ochrony przeciwpożarowej, systemy wykrywania pożaru oraz aktywne środki ochrony przeciwpożarowej i działania służb ratowniczo-gaśniczych. Znajduje ona zastosowanie w projektowaniu budynków nowych i istniejących. Proponowana procedura prowadzi przez proces budowlany od wstępnej koncepcji do fazy realizacji. Jest ona propozycją jednolitego globalnego rozwiązania zarówno w zakresie formułowania strategii przeciwpożarowych, jak i oceny ich przewidywanego funkcjonowania. Praca składa się z siedmiu rozdziałów:

Rozdział 1 ma charakter wprowadzający. Autor stwierdza w nim, że strategie przeciwpożarowe dla budynków w różnych krajach, ich formułowanie i weryfikacja, nie cechują się spójnym podejściem i nawet dla budynków o takim samym profilu ryzyka, mogą się znacznie różnić. Stało się to motywacją Autora do podjęcia badań przedstawionych w niniejszej pracy. Rozdział ten także omawia ogólnie zagadnienie inżynierii pożarowej i koncepcję strategii przeciwpożarowych oraz przedstawia przegląd literatury przedmiotu. Ilustruje on wyjątkowość i złożoność inżynierii pożarowej, która łączy w sobie wiele dyscyplin zarówno z dziedziny nauk inżynieryjno-technicznych jak i nauk społecznych, w tym między innymi inżynierię lądową, inżynierię chemiczną, inżynierię środowiska, inżynierię mechaniczną, czy wreszcie nauki o bezpieczeństwie i nauki o zarządzaniu.

Rozdział 2 analizuje rozwój przepisów przeciwpożarowych na świecie i obrazuje współczesne rozwiązania inżynierii pożarowej, coraz częściej stosowane alternatywnie do tradycyjnych przepisów nakazowych, w szczególności w przypadku bardziej złożonych obiektów budowlanych i niestandardowych budynków użyteczności publicznej. W tym rozdziale wprowadzono także pojęcie "strategia przeciwpożarowa" i przedstawiono sposób, w jaki jest ono wykorzystywane i interpretowane w krajowych i międzynarodowych normach i przepisach przeciwpożarowych. Jednym z celów pracy jest weryfikacja możliwości opracowania metody globalnej (nie lokalnej - krajowej). Przeprowadzono w tym celu analizę podstawowych wymagań przepisów przeciwpożarowych w sześciu krajach, która dowiodła, że w wielu obszarach wymagań w zakresie bezpieczeństwa pożarowego istnieją pomiędzy nimi duże podobieństwa, a niekiedy nawet pełna zgodność. Potwierdziło to przypuszczenia

Rozdział 3 wprowadza autorskie pojęcie holistycznych strategii przeciwpożarowych i omawia jego szczegóły, ze szczególnym naciskiem na kwestie związane z proponowanym globalnym ujednoliceniem metody oceny tych strategii. Omówiono tu także podstawowe cele strategii przeciwpożarowych, do których należą ochrona życia ludzi, mienia, ciągłości produkcji i środowiska naturalnego. Każdy z tych celów Autor dzieli na cztery cele cząstkowe, w konsekwencji proponując, aby każda strategia przeciwpożarowa uwzględniała wszystkie 16 podcelów dla każdego projektu budowlanego. W rozdziale tym opisano, jak

nowa metoda umożliwia ocenę strategii przeciwpożarowych w aspekcie ich dostosowania do określonego nadrzędnego celu ochrony budynku. Ponadto poruszono tu kwestie spójności proponowanej metody z podejściem rozwoju zrównoważonego, oraz możliwości jej wdrożenia do nowoczesnych technik projektowania przy użyciu metod informatycznych (ang. building information modelling – BIM).

Rozdział 4 wprowadza pojęcie scenariusza pożarowego oraz przedstawia przegląd metod oceny poziomu bezpieczeństwa pożarowego i ryzyka pożarowego budynków. Zaproponowano tu nową metodę oceny ryzyka dla przyjętego scenariusza pożarowego. Opiera się ona na analizie prawdopodobieństwa zapłonu i prawdopodobieństwa rozwoju pożaru w aspekcie przewidywanych skutków jego wystąpienia. Wynik analizy w postaci wartości Scenariuszowego Ryzyka Pożaru (ang. Scenario Fire Risk) pozwala na wytypowanie najbardziej niekorzystnych scenariuszy pożarowych dla danego budynku, które następnie powinny być podstawą do prowadzenia dalszych analiz i oceny strategii przeciwpożarowej.

Rozdział 5 opisuje autorską, półilościową metodę indeksową do oceny strategii przeciwpożarowej. Pozwala ona na dokonywanie oceny poziomu bezpieczeństwa pożarowego budynków w oparciu o ocenę punktową ośmiu podstawowych środków zabezpieczeń przeciwpożarowych, wchodzących w skład strategii przeciwpożarowej. Jest ona metodą porównawczą ponieważ zaproponowana ocena prawidłowości zastosowanych w danym budynku rozwiązań polega na porównaniu wartości indeksu ryzyka strategii przeciwpożarowej rzeczywistej ($FSRI_{actual}$) ze wstępnie przygotowanym poziomem odniesienia, jakim jest indeks ryzyka strategii przeciwpożarowej oczekiwanej ($FSRI_{baseline}$). Przedstawiona metoda oceny strategii przeciwpożarowej została zainspirowana brytyjskimi zasadami tworzenia strategii przeciwpożarowych opracowanymi przez Autora w standardzie PAS 911:2007, w połączeniu z metodą indeksową oceny ryzyka Maxa Gretenera. Przewiduje ona usystematyzowany proces ewaluacyjny przebiegający w siedmiu etapach:

1. opis budynku,
2. analiza możliwych scenariuszy pożarowych i wytypowanie scenariusza najbardziej niekorzystnego,
3. określenie parametrów strategii oczekiwanej,
4. analizy wstępne służące do oceny strategii rzeczywistej,
5. ocena strategii rzeczywistej,
6. prezentacja strategii oczekiwanej i rzeczywistej na siatce wartości strategii przeciwpożarowej,
7. obliczenie i ocena indeksu ryzyka strategii przeciwpożarowej.

Opracowana metoda przewiduje analizę ośmiu środków zabezpieczeń: (1) zapobieganie powstawaniu i rozprzestrzenianiu się pożaru, organizacja i zarządzanie ochroną przeciwpożarową, (2) ograniczenie materiałów palnych i źródeł zapłonu, (3) bierne ograniczenia rozprzestrzeniania się pożaru i dymu, (4) detekcja i sygnalizacja, (5) systemy gaśnicze, (6) wentylacja pożarowa i warunki ewakuacji, (7) dyspozycyjność systemów ochrony przeciwpożarowej oraz (8) działania ratowniczo-gaśnicze. W celu międzynarodowego ujednolicenia oceny tworzonych strategii przeciwpożarowych, w ramach opracowanej metody, dla każdego ze środków zabezpieczeń opracowano listę szczegółowych pytań, które pozwalają na dokonanie jego oceny punktowej w skali od 0 do 25. W ten sposób dokonuje się oceny rzeczywistej strategii przeciwpożarowej. Strategię oczekiwaną można ocenić podobnie, za punkt odniesienia przyjmując na przykład lokalne przepisy przeciwpożarowe lub skorzystać z przygotowanej przez autora tabeli wartości domyślnych przypisanych do poszczególnych profili ryzyka budynków (pojęcie profilu ryzyka budynku zaczerpnięto ze standardu brytyjskiego BS 9999:2018). Szczegółowe zestawienie domyślnych oczekiwanych wartości punktowych strategii przeciwpożarowych opartych o profile ryzyka budynku przedstawiono w Załączniku D. Dodatkowo w rozdziale tym przedstawiono, opracowane przez autora, domyślne wartości współczynników wagowych dla poszczególnych środków zabezpieczeń, które także zostały odniesione do profili ryzyka budynku.

Opisane powyżej wskaźniki i parametry liczbowe strategii przeciwpożarowej powiązane zostały przez autora zależnościami matematycznymi, pozwalającymi na obliczenie indeksu ryzyka strategii przeciwpożarowej, stanowiącego podstawę do dokonania oceny, czy zastosowane w środki zabezpieczeń przeciwpożarowych zapewniają wymagany poziom ochrony budynku w przypadku wystąpienia pożaru. Zaproponowana metoda umożliwia także dokonywanie porównań różnych strategii przeciwpożarowych dla jednego budynku, bądź podobnych strategii w różnych budynkach.

W rozdziale 6 przedstawiono trzy przykładowe analizy strategii przeciwpożarowych wybrane spośród opracowań, jakie w latach 2018-2020 zrealizowano dla budynków użyteczności publicznej w ramach testów przedstawionej metody. Prezentowane przykłady dotyczą budynków, które były przedmiotem przebudowy powiązanej ze zmianą przeznaczenia i jednocześnie posiadały nietypowy, skomplikowany układ architektoniczny, wymagający zastosowania rozwiązań ponadstandardowych i opracowania przedmiotowej oceny strategii ochrony przeciwpożarowej. Opracowania te stanowiły załączniki do sporządzanych ekspertyz pożarowych, które następnie podlegały ocenie władz lokalnych w ramach procedur zmierzających do uzyskania pozwoleń na zastosowanie w nich rozwiązań zamiennych i zastępczych w stosunku do wymaganych przez przepisy. Budynki, które wykorzystano jako przykłady to:

- Centrum Nauki i Techniki EC1 (City of Culture) w Łodzi (Polska) - pierwotnie obiekt przemysłowy (elektrociepłownia), przebudowany w latach 2015-19 na centrum kulturalno-rozrywkowe (budynek użyteczności publicznej ZLIII) o nietypowej architekturze, a w szczególności skomplikowanym geometrycznie, wielokondygnacyjnym atrium;
- Hotel Zamek Ryn w Rynie (Polska) - pierwotnie średniowieczny zamek krzyżacki (XIV w), przebudowany w latach 90-tych na obiekt hotelowy (budynek użyteczności publicznej (ZLV)) o nietypowej architekturze, z rozległym przekrytym dziedzińcem przeznaczonym do użytkowania dla dużych grup osób;
- Szpital Chelsea w Londynie (Wielka Brytania) - pierwotnie centrum handlowe, w roku 1992 przebudowane na budynek szpitalny (budynek użyteczności publicznej ZLII), o nietypowym układzie architektonicznym ze względu na znajdujące się w części centralnej wielokondygnacyjne, otwarte pasaże komunikacyjne (dawniej pasaże handlowe).

Dla każdego z powyższych przykładów, w ramach analizy strategii przeciwpożarowej opracowanej dla wybranych części budynków (najbardziej zagrożonych stref pożarowych) przeprowadzono pełną procedurę, zgodną z opisaną tu nową metodą. Obejmowała ona wybór najbardziej niekorzystnego scenariusza pożaru do dalszej analizy (zgodnie z rozdziałem 4) oraz obliczenia indeksu ryzyka pożarowego strategii przeciwpożarowej FSRI dla warunków bazowych i rzeczywistych (zgodnie z rozdziałem 5). W rozdziale tym przedstawiono także wyniki analiz wstępnych i pomocniczych, w tym symulacji CFD rozwoju pożaru i rozprzestrzeniania się dymu, które następnie posłużyły do dokonania ostatecznej oceny punktowej rzeczywistych strategii przeciwpożarowych. Na koniec dla każdego z przypadków obliczono indeks ryzyka strategii przeciwpożarowej rzeczywistej i oczekiwanej. W przypadku Centrum Nauki i Techniki EC1 analizy wykazały, że opracowana strategia przeciwpożarowa od razu była na zadawalającym poziomie ($FSRI_{actual} \leq FSRI_{baseline}$), natomiast w przypadku Hotelu w Rynie i Szpitala Chelsea pierwsza ocena wykazała konieczność wprowadzenia korekt w stworzonej strategii rzeczywistej i dopiero po uwzględnieniu poprawek uzyskany wynik ewaluacji okazał się być pozytywny. Załączniki A, B i C prezentują szczegółowe dane ocen punktowych odpowiednio do trzech budynków, które stanowiły przykłady projektowe.

Rozdział 7 zawiera podsumowanie i wnioski dotyczące przedstawionej rozprawy doktorskiej oraz przewidywane perspektywy rozwoju zaproponowanej metody. Autor wykazał, iż inżynieria pożarowa jest specjalnością multidyscyplinarną, w skład której wchodzą takie dyscypliny jak inżynieria lądowa, inżynieria chemiczna, inżynieria środowiska, inżynieria mechaniczna, czy wreszcie nauki o bezpieczeństwie i nauki o zarządzaniu. Przedstawiony przegląd norm i przepisów przeciwpożarowych wybranych krajów potwierdził możliwości istnienia globalnej metody tworzenia i oceny strategii przeciwpożarowych. Zaproponowana technika analiz ryzyka scenariuszy pożarowych, pozwala na wyznaczanie najbardziej niekorzystnych scenariuszy pożaru stosowanych dalej do oceny bezpieczeństwa pożarowego budynków. Finalnie, opracowana nowa, półilościowa metoda wyznaczania indeksu ryzyka strategii przeciwpożarowej pozwala na tworzenie holistycznych strategii przeciwpożarowych i ich ocenę.

Praca zawiera 5 załączników. Załączniki A-C przedstawiają zestawienie szczegółowych wartości ocen punktowych strategii przykładowych opisanych w rozdziale 6, natomiast załącznik D przedstawia zestawienie ocen punktowych opracowanych do stworzenia bazy strategii oczekiwanych opartych na profilach ryzyka budynków. Załącznik E prezentuje szczegóły programu komputerowego stworzonego przez Autora do opracowywania strategii przeciwpożarowych, ich prezentowania oraz oceny, zgodnie z zaproponowaną metodyką. Program był dotychczas wykorzystywany do testowania metody tylko na rynku polskim, dlatego podano tu tylko wersję polskojęzyczną. W przyszłości planowane jest jego przetłumaczenie na kolejne języki.

Contents

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a	constant for a particular type of building, related to its occupancy, including the ratio of the number of fires in a period to the number of buildings at risk,
A_b	total area of the building, m^2
b	constant for a particular type of building, related to its occupancy,
C_{fi}	consequences of scenario i,
C_g	consequences of fire growth,
C_{ij}	consequence of multiple losses,
D	diffusion coefficient, m^2/s
E_{DET}	score of Detection and alarm communication [DET],
E_{FB}	score of Fire services intervention [FB],
E_{LIM}	score of Control of ignition sources and combustible materials [LIM],
E_{MAI}	score of Maintenance of fire precautions and systems [MAI],
E_{ORG}	score of Organisation and Management [ORG],
E_{PAS}	score of Fire and smoke spread limitation - passive systems [PAS],
E_{SC}	score of Smoke control and evacuation [SC],
E_{SUP}	score of Fire suppression [SUP],
F_i	sequence frequency,
FHI	fire hazard index,
FHI_{AC}	actual fire hazard index,
FHI_{OPT}	optimal fire hazard index,
Fi	frequency of ignition,
FR	fire risk,
FRI	fire risk index,
g	earth’s gravity, m/s^2
h	thermal penetration coefficient, $W/(m^2{\cdot}K)$
k	thermal conductivity coefficient, $W/(m{\cdot}K)$
M_F	molar mass of fuel, g/mol
M_O	molar mass of oxygen, g/mol
n	total number of scenarios,
p	total pressure, Pa
P_{fi}	probability of occurrence of fire scenario i (per year),
P_g	probability of fire growth,
P_i	probability of fire ignition,
P_{ie}	probability of fire ignition due to the environment,
P_{ip}	probability of fire ignition due to the processes,
PH	potential hazard,
PH_{AC}	actual potential hazard,
PH_{OPT}	optimal potential hazard,
PM	ang. protective measures,
PM_{AC}	actual protective measures,
PM_{OPT}	ang. optimal protective measures,
Q	heat release rate, kW

q_r	thermal radiation vector,
$\dot{q}'''$	quantity of heat per unit of volume, kW/m^3
R_i	total risk,
s	unit normal vector,
SFR_g	scenario Fire Risk growth,
SFR_i	scenario Fire Risk (ignition),
T	temperature, K
t	time, s
u	velocity vector, m/s
W_{DET}	weighting factor of Detection and alarm communication [DET],
W_{FB}	weighting factor of Fire services intervention [FB],
W_{LIM}	weighting factor of Control of ignition sources and combustible materials [LIM],
W_{MAI}	weighting factor of Maintenance of fire precautions and systems [MAI],
W_{ORG}	weighting factor of Organisation and management [ORG],
W_{PAS}	weighting factor of Fire and smoke spread limitation - passive systems [PAS],
W_{SC}	weighting factor of Smoke control and evacuation [SC],
W_{SUP}	weighting factor of Fire suppression [SUP],
$\dot{W}_i'''$	rate of generation of „i” cell per unit of volume, kg/m^3
Y_F	mass fraction of fuel in the mixture, kg/kg
Y_F^I	mass fraction of fuel in fuel stream, kg/kg
Y_i	mass composition of „i” cell, kg/kg
Y_O	mass fraction of oxygen in the mixture, kg/kg
Y_O^∞	mass fraction of oxygen in ambient air, kg/kg
α	fire growth coefficient, kW/s^2
$B(x, \lambda)$	source emissivity,
f	external forces vector (excluding earth's gravity),
I_n	radiation intensity for band “n”, W
$I_b(x)$	source term derived from Planck's function,
I_λ	radiation intensity of the wave length λ,
$\kappa(x, \lambda)$	local absorption coefficient [5], 1/m
ρ	density, kg/m^3
Σ	Stefan-Boltzmann coefficient, W/(m^{2}K^4)
$\sigma(x, \lambda)$	local dispersion coefficient,
τ	viscous stress tensor.

List of the most important other abbreviations

ADB	Approved Document B,
ASET	Available safe escape time,
BS	British Standard,
BSI	British Standards Institution,
CEA	Comité Européen des Assurances,
CEN	Comité Européen de Normalisation,
CFD	Computational fluid dynamics,
EN	European Union,
FDS	Fire Dynamics Simulator,
FIRTO	Fire Insurers Research and Testing Organisation,
FM	Factory Mutual,
FOC	Fire Offices Committee,
IFE	Institution of Fire Engineers,
IFSS	International Fire Safety Standards,
ISO	International Organization for Standardization,
LES	Large eddy simulation,
MBA	Master of Business Administration,
NFPA	National Fire Protection Association,
NIST	National Institute of Standards and Technology,
NZ	New Zealand,
NZFS	New Zealand Fire Service,
PAS	Publicly Available Specification,
PD	Published document,
RSET	Required safe escape time
SFPE	Society of Fire Protection Engineers,
UK	United Kingdom,
UL	Underwriters' Laboratories,
TMA	Tensile membrane action.

1. General Introduction

1.1. Hypothesis and research motivation

Despite the maturity of the science and accepted principles behind fire engineering, it is believed that the application of the discipline for the modern built environment is woefully out of date. These observations follow a career in the national and international fire industry. The key issues identified are:

- There is still not a full understanding of the scope and range of the subject matter outside the industry itself. In reality, fire engineering combines the learnings from many other core disciplines.
- Despite the global approach adopted by architects in forwarding ever more innovative building designs, they continue to be faced with national restrictions when it comes to applying fire safety. This is a distinct barrier to the consistency of approach in building design.
- Fire codes continue to focus on life safety as typically required by national legislation. However, the opportunity to consider wider issues of property, asset, and business protection as well as the protection of the environment continue to be missed. This is particularly relevant to more complex building profiles, such as those designed to be used by the public.

The Author postulates that the current methods of fire strategy formulation and evaluation by third parties , adopted around the world, need not be the status quo. It is believed that a greater level of consistency of approach can be introduced by considering fire strategies on a more holistic basis. Consequently, the research needs to evaluate and conclude a series of related subjects, including;

- A better understanding of the "bones" of fire engineering and the subjects of fire safety and protection.
- A review of the history of fire safety legilsation and standardisation in order to appreciate how and why the current status of the specification fire safety for buildings exists.
- A review of national requirements for fire safety and whether a singular global approach for fire safety and engineering is possible.
- Fire risk and fire scenario determination is typically used around the world to determine appropriate levels of fire safety and protection. Can the methodology be improved?
- Given that there is no current and consistent method for the evaluation of fire strategies, can a system be developed to allow the quantification of *good or bad* fire strategies.

The research presented in this Thesis reflects the 30 years of the Author's experience in the field of fire safety and protection engineering in the UK, Europe, and internationally. An initial hypothesis, developed back in 1996, questioned whether the theory and practice behind the formulation of business strategies could be applied to the world of fire engineering. This was prompted by the Author's studies leading towards an MBA from City University Business School in London, which was completed in 1993. At that time, business theories and strategy were mostly influenced by American expertise, with the natural home of business strategy resting at Harvard Business School, renowned as one of the top establishments for the subject in the world. A key leader in the development of business strategies is Michael E Porter. He is credited as being the founder of modern business strategy and is described as one of the world's most influential thinkers on management and competitiveness. One of his earliest books (1) covered competitive strategy in business. In this publication, he had created a series of analytical models that could be used to evaluate and compare business strategies so that the key features and requirements for a specific business profile could then be developed.

It was postulated that similar models could be created to assist in the development of fire strategies. Early concepts were conceived by the Author and published in 1996 by a UK fire safety journal (2). It was a decade later when the opportunity arose to write a British Standard for fire strategies. The British Standard Specification - PAS 911: Fire strategies – guidance and framework for their formulation was published in 2007. Some of the early fire strategy development models, together with several new ideas, were incorporated into PAS 911.

The original concept behind the development of a holistic methodology leading to this Thesis followed liaison with London Fire Brigade in 2016 (3). They related problems that they faced daily when approving fire strategies for new build or modified public buildings. It was subsequently found that their concerns, and the specific problems they face, are relatively commonplace around the world.

A holistic and consistent framework is being developed to overcome such shortfalls in the currently adopted methods. It is also designed to cover other issues that the Author believes are increasingly important in the modern world of building regulation fire safety, with the belief that they can be interconnected into a single (global) fire strategy methodology.

The approach to the subject matter of this Thesis was initially presented in a book by D. Brzezinska and P. Bryant; *Fire strategies for buildings*, Lodz University of Technology (4) It was inspired by P. Bryant's book *Fire Strategies - Strategic Thinking* (5), Kingfell, London and the British Standard BS PAS 911 covering fire strategies (6). The British Standard was the first published document covering the current concepts as presented in this Thesis.

The book by Brzezinska and Bryant (4) gave a Polish view of the problems associated with building fire strategies and introduced a semi-quantitative methodology for a building's fire safety evaluation. The method was based upon the fire safety objectives designated for a specific building profile and included the scoring of safety measures applied in the fire strategy and calculation of a fire risk index. Given that the main objective of fire protection of public buildings is life safety, the fire strategies would focus on this objective. It is a comparative method in which an actual fire strategy is compared with a baseline strategy, corresponding to the building's risk profile, as defined by national standards such as British Standard BS 9999 (7), or resulting from other national requirements, as appropriate.

The intention was to create a new, uniform, fire strategy evaluation methodology for public buildings. This would incorporate an assessment of structural and internal passive fire protection, active fire detection, and protection systems, and the management of fire safety within the building profiles. The methodology will be applicable to the design process of both new build projects and existing buildings. It will be able to guide the building process from the building design feasibility stages through to the construction phase.

The research presents a detailed description of a new semi-quantitative, holistic method for assessing fire strategies in public buildings. The thesis includes a novel method of assessing fire risk by increasing the number of assessed parameters, the probability of fire ignition via the environment and processes within a given area, as well as the probability of fire growth. A suitably amended risk assessment formula is proposed that can be used for determining suitable fire scenario risks for subsequent evaluation. This analysis is then used to allow for evaluation of a "Fire Strategy Risk Index"; a method of assessing proposed or actual fire strategies against a baseline fire strategy. The formulated methodology has been validated on a selection of operational public buildings, from which the three are presented at the final part of this Thesis:

- EC1 Łódź - City of Culture, Poland;
- A Castle converted to a hotel, Ryn, Poland;
- A Hospital located in Chelsea, London, UK.

1.2. State of the art review

Fire engineering, also referred to as fire *safety* engineering has evolved to the level where it can now be described as a mature discipline. The general scientific principles behind fire ignition and growth are largely understood, although the changing architectural needs for building design requires and will always require ongoing research. The human interaction with fire continues to be studied around the world to assist those involved with ensuring safe evacuation in a fire scenario from an increasing array of building designs – particularly those designated for use by the general public. This is mainly driven by the increasing global acceptance of the principles of a scientific approach for fire safety design of buildings, based upon specified performance objectives. It is hoped by many in the industry that this will gradually replace the more traditional prescriptive fire safety rules of previous decades. Nevertheless, prescription continues to be favored as a means of applying fire safety on a national basis. The basis and reasons for this are covered in the early chapters of this Thesis.

Whilst fires continue to destroy life, property, business, and the environment, there will always be a continuous need to advance both fire science and its application. Everything from new construction methods for building stability in a fire to controlling a fire via the application of water droplets will be the subject of numerous research papers and doctorates, now and into the future. Similarly, the advance of the use of computer models to simulate fire spread using 3D building arrays, to assist fire engineers in developing better fire safety design solutions will continually evolve. As an example of ongoing research concerning fire engineering for public building profiles, here are some relevant articles:

"*Reliability of fire (point) detection system in office buildings in Australia - A fault tree analysis*" (8) assesses the various failure modes of fire detection systems based upon a study of office buildings in Australia. Note that the requirements and rules for fire detection systems tend to be based on more commonly accepted principles globally. Section 2.5 of this Thesis includes an evaluation of national approaches to the specification of fire detection systems.

"CFD study of fire-induced pressure variation in a mechanically-ventilated air-tight compartment" (9). This paper examines the approach to computational fluid dynamics (CFD) simulations of pressure and ventilation flows due to a fire in airtight compartments that use mechanical ventilation. Smoke control systems, particularly those making use of mechanical systems, are increasingly used in more complex building arrangements and sometimes used to provide a trade-off to allow for greater travel distances. This can only be determined by examining smoke movement in local building topology via the use of CFD modelling. This article examines the specific case of airtight compartments, which can be problematic given the absence of makeup supply air to support smoke extraction. CFD analysis play a key role in some of the analysis used for public buildings, as included in Chapter 6.

"Fire Safety Analysis of Building Partition Wall Engineering" (10) provides a review of the factors behind the use of wall partitioning, focusing on public buildings such as shopping malls, office buildings and hotels. Masonry, skeleton (lightweight) and slat (plate) partitioning options are considered. The article also considers the relationship with other systems that are part of the building fire strategy including smoke detection and smoke control. The research is effectively a summary of the considerations when using partition walls as part of the fire strategy (although the term *fire strategy* is not specifically used). Note that the national treatment of passive fire protection in building design is also explored in section 2.5 of this Thesis. The fundamental issues of fire engineering with civil engineering design are considered in the next section (1.3).

"Hospital evacuation: Exercise versus reality" (11) is a Dutch study of evacuation within the often complex environments of a Hospital. Note that this includes an evacuation from all types of emergency scenario. The paper concluded that a test of emergency preparedness tended to benefit by training exercises prior to the event, whereas actual real drills required a different method of evaluation. The key message from the article, however, was that the arrangements for the specific Hospital were successful and required little additional adjustment. The subject of evacuation tends to be a popular choice for many researchers. It considers both the psychology of those evacuated from buildings, with the means of escape arrangements and supporting systems that are required. Today, CFD modelling has also been applied to evacuation analysis, and some modelling programmes can combine fire spread and evacuation evaluation. The issues covered in Hospital fire strategies are introduced in chapter 6 when a Hospital in London is used as one example for the illustration of the methodology proposed by this Thesis.

New and existing buildings are increasingly covered by a document referred to as a fire strategy. A fire strategy is a document that encompasses a range of fire safety management arrangements with active and passive fire protection systems (6). The term has become increasingly used, although is not widely fully understood. It is rare to find a journal article or conference proceedings that specifically covers the term "fire strategy". Chapter 2 provides a detailed overview of how fire strategies are developed.

This Thesis accepts that the current science and engineering behind the subject of fire safety and protection are mature and that there continues to be a need to further develop the discipline as new ideas, concepts, and systems come along. Nevertheless, the prime purpose of this Thesis is to suggest that the *application* of fire safety and protection requires a suitable overhaul. This chapter and the next provides a case to support this notion. The final part of this Thesis introduces a novel concept to assess fire strategies using a semi-quantitative methodology developed from earlier ideas introduced to the fire industry by the Author over twenty years ago.

1.3. Fire engineering - development as a separate and unique engineering discipline

Fire engineering emerged in the early 20th century as a distinct discipline, separate from other engineering groups, due to acknowledgement of the complexities of protecting buildings against an increasing array of fire hazards. Due credit for the early advancement of fire safety and protection must be largely given to the insurance industry and the City of London Insurance Market in particular (12). The Sun Fire Office (13) innovated the control of fire safety for buildings by issuing fire marks (metal plaques identified with the name of the insurer) from 1710. These marks were used to help identify those premises that were insured so that the insurer's fire brigade would attend to a fire impacting on that premises. Formalising such services helped to improve the practice and consistency of firefighting and the idea was quickly taken abroad.

The Fire Offices Committee (FOC) (14) (15) was formed in 1868 by a group of British fire insurers, primarily for the purposes of insurance tariff setting for their insured risks. They were early pioneers in advancing the knowledge of fire safety and control measures to limit their exposure. This included early codes for elements of passive and active fire protection systems such as sprinkler systems and fire detection systems. They also gradually introduced schemes for approving elements of fire protection, from fire walls and linings, to sprinkler and detection systems. This approval involved a technical assessment of components of a system as well as the interaction of such components as part of a system. This usually involved testing to determine compliance with relevant fire standards. At one time, the Insurers even had their own test laboratory – the Fire Insurers Research and Testing Organisation (FIRTO), located in Borehamwood, UK. In 1953, a European insurers' organisation was set up to help develop European rather than national interests (12). The organisation was known as the Le Comité Européen des Assurances (CEA) and is still based in Paris, France. One of their objectives was to standardise a Europe wide response to fire safety, with a focus on property protection. The Author of this Thesis was involved with the development of both FOC and CEA fire safety standards in the early 1980s.

As with the UK, the USA have their own agencies who represent insurers' interests – Factory Mutual (FM) and Underwriters' Laboratories (UL). The origins of FM date back to the 1830s when a mill owner formed his own mutual insurance company with other factory owners (16). Today, FM (16) is a globally recognised property and business insurance company incorporating risk professionals who evaluate and advise on risks, as well as providing test facilities. UL (17) was also formed in the latter part of the nineteenth century via a proposal to create a test laboratory for the benefit of US insurance underwriters. They state that one of their objectives is to promote safe, secure, and sustainable living and working environments for people by the application of science, hazard-based safety engineering, and data acumen. Part of their offering is in the provision of codes and the certification of equipment.

Insurers have played a vital role across nations in helping develop the science and engineering behind the subject of fire engineering. In fact, many of the fire safety codes detailed in this Thesis were influenced by the work of insurance organisations (12).

Fire engineering, as a discipline of study, has only really been acknowledged in the last few decades. It is claimed that the first formal degree course was introduced in the United States in 1903 (18) by the Armour Institute of Technology (later becoming part of the Illinois Institute of Technology). In the same year, the college introduced a core discipline of chemical engineering.

The real advent of formalised education in the subject was in the 1970s and onwards. The University of Edinburgh is well recognised as a focal point for study and attracted eminent names from the time. Fire engineering icons such as Professor David Rasbash, and Professor Dougal Drysdale were both involved with the University (19).

From this point forward, the subject, the science, and engineering behind the subject, have continuously developed with graduate and post-graduate courses now available on an international basis.

The main representative bodies for the profession are the Institution of Fire Engineers (IFE) and the Society of Fire Protection Engineers (SFPE). The IFE (20) was founded in the United Kingdom in 1918 and represents the interests of those practitioners from graduate to chartered engineer level. It is now recognised as an international institution with members from most parts of the world. The SFPE (21) was established in 1950 in the United States and incorporated as an independent organization in 1971. It states that it is the professional society representing those practicing the field of fire protection engineering.

The Author (5) identifies fire engineering as incorporating many engineering disciplines. The story given in this chapter so far reflects that fire engineering is largely well represented, derives from robust bones, and is designed to generate future generations of fire professionals. Nonetheless, those not in the profession may fail to understand how wide the subject is, and how it draws in the knowledge and experience of many other areas of engineering. This can be best illustrated by the diagram given in *Fig. 1* with the following descriptions:

Civil Engineering (22) (23) (24) is neatly described as everything to do with the built environment. As well as the discipline behind the construction of buildings, civil engineers also design roads, railways as well as infrastructures such as water and gas pipelines. A subset of this discipline is structural engineering, which is described as the study of the design of structures and non-structural elements that bear a load. Of critical importance is in understanding how structures respond to fire exposure. Consequently, this is of direct relevance to fire engineering. Furthermore, civil engineering is the main discipline to increasingly forward the use of BIM (Building Information Modelling) as a basis of building design and construction (25) (26). BIM will revolutionise the built environment and will influence the way fire safety and protection, and fire engineering principles are applied. Chapter 3 – section 3.5 describes BIM in more detail.

Mechanical engineering (27) (28) is described as a branch of engineering concerned primarily with the industrial application of mechanics and with the production of tools, machinery, and their products. This is the discipline that applies physics, mathematics, and materials science. It is one of the oldest and broadest of all engineering disciplines. In many ways, mechanical engineering is similar to chemical engineering in that it helps to understand the forces behind fire growth and spread. It is also relevant to control means such as the use of mechanical smoke control systems.

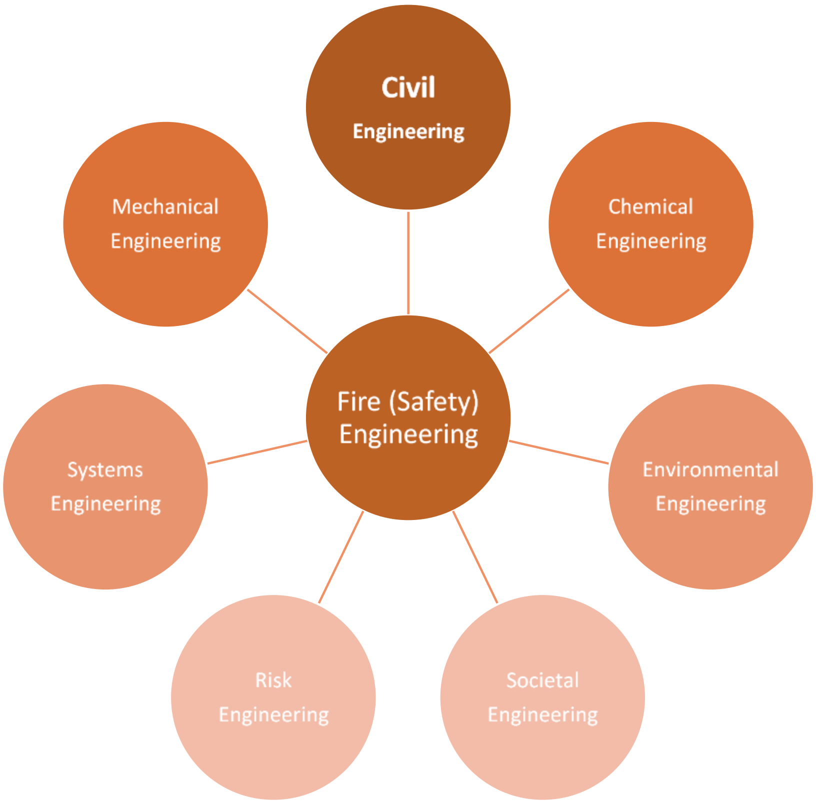


Fig. 1. The interdependency of fire engineering with other engineering disciplines (47).

Chemical engineering (29) (30) is a discipline influencing many areas of technology. Chemical engineers conceive and design processes to produce, transform and transport materials from experimentation in the laboratory to full-scale production. Note that it is the scientific principles behind chemical engineering that are fundamental to the understanding of fire ignition and growth. Furthermore, the engineering discipline is relevant to fire control, particularly when it comes to fire suppression technologies.

Environmental engineering is a discipline with two variants. The most simplistic (31) is to control a working environment for process requirements or for the comfort of people. This covers the use of heating and ventilation systems, amongst other building internal environmental factors. A US (32) description of the discipline of environmental engineering defines it as the application of engineering principles to improve and maintain the environment for the protection of human health, for the protection of nature's beneficial ecosystems, and for environment-related enhancement of the quality of human life. Both understandings are relevant to fire engineering, given that the internal environment of a building can play both a part in fire ignition and growth and in the control measures such as the maintenance of tenable conditions for escape. The wider context of the impact of fire and firefighting on the environment is similarly highly relevant to future applications of fire engineering. The environmental impact on a fire scenario is developed in Chapter 4.

Systems (and industrial) engineering (33) (34) is concerned with the design, improvement, and installation of integrated systems of people, materials, information, equipment and energy. It draws upon specialized knowledge and skill in the mathematical, physical, and social sciences, together with the principles and methods of engineering analysis and design. This is used to specify, predict, and evaluate the results to be obtained from such systems. Fire engineering is an excellent example of a systems engineering approach. The whole purpose of a fire strategy is to consider several factors covering the building, processes and occupancy profiles and provide an integrated set of complementary systems (fire detection, control, suppression, etc.) to satisfy a range of fire scenarios. Fire engineering is an excellent example of a systems engineering approach. The whole purpose of a fire strategy is to consider several factors covering the building, processes and occupancy profiles and provide an integrated set of complementary systems (fire detection, control, suppression, etc.) to satisfy a range of fire scenarios.

Societal engineering (35) is described as the study of the creation and influence of human societies. It is a field of social science dealing with those social dynamics which operate at a local or large-scale level. Social engineering can also be understood philosophically as a deterministic phenomenon where the intentions and goals of architects are aligned with societal requirements. Similarly, fire safety standardization incorporates such aims. The psychology of human behaviour in a fire is a deciding factor in the design of means of escape (5). Note that there is a separate scope of social engineering that is related to internet security which is not relevant to this discussion.

Risk engineering (36) is the application of engineering skills and methodologies to the management of risk. It involves hazard identification, risk analysis, risk evaluation and risk treatment. This is directly relevant to fire risk analysis and scenario determination and is covered in Chapter 4.

In conjunction with the primary disciplines, there are a few secondary disciplines that will impact on fire engineering albeit, not directly. These include electrical/electronic engineering, computer engineering and materials engineering.

Table 1 provides a list of how the primary engineering disciplines can be applied to each of the eight fire safety factors. This makes use of the eight elements, or nodes, of the fire strategy value grid (6). This grid (see *Fig. 2*) is an idea originally developed by the Author to explain how there are eight key elements for each and every fire strategy. Each of these can be separately adjusted to provide for an optimum fire strategy for any given building profile. What can be revealed by *Table 1* is that both chemical and risk engineering play a dominant role in all aspects of a fire strategy.

Note that a derivative of this diagram will be used later as part of the proposed semi-quantitative analysis given in Chapter 5.

Table 1: Core engineering discipline relationship with a fire strategy.

Fire strategy input	**Primary engineering discipline**
Control of ignition sources	Chemical, Risk
Control of combustibles	Chemical, Civil, Risk, Environmental
Fire compartmentation	Chemical, Civil, Risk, Mechanical Systems
Smoke control systems	Chemical, Mechanical, Systems, Environmental, Risk
Automatic fire detection	Chemical, Mechanical, Systems, Environmental, Risk
Automatic fire suppression	Chemical, Mechanical, Systems, Environmental, Risk
Fire service intervention	Chemical, Mechanical, Systems, Environmental, Risk, Societal
First aid fire fighting	Chemical, Environmental, Risk, Societal

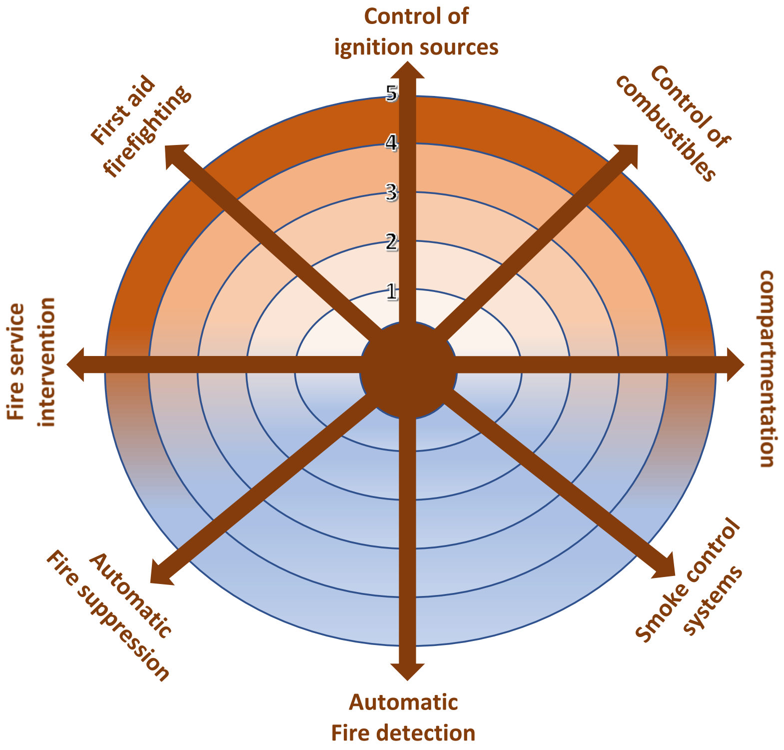


Fig. 2. Fire strategy value grid (6).

Even though there is a close relationship with chemical and risk engineering, fire engineering is most often closely associated with civil (structural) engineering. The connection between the subjects is explicitly understood and can be found in many technical universities where combined fire, and civil, or structural, engineering courses are offered at graduate and post graduate levels. The next section assesses the interdependency between fire engineering and civil engineering.

1.4. Why fire engineering could be regarded as a sub-set of civil engineering

As highlighted in the previous section, the subject of fire engineering is shown to have a degree of dependency on a range of other engineering disciplines. Those who work outside the field may not realise this. It is commonly assumed that a qualified fire engineer will have an in-depth knowledge of every aspect of the subject. Fire engineering is probably unique as a discipline in that it encompasses so many other engineering subjects, as well as sciences outside of engineering, such as human psychology. Consequently, fire safety and engineering specialists tend to have specific areas of expertise within the discipline. For instance, a fire engineer with great levels of expertise in computational fluid dynamics and modelling fire behaviour, may not have the same depth of knowledge in the efficacy of fire sprinkler systems.

The relationship between structural engineering and fire engineering is fully understood within both professions, and one is often seen as a core element of the other. As an example, the primary modules of a combined fire and civil engineering graduate course, taken from an Australian University (37), can assist in explaining the mutual parameters.

Structural engineering covers a range of subjects concerning construction technique and the materials used. A primary component of analysis is in the understanding of shear stresses of both horizontal and vertical components, deflection in beams, truss and frame structures as well as column and beam buckling. The performance of materials such as steel, concrete and timber are an equally important consideration. A notable example of how fire engineering has influenced structural engineering is in the understanding of tensile membrane action (TMA). Typically, designs for steel frame buildings had focused on controlling the temperature of individual steel members rather than considering the structural performance of a building, holistically, in the event of a fire. This typically has required that all structural steel columns and supports are contained within fire resisting cladding or other materials that provide protection in a fire. Wang (38) highlights that the ability of a reinforced concrete slab to "bridge" over damaged loadbearing steel beams is the result of TMA. In such situations, floor slabs can withstand loads many times higher than the design strength of the floor at small deflections. This has significant implications for the necessity of fire resistance and fire protection of steel-framed buildings. Bailey *et a*l (39) have undertaken research for a fire engineering design for multi-storey, steel frame buildings that eliminated the need for extra fire protection for up to 40% of steel floor beams, with significant savings.

Transport and Tunnel Engineering covers road, rail, bridge and airport design as well as the related infrastructure, such as railway stations, airport termini, etc. In some cases, it is the specific considerations of the impact on fire that have most influenced the approach to civil engineering design. One such example within the UK was the introduction of the Sub-surface Railways Act (40) in 1989. This act was published because of the Kings' Cross underground fire in London in 1987 where 31 persons lost their life due to a fire engulfing a sub-surface concourse. This piece of legislation radically updated design criteria for underground railway stations and has been used as a blueprint for metro stations around the world.

The construction of tunnels has been similarly influenced by the need to ensure suitable levels of fire safety and protection. There have been numerous fire incidents in tunnels over recent decades. One notable example, often used to illustrate the critical issues, is that of the Mont Blanc tunnel. This Tunnel is a highway tunnel under the Mont Blanc mountain in the Alps. It links Chamonix, Haute-Savoie, France with Courmayeur, Aosta Valley, Italy. This tunnel experienced a major fire in 1999 (41). A Belgian truck carrying margarine and flour caught fire and stopped almost 7 km into the tunnel. The fire quickly spread to the vehicles behind the truck for over 1 km. The intense heat and smoke filled the entire tunnel section, preventing emergency rescue and firefighting operations. The fire burned for two days and reached temperatures of 1000°C, killing 39 people. Most drivers stayed in or near their vehicles. Those who tried to escape collapsed due to smoke inhalation The CO content in the smoke was reported to raise quickly over 150 ppm within minutes. The fire lead to several changes in tunnel design. Tunnel lining materials were improved. The frequency and availability of "safe areas" was also greatly improved. Given the increase in tunnel building, particularly in Scandinavia, specialist fire safety in tunnel conferences have become extremely popular (42) with new concepts continually being offered to advance tunnel construction criteria.

The next subject is **Geotechnical (Soil) Engineering.** All structures such as buildings, roads, bridges, airports are supported on the ground. The ground characteristics play a vital role in the stability of the building above or below. This subject covers the characterisation and classification of soils and testing procedures. A key determinant is how the soil may be influenced by water. In a major fire, typically thousands of litres of water or foam will be used to fight the fire. Firefighting water run-off is habitually the result, and will completely saturate the soil. This therefore is an important consideration.

1.5. History and impact of fire engineering

It could be said that the subject of fire safety and protection is sufficiently mature that there is not a need to seek fundamental improvement. Fires affecting most building profiles are relatively rare, although residential fires, in terms of frequency, continue to outstrip other building fires. Fatalities caused by fire, or by the effects of fire, are rare. As an example, UK fire statistics has shown a general decline over the last two decades as illustrated in *Fig. 3* (43).

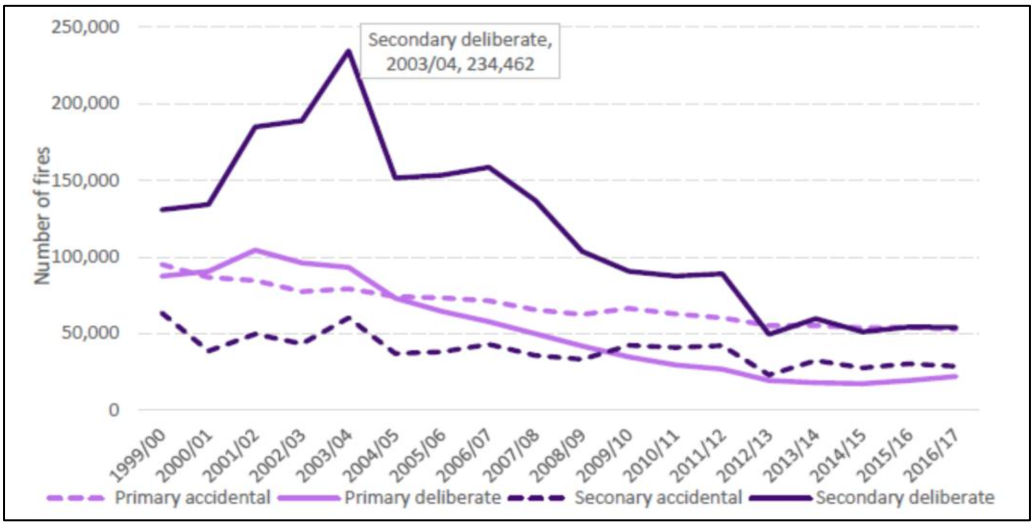


Fig. 3. UK Fire statistics – trend for accidental and deliberate fire (43).

This includes both accidental fires as well as fires caused by deliberate causes such as arson. *Fig. 3* also breaks the statistics down into primary and secondary fire types. *Primary* includes more serious fires that cause harm to people or damage to property. *Secondary* are generally small outdoor fires, not involving people or property.

A similar trend is shown in the United States (44) which also divides fires up into types as shown in *Fig. 4*.

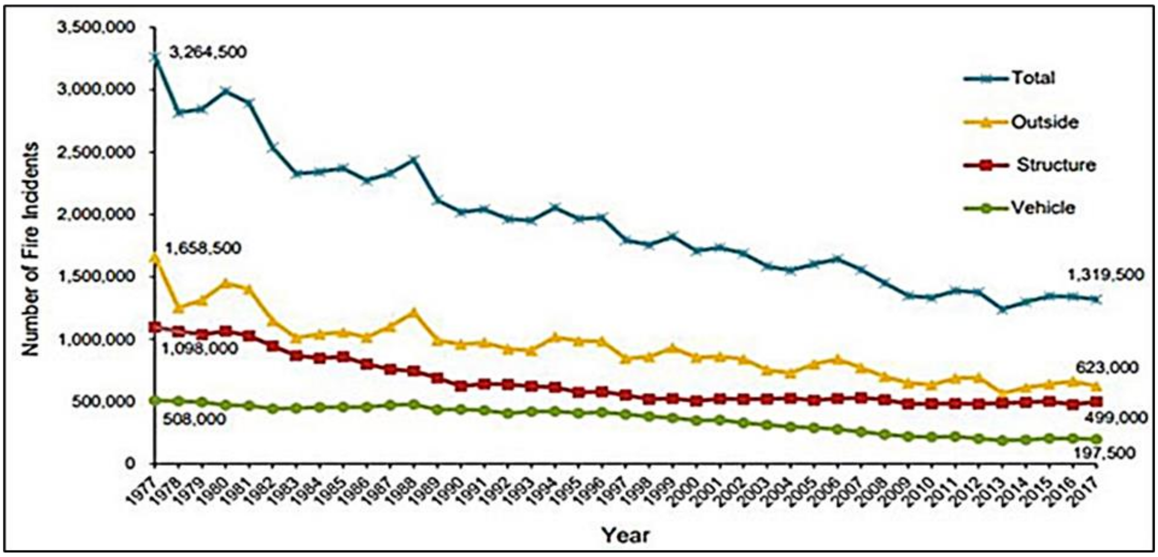


Fig. 4. US Fire statistics – trend in number of fire incidents (44).

The detail behind the statistics does not naturally infer success. Although deaths caused by fire are generally shown to be decreasing (roughly in line with the decrease in fire incidents), there are some additional lessons to be learned. For instance, according to the United States' National Fire Protection Association (NFPA) fires in the USA in 2017 caused approximately $10.7 billion (44) in property damage and there is no sign of this figure declining over time. *Fig. 5* shows the trend in the USA of the dollar loss per structural fire. Even after the value is adjusted for inflation and other costs, the problem has not been adequately tackled. There is more to do.

When it comes to business, the impact of a fire can often be disastrous. US Insurer NFU (45) highlight that 80% of businesses fail within 18 months of a major fire incident. Safety Management Journal (46) put this figure at 70% (even though they state that an exact figure is hard to determine exactly). Nevertheless, the figure is high and is unlikely to reduce unless businesses heed the warnings and take appropriate actions. The environmental damage caused by a fire is another factor rarely considered outside of wildfires. The costs of these incidents will be in the billions of dollars, but this does not consider the cost to the planet itself. Outside of wildfires, environmental damage due to a building fire is often far less publicised and possibly still not understood. Consequently, the status quo *viz a viz* fire safety may require re-examination, specifically in the way fire safety is specified, managed, and audited (47).

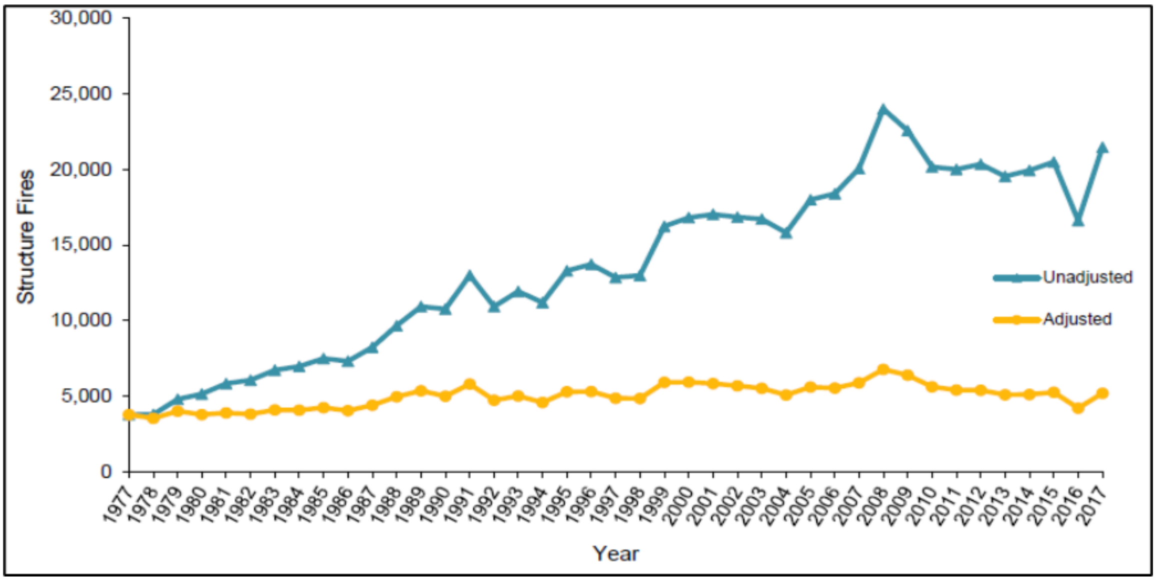


Fig. 5. Average loss per structure fire in the US (44).

In the book "Fire strategies – strategic thinking" (5), the subject of fire safety engineering is described as a "black art". This points to a certain degree of subjectivity in decision making, even if prescription has been historically associated with standardising fire safety. It is recognised that there is a wealth of codes, standards, rules around the world that determine how nations ensure buildings are safe from fire. With so much in the way of national and international guidance, it could be argued that opinion plays little in the development of a fire strategy. After all, the fire engineer follows a set of rules covering means of escape, the use of active and passive fire protection, facilities for firefighters, and so on. The limitations of following prescriptive fire safety rules for varying building styles were recognised decades ago. Prescriptive fire safety rules have been around from the early days of standardisation. Major revisions are either because of new lessons learned by the scientific and engineering communities or the result of a major fire. This similarly applies to national fire safety legislation.

Rules for fire safety of buildings date back centuries. The protection of people against the worst ravages of fire, is a principle that has been around for probably as long as civilised society itself. Such rules are typically required to support the relevant national fire safety legislation, current at the time of preparing those standards. Prescriptive rules would provide absolute guidance such as travel distance to a place of safety, the detailed application of active and passive fire protection, and means for firefighting. Consequently, new, and innovative building design, would be severely restricted (5).

Performance based approaches, which allow for greater levels of flexibility in the application of fire safety, have become the solution over the last few decades. Without such progress, it could be argued that the more ambitious building designs seen today, would never have become a reality. Whereas prescription limits flexibility, the flip side is that flexibility allows a greater degree of diversity in approach, in the assumptions made at the outset, and in the methods used to arrive at a fire engineered solution (5).Performance-based fire engineering is covered in Chapter 2.

An issue that underlines the requirement of a consistent framework for fire strategy evaluation, as espoused by this Thesis, is that of verification and approval of fire strategies. Enforcement Authorities have stated problems with respect to the receipt of fire strategy documents. Typically, every submitted fire strategy differs in the degree of detail, as well as format (3). Some strategies adopt a pure performance-based approach using CFD modelling. Some tend to bridge the gap between prescription and performance setting. Some are ambiguous with respect to the assumptions and decisions made. All of this introduces a dilemma for those tasked with having to ensure that the fire strategies are indeed good enough. It was a much simpler task when strategies used prescription. Now the task has become much trickier (3).

Moreover, building design itself had become much more complex, introducing further frustration for enforcement Authorities who typically cannot afford the resource and cost required to properly analyse the strategies. This is particularly the case for complex and non-standard buildings designed for the public.

It is suggested that a consistent methodology that would allow for fire engineers to follow due process. Given that the issue is a global problem, then the process should also be global (3). One of the conclusions from the fire statistical trends raised earlier, is that objectives outside of life safety, remain a concern. National legislation tends to focus on life safety (48), so consequently, fire strategies would be focused primarily towards life safety requirements. Some strategies would venture out - to consider other objectives such a property protection, possibly following an instruction from stakeholders such as insurers. Preparing a fire strategy for a new building is often a golden opportunity to undertake a full and thorough objectives review at the onset of a construction project.

The concept of introducing threat analysis is in recognition that our social environment is changing. New threats could lead to new fire scenarios that may not have been properly considered in the past. A fire engineered solution should incorporate a proper consideration of threats that could impact on the building, its occupancy, and its processes.

Most fire strategies are based upon the concept of a single fire event. It is doubted whether most fire engineers, when applying their national codes to a new building project, are even aware of that fact. Some codes accept the principle that anything other than this event is regarded as an extreme event (7). Furthermore, it is not uncommon for fire strategies to state that “extreme events” are not allowed for. Many believe that an extreme event is something like a major explosion (5). Note that two independent fires in different parts of a building may be regarded as an extreme event (5).

Returning to the issue of auditability of fire strategies and their prior preparation, it is deemed desirable that there is a method to allow a comparison between different fire strategies. The method could allow an assessment of an offered fire strategy (referred to as an actual fire strategy), against one that is based fully on the requirements of national codes. This strategy can be referred to as a baseline fire strategy. The methodology should provide for a system of indexing to allow a strategic assessment of proposals (4). This supposition is the basis of this Thesis.

2. Fire safety regulations and standards

2.1. The history of fire regulations

If there is a want to change the direction of fire strategy formulation, or indeed, if it is concluded that there is not such a need, then the steps that have led to now must be re-examined. An early leader in the field of fire safety - the United Kingdom, provides one example of the progression of fire safety regulation (12) (49).

The United Kingdom, as with most parts of Europe, had used stone masonry for centuries to create their major buildings such as castles, churches, country houses, and so on. This included inner parts of the building. Such structures were acknowledged as providing inherent fire protection by separating one section of a building from another, such that a fire could be relatively easily contained. This would give the best chances of fighting the fire before it could engulf the whole building. The same building style was not extended to most smaller buildings throughout Britain at the time. This was evident following the Great Fire of London in 1666 when the fire destroyed 13,200 houses, 87 parish churches, St Paul's Cathedral, and most of the buildings of the City of London. There were several key lessons from that fire (50). These included:

Lack of passive fire protection was the most significant issue at the time. London consisted of a labyrinth of medieval streets with wooden, thatched houses. The risks associated with thatched roofing were already well known and such constructions were officially prohibited, but this was, overall, ignored. Furthermore, six and seven-storey timbered tenement dwellings were expanded on the upper floors to form overhanging jetties in narrow streets. This enabled a fire to easily jump to neighbouring houses. Note that these jetties were also forbidden by proclamation set by King Charles II;

Combustible materials were largely uncontrolled. Open fireplaces, candles, etc were commonplace in such houses. Many stored gunpowder. Some of the buildings were also used as a workplace to include foundries, smithies, glaziers, etc;

Firefighting was represented by trained bands who patrolled the streets at night for fires and other potential emergencies. Equipment such as axes and firehooks were made available for pulling down buildings. Laws required Parish churches to have long ladders for accessing towers. Early forms of fire engine were also available. These proved to be unusable in many cases. Problems included the long distances to get to a fire, limited reach, no hoses, and the inability to access narrow streets due to their width.

The fire revealed inadequacies in the rules for fire safety. This led the King to introduce legislation that buildings should no longer be built of wood and that roadways should be widened to reduce the risk of fires jumping from one block to the next. Consequently, fire safety requirements and regulations were prepared (51).

Statutory provisions continued to evolve, often because of fires that killed many people. In the 19th century, detailed stipulations were made for the safety of people within premises in a fire situation. These were swiftly taken up by many parts of the world, particularly in countries that were regarded as being part of the *first world* as well as those who were part of the British Empire. Prior to this, large scale, ad-hoc, tests were carried out in the mid-18th century (49) with the recognition that fire should be confined to the room of origin rather than the building. It was not until the end of the 19th century that standard fire tests were used.

British fire safety legislation, together with the accompanying rules, tended to develop piecemeal, following major fires in a range of building profiles. Legislation relevant to fire safety included (49):

- The Explosives Act (1875)
- The Petroleum (Consolidation) Act (1928)
- The Factories Act (1937)
- The Fire Services Act (1947)
- The Factories Act (1961)
- The Licensing Act (1961)
- The Offices, Shops, and Railway Premises Act (1963)

In 1971, the UK's Fire Precautions Act (49) replaced previous relevant legislation. One of the key features of this Act was that building occupiers were required to hold a fire certificate. This certificate described the range of fire safety provisions included and may also include plans showing their location. Authorities had the option of closing premises where it was believed that occupants were at risk. In a way, these certificates were not dissimilar to the objectives inherent in a fire strategy document now required.

But major fires continued. On each occasion, legislation was introduced or reviewed. In Manchester, a major fire in a retail department store in May 1979 (52) led to a death toll of ten, with many others seriously injured. The subsequent investigation found that most of those who died were in the restaurant above the main shop. It was stated that the smoke was so thick, the shoppers could not find their way to the exits. Note also that iron bars were installed on the windows, preventing escape or rescue via these access points. Although there was a specific Act in force at the time of the fire (The Fire Precautions (Factories, Offices, Shops, and Railway Premises) Regulations 1976) (49), it was found that the store in question did not have a fire certificate, although they were in the process of making improvements. The fire also prompted calls for sprinkler systems in department stores as well as better staff training. Two other major fires led to a new legislation. One was the Bradford Football Stadium fire (53) in May 1985, when 56 spectators were killed and upwards of 265 injured. This led the way to the Fire Safety and Safety of Places of Sport Act (1987) (49). It was the King's Cross Underground Station fire on 18 November 1987 (54), which resulted in the loss of 31 people, in horrific circumstances that led to the Fire Precautions (Sub-surface Railway Stations) Regulations in 1989 (40).

Moving forward in time, to 2005, the UK introduced legislation that avoided the continual need to catch up with the impact of new fire-related disasters. The UK Government's Regulatory Reform (Fire Safety) Order 2005, was enforced from 2006 (48). For the first time in UK fire safety history, a proactive approach was taken to ensure appropriate levels of fire safety are applied. This was based on the requirement for a fire safety risk assessment. Relevant fire safety provisions and precautions could then be applied, relevant to the perceived fire risk. This had one drawback in that it relies upon the decisions made by the fire risk assessor. Assessors often had different opinions, despite the availability of a set of national guidance documents. Third party certification schemes were set up to increase the level of professionalism in the undertaking of fire risk assessments. Nevertheless, opinion is still a key ingredient in fire risk assessment. The fire risk assessment process mostly applies to existing operational buildings although it will be used later in this Thesis to allow for a semi-quantitative approach to the evaluation of fire strategies.

Nowadays, for new or modified buildings, the legislative requirements are typically supported by the UK Building Regulations and specifically Approved Document B (ADB) (55) which covers fire safety. Note that this document is provided in two volumes, one for dwellings and the other for non-dwellings. ADB further divides requirements up into five parts:

B1. Means of warning and escape;
B2. Internal fire spread (linings);
B3. Internal fire spread (structure);
B4. External fire spread;
B5. Access and facilities for the fire service.

British Standards Institution had published a range of fire safety standards to support legislation for many decades. Typically, it was the BS 5588 series of standards (56) that specified overall fire safety requirements for buildings. The series of standards has mostly been withdrawn in favour of BS 9999 (7). There are several other British Standards that cover most aspects of passive and active fire protection as well as fire safety management. Some of which are also European and/or international standards. BS 9999 provides recommendations for the design, management and use of buildings to achieve reasonable standards of fire safety for all people in and around them. It also provides guidance on the ongoing management of fire safety within a building throughout its entire life cycle, including information for designers to ensure that the overall design of a building assists and enhances the management of fire safety. More recently a British Standard BS 9997 (57) was published to enhance fire safety management techniques. BS 9999 recognised that additional flexibility is required and included the technique of risk profiling. The risk profile was made up of two parameters: the potential rate of fire growth, and the occupancy profile (e.g. occupants' knowledge of the building, the possibility that occupants are not awake during a fire, etc.). When it comes to consideration of objectives, BS 9999 acknowledges that it is primarily intended to safeguard the lives of building occupants and fire-fighters. It points out that issues such as protection of property, the environment, communities, and business/service viability are outside of its scope.

2.2. Performance based fire engineering

The Society of Fire Protection Engineers (US) (21) define performance-based design as an engineering approach to fire protection design based on; (a) established fire safety goals and objectives, (b) analysis of fire scenarios, and (c) quantitative assessment of design alternatives against the fire safety goals and objectives using engineering tools, methodologies, and performance criteria.

The concepts behind a performance-based approach were introduced from the 1970's onwards, to allow greater flexibility in the design and application of fire safety and protection systems. From the 1990s, standards were introduced to provide guidance regarding the application of a performance-based approach. One such example is a standard, referred to as a "Draft for Development", introduced by British Standards Institution (BSI) in

1997. This was titled DD 240-1 (58). The scope of the standard highlighted that it provided a framework for an engineering approach to the achievement of fire safety in buildings by giving guidance on the application of scientific and engineering principles to the protection of people and property from fire. A second supporting standard, DD 240-2 (59) was also published to provide commentary on the equations given in Section 1. This Draft for Development was acknowledged as a breakthrough in allowing building designers the option of applying fire safety to a building based upon performance objectives determined for that building.

The idea was that one or more meetings would be held involving relevant stakeholders who would set these performance objectives. These meetings were described as "qualitative design reviews", in that the qualitative decisions made would guide the subsequent quantitative analysis. The key concepts of DD 240 were developed further by BSI when, in 2001, British Standard BS 7974 (60) was published to supersede DD 240. As well as providing the same framework for an engineering approach to the achievement of fire safety in buildings as described for DD 240-1, it also provided a "rational methodology for the design of buildings". The standard was intended to apply to the design of new buildings and the appraisal of existing buildings. The key benefits highlighted by the British Standard were that it provided:

- the designer with a disciplined approach to fire safety design;
- the safety levels for alternative designs to be compared;
- basis for selection of appropriate fire protection systems;
- opportunities for innovative design;
- information on the management of fire safety for a building.

The main standard is supported by several guidance documents published as "Public Documents" or PDs. These documents were designed to provide fire safety engineers with additional information to allow them to formulate effective and relevant performance-based fire strategies. Each PD, also referred to as a sub-system, covers a specific area of consideration:

- initiation and development of fire within the enclosure of origin (Sub-system 1);
- spread of smoke and toxic gases within and beyond the enclosure of origin (Sub-system 2);
- structural response to fire and fire spread beyond the enclosure of origin (Sub-system 3);
- detection of fire and activation of fire protection systems. (Sub-system 4);
- fire and rescue service intervention (Sub-system 5);
- human factors. Life safety strategies. Occupant evacuation, behaviour and condition (Sub-system 6);
- probabilistic risk assessment (Sub-system 7);
- property protection, business and mission continuity, and resilience (Sub-system 8).

Other than for sub-system 8, the principles given are to ensure that the building provides for suitable life safety measures to allow persons to safely evacuate from a building in a fire (60). This is based upon two factors:

Available Safe Escape Time (ASET) (61) represents the time duration for which safe conditions will prevail before escape routes become untenable. This can be determined by using the sub-systems given above. The duration can be based upon factors such as structural stability, separating escape routes from risk areas by passive fire protection, and the use of active systems to prevent fire and smoke affecting the means of escape for an enhanced period, thus increasing the ASET value;

Required Safe Escape Time (RSET) (61) represents the time necessary for occupants to safely escape from a fire, either to a final place of safety (such as outside of the building), or to a relative place of safety (such as a refuge). Clearly, in the latter case, this will require enhanced measures to ensure refuges remain safe for the required period until they are able to evacuate to a final place of safety. This period can be reduced by measures such as suitable fire detection and alarm systems, the type of response to the alarm, and the efficacy and sizing of horizontal and vertical escape routes. The RSET is made up of the summation of time periods from detection, to alarm, pre-movement, and evacuation (Fig. 6).

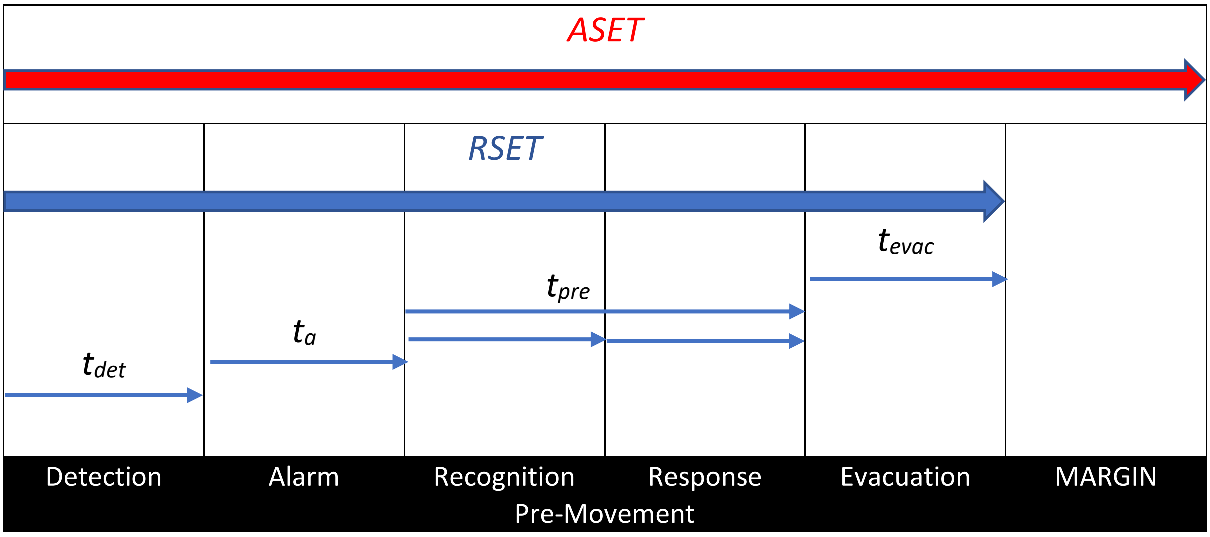


Fig. 6. Breakdown of ASET & RSET timing factors (61)

The objective is that the ASET is calculated to be a suitably large margin of time that that calculated for the RSET. *Fig. 6* provides a breakdown of the principle periods of time making up the RSET. Rather than calculate the above from first principles, computer models are often used to determine both conditions. Early versions made use of what were called "zone models". Zone models are usually based on simple room dimensions and divide rooms or enclosures up into one or more zones. A "two zone" model, for instance, would consider an upper layer consisting of heated products of combustion and a lower layer of cooler air relatively free of combustion products. The models would allow for an assessment of the conditions over time by considering variations in location of the fire and the expected fire size. The impact of openings in the room such as via doors or windows can also be assessed. The models could help predict the time to detection and operation of systems such as sprinkler systems as well as predict time to flashover. There are limitations in such models in that, for instance, the predicted temperature within the hot layer would be the same throughout.

Field models, that use sophisticated computational fluid dynamic (CFD) algorithms are more commonly used today. They work on the principles behind *Navier-Stokes* equations (62) appropriate for low speed, thermally driven flow, with an emphasis on smoke and heat transport from fires. At any point in time, it is possible to find the temperature, velocity, and gas concentrations at any point. Such systems can help assess complex building designs and particularly 3D models. There are many modelling programmes available today. One of the most sophisticated are separate packages "Smartfire" and "Exodus" which are produced by the UK's University of Greenwich (63) . These packages enable both ASET and RSET conditions to be modelled simultaneously in real time. Adjustments to the criteria can even show how many persons could be affected by smoke and fumes. An example of the visual display of Exodus is shown in *Fig. 7*.

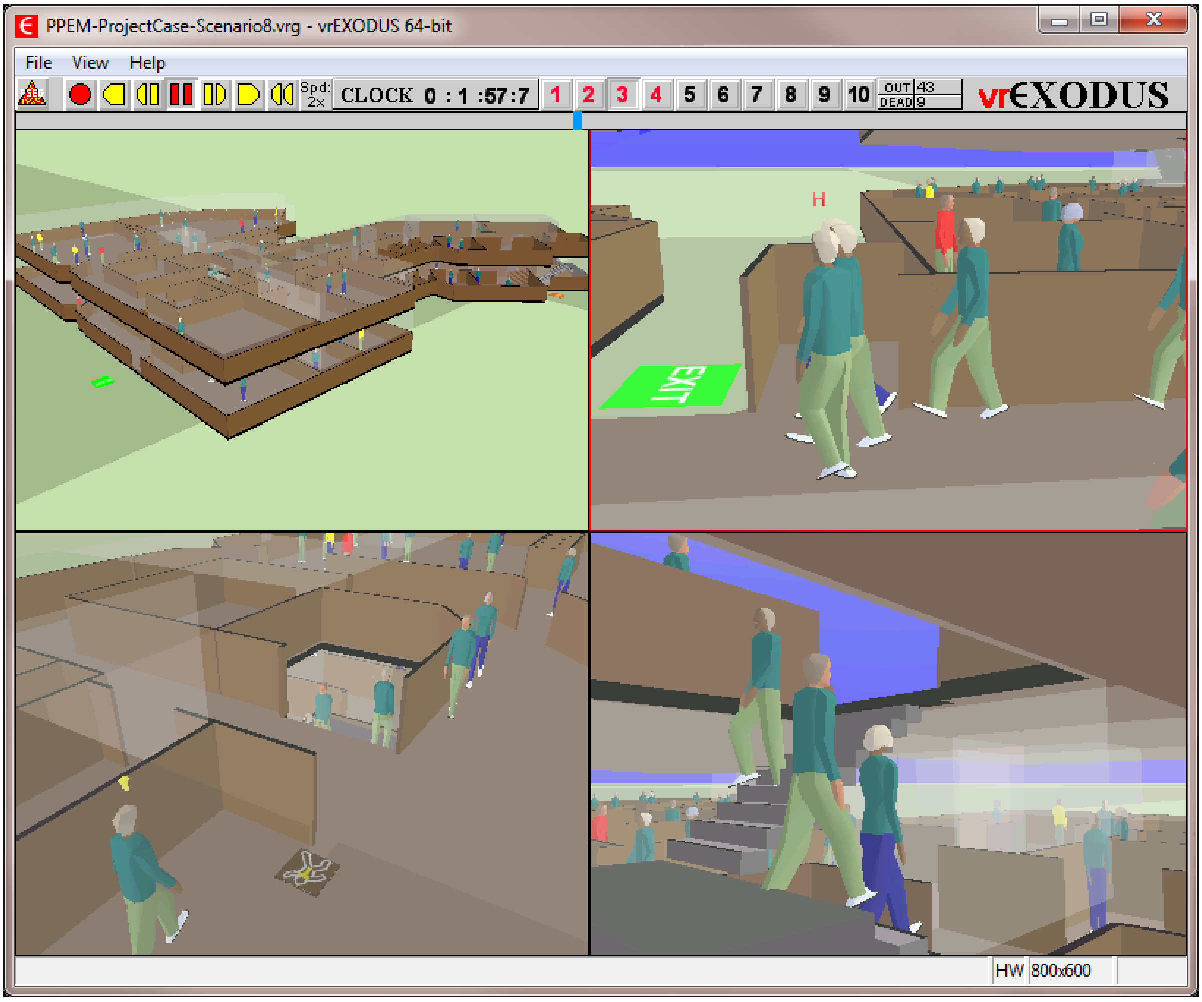


Fig. 7. Visual display of "Exodus" evacuation modelling (63).

The most widely used field model worldwide is known as FDS (Fire Dynamics Simulator) (64) and is produced by NIST (National Institute of Standards and Technology) in the USA. It is this model that was used for the analysis in the latter part of this Thesis.

When assessing life safety parameters, it is necessary to adopt established tenability limits that would ensure a specific safety level for people during a fire. In Poland, such criteria was regulated in 2011 (65) based on British Standard requirements from PD 7974-6 (66). According to them, critical parameters on evacuation routes are considered:

- smoke at a head height ≤ 1.8 m from the floor, limiting the visibility of building features and luminescent evacuation signage to not more than 10 m, and;
- air temperature at a head height ≤ 1.8 m from the floor not exceeding 60°C and, in the ceiling layer at a height of > 2.5 m, not exceeding 200°C due to the associated thermal radiation.

The FDS program enables three dimensional simulations of fire growth and smoke spread based upon the CFD calculations using the Navier Stokes equations for fire-driven fluid flows, with emphasis on smoke and heat transport. The program is aimed at solving practical problems in fire protection engineering whilst, at the same time, providing a tool to study fundamental fire dynamics and combustion (67).

To describe the turbulence phenomenon, the FDS program utilizes large eddy simulation (LES); the process of turbulent mixing of gaseous fuel and combustion products with combustion ambient air. This simulates most fires and determines the fuel combustion rate as well as the smoke and hot gases spread rate. The basic assumption when utilizing LES is that most eddies arising in the process of gas mixing, are sufficiently large to be computed with satisfactory approximation accuracy by means of the fluid dynamics equations. All small eddies are computed with high approximation accuracy or are neglected (67).

The following models for description of process fluid mechanics were employed in the FDS program:

- hydrodynamic model;
- combustion model;
- thermal radiation model;
- model of thermal penetration through barriers;
- pyrolysis model.

The **hydrodynamical model** allows the FDS program to numerically solve an appropriate form of the Navier-Stokes equations for fire-driven fluid flows with emphasis on heat and smoke transport. The basic equations used in simulations are the following equations of mass, momentum and energy for thermally expandable multicomponent perfect gases (68):

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho u = 0 \qquad (2.1)$$

Mass conservation equation:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot \rho Y_i u = \nabla \cdot \rho D_i \nabla Y_i + \dot{W}_i''' \qquad (2.2)$$

The equation of mass conservation (Eq. 2.2) is solved for each component of the burning mixture. At the same time, the following conditions must be met:

$\sum_{i=0}^{N} Y_i = 1,\ \sum_{i=0}^{N} \rho D_i \nabla Y_i = 0\ i,\ \sum_{i=0}^{N} \dot{W}_i''' = 0$

where N denotes the number of components in the mixture. In equation 2.2, Y_i is the mass fraction of "i" component, D_i is the diffusion coefficient of "i" component in the mixture, and $\dot{W}_i'''$ denotes the rate of generation of "i" component.

Energy conservation:

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot \rho h u - \frac{Dp}{Dt} = \nabla \cdot k \nabla T + \sum_{i} \nabla \cdot h_i \, \rho D_i \nabla Y_i - \nabla \cdot q r \tag{2.3}$$

Momentum conservation:

$$\rho\left(\frac{\partial u}{\partial t} + (u \cdot \nabla) u\right) + \nabla p = \rho g + f + \nabla \cdot \tau \tag{2.4}$$

where:
D – diffusion coefficient,
f – external forces vector (excluding earth's gravity),
g – earth's gravity,
h – thermal penetration coefficient,
k – thermal conductivity coefficient,
p – total pressure,
q_r – thermal radiation vector,
$\dot{q}'''$ - quantity of heat per unit of volume,
T – temperature,
t – time,
u – velocity vector,
$\dot{W}_i'''$ - rate of generation of „i" cell per unit of volume,
Y_i – mass composition of „i" cell,
ρ - density,
τ - viscous stress tensor.

The **Combustion model** analysis evaluates the combustion process employed by assessing the mixing of fuel with oxygen. It is assumed that large scale convection and radiation phenomena are computed directly, whilst small scale processes of short duration must be approximated. It also assumes that the combustion process is limited with respect to mixing of substrates and that the rate of reaction of fuel with oxygen is infinitely high, which means that the simultaneous presence of both fuel and oxygen in the mixture is not possible. Hence, the individual fractions of the gas mixture can be described as a function of parameter *Z (x,t)* in all the elements of the area filled with gas mixture (67).

The combustion process can be described by general reaction:

$$v_F Fuel + v_O O_2 \longrightarrow \sum_i v_{P,i} \, products \tag{2.5}$$

The value of v_i are the stoichiometric coefficients of the general reaction of combustion of fuel „F" in oxygen „O" producing product „P". Parameter Z is defined as:

$$Z = \frac{sY_F - (Y_O - Y_O^{\infty})}{sY_F^I + Y_O^{\infty}} \tag{2.6}$$

while:

$$\mathrm{s} = \frac{\mathrm{v_O M_O}}{\mathrm{v_F M_F}} \tag{2.7}$$

where:
Y_O^∞ - mass fraction of oxygen in ambient air,
Y_F^I - mass fraction of fuel in fuel stream,
M_O – molar mass of oxygen,
M_F – molar mass of fuel,
Y_O - mass fraction of oxygen in the mixture,
Y_F - mass fraction of fuel in the mixture.

The value of *Z* oscillates between *Z=1* in the area filled exclusively with fuel and *Z=0* in the areas filled exclusively with pure air (Y_O^∞).

The thermal radiation model in the FDS program is based on the heat transfer equation for scattering gas:

$$s \cdot \nabla I_\lambda(x,s) = [\kappa(x,\lambda) + \sigma(x,\lambda)] I(x,s) + B(x,\lambda) + \frac{\sigma(x,\lambda)}{4\pi} \int_{4\pi} \Phi(s,s') I_\lambda(x,s') d\Omega' \qquad (2.8)$$

where:
I_λ - radiation intensity of the wave lenght λ,
$B(x,\lambda)$ - source emissivity,
s – unit normal vector,
$\sigma(x,\lambda)$ - local dispersion coefficient,
$\kappa(x,\lambda)$ - local absorption coefficient [5].

The right part of the equation (2.9) describes the phenomenon of gas flow from different directions. When assuming the lack of gas scattering, the equation (2.9) takes the form:

$$s \cdot \nabla I_n(x,s) = \kappa_n(x)[I_{b,n}(x) - I(x,s)] \qquad (2.9)$$

In practice, the radiation spectrum is divided into adequately narrow bands, each of which is analyzed by means of an equation (2.10) which, in the case of an individual band, has the form:

$$s \cdot \nabla I_n(x,s) = \kappa_n(x)[I_{b,n}(x) - I(x,s)], n = 1 \ldots N \qquad (2.10)$$

where:
I_n - radiation intensity for band "n",
$I_b(x)$ - source term derived from Planck's function,
κ_n - absorption coefficient for band „n".

Hence, the source term can be presented in the form of:

$$I_{b,n} = F_n(\lambda 4 max_{min}) \qquad (2.11)$$

where:
σ - Stefan-Boltzmann coefficient.

After the calculations for individual bands are performed, they are summed up according to the following formula (2.12):

$$I(x,s) = \sum_{n=1}^{N} I_n(x,s) \tag{2.12}$$

2.3. The use of fire strategies for building fire safety

The term fire strategy has gradually crept into the fire safety dictionary of terms. At the time of writing this Thesis, even Wikipedia precluded the term. In the book "Fire strategies – strategic thinking" (5), it is pointed out that a fire strategy is more fundamental than may be commonly understood. Taking the example of a residential apartment, the "implicit" fire strategy will be that the building was constructed in accordance with national building regulations (all of which contain fire safety requirements). The electrical system within the apartment will contain safety systems to prevent overheating or sparks igniting the furnishings. In some cases, a smoke alarm may be fitted to alert sleeping occupants of a fire. All these provisions put together amount to a fire strategy. Consequently, everything constructed for people to live, play, or work in will have a fire strategy.

The book (5) describes that a fire strategy needs to have the following five properties:

1. to be specific to the unique set of fire-related parameters of the building or structure to which it applies, of the processes within, and of the occupancy profiles. This is later referred to in this book as "the terrain." There is no such thing as a "generic" fire strategy;
2. to be a clear and concise document, despite the necessary and sometimes complex processes throughout its drafting. It will need to be understood by all parties affected by it and not just by fire safety professionals involved in its preparation;
3. to have the necessary level of detail to enable, for instance, fire safety management plans to be drawn up and to provide the design criteria for passive and active fire protection. At the same time, it should not be so detailed that it is inflexible to changing fire safety and protection technologies or philosophies;
4. to have realistic and achievable goals relevant to the local / national fire safety requirements. A strategy will need to take into account practical, logistical, and commercial limitations. A complex "all bells and whistles" strategy may be desirable from the Section of a specifier or enforcer, but if it cannot be made a reality, it won't be, and thus the process would mostly be a waste of time and money;
5. a fire strategy is an organic document. It should be modified and adjusted for it to remain true to its inherent goal, and that is preventing and mitigating fire incidents and their impact. Drivers that dictate the need for modification of the document include changes in legislation or stakeholder requirements, revised building structures or layouts, changes in occupancy or use of the building, and new available technology or research.

Whereas other engineering disciplines make use of known laws, fire safety engineering is rarely absolute in its science and application. Therefore, traditionally, a strongly prescriptive approach has been applied for the fire safety and protection requirements of buildings and in the standards used.

Most nations make use of the application of fire safety law to ensure that minimum standards are applied. These laws are often supported by national or international codes or standards, which provide specific details which should be followed. However, such an approach has often restricted advances in building design.

Note that the primary aim of British Standard Specification PAS 911 (6) was to promote strategic thinking, something that was further examined in the book "Fire strategies – strategic thinking" (5). In fact, the subject matter contained within this book was designed to be the next iterative step in that process.

British Standard Specification PAS 911

This document was published to provide a methodology for the preparation of fire strategies, whether they use prescriptive standards or a performance-based approach. This document does not give recommendations or requirements for the fire safety design of buildings. What it does aim to do is to provide a consistent platform for fire strategies, such that they will follow a consistent format, whatever the building type is, and wherever it is.

There was a time when all standards were prescriptive; they provided detailed criteria that fire engineers were required to follow, and these would allow for a straightforward fire strategy document. This made life very easy for both practitioners and those auditing their results. The intention of prescription is that the fire strategy either conforms to the standards, or not. The advent of performance-based codes, as described earlier in this Thesis, has added another way forward, although most countries continue to support prescription over performance-based engineering. A hybrid approach using a combination of performance-based and prescriptive guidance is another option, whereby fire protection systems and designed in accordance with prescriptive codes whilst aspects such as evacuation routes are designed on the basis of performance-based engineering solutions. *Fig. 8* shows two pie charts, one representing a prescriptive approach and the other, a performance-based approach (69).

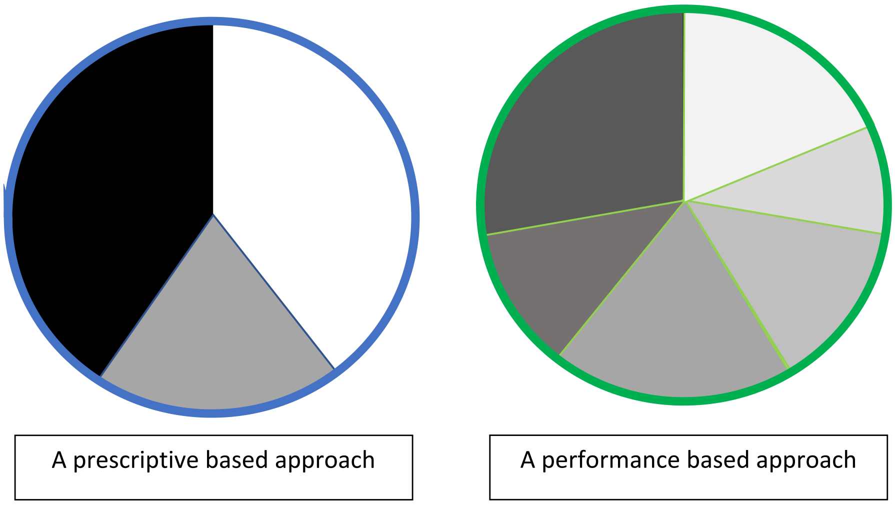


Fig. 8. Pie charts illustrating the differences in approach for the formulation of fire strategies (69)

Prescriptive rules are designed to be "black and white," that is, there is a right way and a wrong way. In an ideal world of prescription, there would just be black and white. However, it is known that no building, or use of a building, is likely to allow for every element of the standard to be met in full, unless the building is extremely standard in its construction and layout as well as use. Alternatively, the standards themselves may not be so precise as to cover every detail. There is also the possibility that the standard, or the building, has not been properly understood and the outcome is full compliance by default.

If a prescriptive standard has been fully and thoroughly used, and the building has been properly assessed, there will be aspects that cannot be made to comply exactly and are thus depicted by an area of grey. These grey areas are known as variations or deviations from the standard. These areas of grey may be accepted or rejected by those who will approve the fire strategy.

A performance-based approach will not lead to any obviously right or wrong answer. Instead, a solution may be effective to a lesser or greater extent. That is, there will be degrees of grey with no absolute right or wrong approach.

2.4. The use of fire safety standardisation in the formulation of fire strategies – a global perspective

Most nations utilise their own *national* fire safety standards when formulating and evaluating fire strategies. These typically derive from the requirements and needs of their building regulations and fire safety legislation, which are often taken from historical requirements, possibly updated following a specific national fire event. Some nations may adopt fire safety standards that are quite unique to that country. Some may take standards from other countries and modify them for their own use. Some may simply directly specify standards from other countries. In some cases, the national situation is made worse when regions within a single country take differing approaches to fire safety standardisation. As an example, Rodrigues *et al* (70) point to the regionality of fire safety standards in Brazil. They highlight that individual states within the country have created a diversity of regulations from state to state, with varying mandatory prescriptive requirements for fire protection systems. They believe that the only real way forward is for Brazil to start considering fire safety at a federal level by bringing together regional stakeholders. They also support adoption of fire safety engineering, which is based upon scientific, rather than historical, determination.

Ideally, as engineering and science becomes increasingly global, fire safety specification should follow suit. International standardisation would seem to make sense. The International Standards Organization (ISO) was formed in 1946 when delegates from 25 countries met in London and decided to create a new international organization "to facilitate the international coordination and unification of industrial standards" (71). They have now published over 22,612 International Standards covering almost all aspects of technology and manufacturing with 164 countries taking part. Within the realms of fire safety standardization, they did aim to prepare a set of relatively prescriptive standards covering most aspects of fire safety. They have had some success with internationally accepted requirements for some components of fire protection systems such as sprinkler systems.

However, most countries still rely on their own national standards over internationally produced standards (54). In quite a few cases, they may adopt NFPA or British Standards and amend to fit with their legislative requirements. Nonetheless, international standards for fire safety have been produced, albeit these are largely advisory in nature and are focused on performance-based approaches. A range of standards have been published by their Sub-Committee ISO/TC 92/SC 4: Fire safety engineering. Some relevant examples include:

- ISO/TR 16576: Fire safety engineering -- Examples of fire safety objectives, functional requirements and safety criteria (72);
- ISO 16732: Fire safety engineering -- Fire risk assessment (73);
- ISO 16733: Fire safety engineering -- Selection of design fire scenarios and design fires (74);
- ISO 23932: Fire safety engineering (75).

Another initiative has determined that the problem with multiple differing standards mean there is no single authoritative way to work. The International Fire Safety Standards (IFSS) group has been formed to bring greater consistency by setting minimum levels of fire safety and professionalism across the world. In 2018, the IFSS Coalition was launched at the UN in Geneva, Switzerland (76). In the context of the IFSS Coalition's work, an international standard is something that is established and agreed at a global level and implemented locally (76). The coalition has stated that it will provide universal rules that classify and define fire safety standards at project, state, national, regional and international levels. They refer to research, which has shown that inconsistent approaches to the assessment and regulation of fire safety can lead to a loss of confidence by governments, financiers, investors, occupiers and the public in buildings and, in extreme cases, result in lo ss of life. Their end objective is that all higher-risk buildings to which occupiers and the public have access will publicly display a certificate of compliance with the IFSS.

As well as working at an international level, most of the European nations have participated in preparing European fire safety standards covering, mostly, the construction of buildings, and, specifically, components of fire safety systems. The CEN (Comité Européen de Normalisation) Eurocodes are produced to ensure trading consistency for construction products and engineering services and ensure free circulation within the Community (77). Further, they are meant to lead to more uniform levels of safety in construction in Europe. The EN Eurocodes are designed to be the foremost reference design codes. The intention is to withdraw all conflicting national standards. It is mandatory that the Member States accept designs to the EN Eurocodes. This will not apply to the UK after December 2020 due to the UK leaving the European Union although they may choose to continue to use the standards.

The Eurocodes (78) apply to the structural design of buildings and other civil engineering works including: geotechnical aspects, structural fire design, situations including earthquakes, execution and temporary structures. The Eurocodes cover the basis of structural design (EN 1990) (79); actions on structures (EN 1991) (80); the design of concrete (EN 1992) (81), steel (EN 1993) (82), composite steel and concrete (EN1994) (83), timber (EN 1995) (84), masonry (EN 1996) (85)and aluminium (EN 1999) (86) structures; together with geotechnical design (EN 1997) (87); and the design, assessment and retrofitting of structures for earthquake resistance (EN 1998) (88). All of the EN Eurocodes relating to materials have a Part 1-1 which covers the design of buildings and other civil engineering structures and a Part 1-2 for fire design. The codes for concrete, steel, composite steel and concrete, and timber structures and earthquake resistance have a Part 2 covering design of bridges. These Parts 2 should be used in combination with the appropriate general Parts (Parts 1).

Note that the Eurocodes are supported by several other EN standards for fire safety. One such group are the EN 54 series which covers fire detection and alarm systems over many parts (89) . Moreover, the EN documents are, overall, prescriptive in nature. If anything, it is the international approach headed by ISO that is promoting a performance-based methodology to the subject of fire safety. Given this, recognised procedures for performance-based fire safety engineering could be potentially used for the global specification of fire safety. There are two points to consider. The first is that countries are not obliged to use such standards. Secondly, as identified above, most countries still see the need to require buildings to meet with their own fire safety standards, whether they are prescriptive, or performance based. This is unlikely to change soon. Basically, enforcement agencies are unlikely to accept a truly international approach unless their national fire standards committees and other national stakeholders fully embrace this new status quo.

2.5. Analysis of treatment of fire safety in a varied selection of countries

As intimated in the previous section, countries tend to rely on their own national fire safety codes. A national assessment of requirements would help to understand if variations between countries are such that a global solution is possible. A special assessment was undertaken for this Thesis. A group of peer fire engineers from a selection of countries were issued with a series of questions. The countries chosen were (in alphabetical order): China, India, Iran, New Zealand, Poland, UK, and USA. The responses are given below.

Question 1: *What is / are the most applicable fire safety codes utilised in your country?*

China have their governing building code titled GB 50016-2014 Code for fire protection design of buildings (90). The Code is called up throughout China and allows for both prescriptive as well as performance-based approaches, although evaluation methods such as risk profiling are typically not utilised. China has a separate standard for high rise buildings titled GB 50045 (91) which covers residential buildings above 27 m and all other building uses above 24 m. It should be noted that Hong Kong applied their own codes prior to handover back to China in 1997. These were inevitably based upon requirements from the UK.

India makes use of five main codes: IS 1641 (92):, IS 1642 (93), IS 1643 (94), IS 1644 (95) and IS 1646: (96)

IS 1641 provides a classification of 9 risk profiles (incl. residential, educational. Business, industrial, etc.). These are then sub-classified into types. Note that these standards were produced in the 1980s and 1990s, so the principles of performance-based engineering were not as well known.

The Iran National Building Regulations: Section 3 - Fire Protection in Buildings (97) is their most relevant code. The document been mostly adopted from NFPA Codes, British Standards, and Iranian Building Codes. It has no English version and is written in the local language (Farsi). The regulations are prescriptive but allows for a performance-based approach. At the time of receiving information, it is believed an approved performance-based design has not yet been used. Risk profiling is also typically not used for the civilian applications but is for industrial applications.

The New Zealand primary fire safety requirements are covered by their Building Regulations' C Clauses (98). These documents are produced by Ministry of Business, Innovation and Employment. These are: C1: Objectives of Clauses C2 to C6; C2: Prevention of fire occurring; C3: Fire affecting areas beyond the source; C4: Movement to a place of safety; C5: Access and safety for firefighting operations: establish the presence of hazardous substances or process in the building; C6: Structural stability. Note also that New Zealand make use of a range of verification methods (VMs) and Acceptable Solutions (ASs) to support or allow modification from the C Clauses. This includes a 10 Section fire scenario assessment. This is covered in Chapter 3

In Poland, their prescriptive Building Regulations (99) are adopted for fire safety requirements. The Regulations allow, when deemed appropriate, the use of performance-based methods and engineering calculations (100). In such case they tend to either make use of British Standards (some of which are regulated as European standards) as well as relevant NFPA guidance. Risk profiling is currently not commonly used.

The UK Building Regulations - Approved Document B (55) is the document that is mostly used to formulate building fire strategies. British Standard BS 9999 (7) also used where a degree of flexibility is necessary. As advised in the previous chapter, BS 7974 (60) is the primary standard for a performance-based approach.

For the United States, the NFPA Life Safety Code 101 (101) is most relevant. NFPA 101A (102), Guide on Alternative Approaches to Life Safety, allows for an engineering solution to correctly determine an equivalency methodology against NFPA 101, so allows for greater flexibility. The equivalency utilises numerically based fire safety evaluation systems with minimum mandatory values. The standards cover a wide range of occupancy types and provide specific guidance on a chapter by chapter basis for different building use profiles such as: Health care; Residential board and care; Detention and correctional; Business; Educational

Question 2: *What are the key criteria for means of escape?*

The Chinese code (103) bases requirements on building height and whether the building is sprinkler protected. There are no limiting criteria on vertical travel distance. Furthermore, there are no special requirements for the evacuation of mobility impaired persons. Where a performance-based design is proposed, then ASET/RSET criteria is used. Note that Hong Kong did have extensive requirements prior to 1997 for means of escape as specified in their Code of Practice (104)for provision of means of escape in case of fire. The Code incorporated a series of tables for the key dimensions including travel distances which are not dissimilar from British Standards. Some differences did exist. For instance, exit routes should have a clear head height more than 2 m. Buildings less than 6 storeys are permitted to have a single escape staircase.

Typically, Indian Standard IS 1644 (95) bases the requirements of means of escape on the building profile. In general, it is required that every floor of a building should have a minimum of two separated exit routes. The Indian standard also determines the total width of exit routes based upon occupancy numbers and the type of exit route (stairway, ramp, or door). A standard unit exit width is given as 50 cm. Occupancy numbers per exit width can vary from 25 for residential or educational buildings, to an exit stairway, through to 75 for most categories of building profile, to an exit door. Not also, that additional factors may be used in some cases to allow up to 100% increases in occupancy numbers. Typical travel distance to an exit is stated as 22.5 m, although this can increase to 30 m or even 45 m for industrial buildings. Given the age of the standards, issues such as RSET/ASET are not covered although it is understood that performance-based approaches are being adopted.

Iran (97) makes use of tables to determine the means of escape criteria. This is based upon occupancy type and numbers, as well as if the building is sprinkler protected. As an example, for each floor of a building, a single escape route is acceptable for 1 to 500 occupants, 2 escape routes for occupancy numbers between 501 to 1000 and 4 escape routes for occupancy numbers more than 1000. For other building types such as residential units, industrial buildings, car parks, etc, a single route is determined to be adequate. Escape route widths are based upon a table but should be at least 1,100 mm, although in some cases, 900 mm is permitted. For large projects RSET / ASET analysis may be used but this is rare

In the case of New Zealand (98), typically, a permitted single means of escape can serve up to 500 people, which can be floor or total area. As an example of travel distances for Sleeping Risks, dead end "open path" travel distances (where exit can only be assumed on one direction) are stated as between 25 m to 50 m. These are based upon whether there are fire detection and sprinkler system and place. It also states that total "open path" travel distances (i.e. to a place of safety) can vary between 60 m to 120 m. For offices, the maximum travel distances expand to 75 m and 150 m respectively. Minimum escape route widths are stated as 850 mm for horizontal travel and 1000 mm for vertical travel (for offices). Some variations to this are accepted under certain conditions.

The Polish technical regulations for buildings (105) usually measure escape distance to an enclosed staircase fitted with fire doors or to a final place of safety. For the highest risk category (explosive zone) or for buildings with higher occupancy densities or used as hotels, the maximum one-way travel distance is only 10 m and increases to 40 m where two-way escape is possible. Standard public buildings increase these two figures respectively to 30 m and 60 m. For warehouses with relatively low fire loading or for many types of dwellings, the figures increase again to 60 m and 100 m respectively. These figures may be increased by 50% when either sprinkler system or smoke control systems are used. When both are used a 100% increase is permitted. In the case of smoke control systems, it is obligatory to prove their performance by an engineering assessment.

The United Kingdom requirements derive from their Building Regulations, and specifically Approved Document B (55). BS9999 (7) however, allows for some additional variation based upon Risk Profile. The standard provides a limiting factor that where single escape routes are provided such that a maximum occupant capacity of 60 in a room, tier or storey and the travel distance limit for travel in one direction only is not exceeded. Between 60 and 600 occupants per floor, then two separate escape routes should be provided. For occupancies over 600, then three separate routes should be provided. In terms of travel distance, this is also based upon risk profile. The maximum allowed for low risk buildings is 90 m two way and 30 m for one way only travel. For offices, these figures are 75 m and 26 m respectively. Allowances are given for sprinkler installations. Dimensioning of escape routes is also based upon risk profile.

In the case of the United States, it should be noted the means of egress will vary slightly based upon the building profile (101) (106). Travel distances are measured from any point on a floor to the protected escape route (e.g. stairway). A single exit is allowed for areas with a total occupant load of less than 100 persons, provided that the exit shall discharge directly to the outside, and the total distance of travel from any point, including travel within the exit, does not exceed 100 ft (approx. 30 m). This also applies to buildings with less than 3 floors, with some exceptions.

In other cases, duplicate exits are required with travel distances to an exit shall not exceeding 200 ft (61 m) and 300 ft (91 m) in business occupancies protected throughout by an automatic sprinkler system. Dead-end corridors must not exceed 50 ft (15 m). Some of the acceptable dimensioning of staircases, etc is also based on occupancy numbers and building profile and height although the detail is not as great as it is for the UK approach.

Question 3: *What are the key requirements for construction factors of fire resistance and compartmentation?*

The Chinese Code (103) bases structural and internal fire compartmentation on building height and use. Internally, a fire resistance of up to 180 minutes is specified. Protected staircases are afforded 120 minutes fire separation from risk areas. Ultra-high-rise buildings such as Shanghai Tower has a minimum of 180 minutes fire resistance against fire-induced progressive collapse.

Indian Code IS 1642 (93) bases fire resistance requirements on four building "Types". The standard quotes a minimum fire resistance for any Type for separation of exit way corridors as 60 minutes. Shafts and stairways for all building types are required to meet a minimum of 120 minutes fire resistance. For Type 1 buildings (highest risk) – load bearing elements of exterior walls and fire walls, the quoted fire resistance is 240 minutes. The Standard also provides a range of building material options to meet with the requirements. For buildings greater than 15 m in height, it is recommended that all floors should be compartmented with a maximum fire zone of 750 m^2 (or 500 m^2 for profiles such as shopping centres). Where a sprinkler system is installed, then this fire zone size can be increased by 50%. The maximum distance between compartment walls is given as 40 m.

The Iran National Building Regulation (97) bases compartmentation requirements on ten occupancy types including residential, educational, health care, industrial, offices, and warehouses. Then, specific to each type, varying requirements are given for different elements of the building including load bearing members, exterior walls, separation walls between different compartments, staircases, corridors, etc. The minimum rating is 60 minutes fire resistance and maximum rating is 180 minutes. The installation of a sprinkler system also has an impact. For example, load bearing elements for non-sprinklered buildings are specified at 180 minutes, reducing this figure to 60 minutes for sprinklered buildings. For separation walls between an industrial occupancy and public occupancy (such as ceremony halls, restaurants, waiting halls) the fire resistance should be rated at 180 minutes.

New Zealand requirements (98) for offices and commercial spaces, for life rating, the minimum fire resistance is given as 60 minutes, and for property protection, 120 minutes. In some cases, and based upon storage height, and location of the boundary, the rating is increased to 180 minutes. Where sprinkler systems are fitted, then these figures can be halved. The minimum fire resistance rating for residential apartments is given as 30 minutes.

For high risk buildings such as warehouses, 240 minutes is the maximum level of fire resistance given.

The Polish Technical Regulations (65) base the construction elements of fire resistance and compartmentation on building height and profile. They divide buildings into five distinct classes (A to E) based upon a combination of building profile and height. The class may be decreased when either sprinkler system or smoke control systems are used. These classes can then be used to define fire resistance properties of building elements and fire separations. For instance, the highest, class A, requires the main construction elements of the building are rated at 240 minutes. In contrast, category E does not have a fire resistance requirement other than for the separation between two fire zones, where the fire resistance required is at least 15 minutes. Furthermore, maximum fire zones are limited from 2,000 m^2 to 10,000 m^2 for standard public buildings or even to 20,000 m^2 in warehouses. These figures may be increased by 50% when either sprinkler system or smoke control systems are used.

United Kingdom's BS 9999 (7) once again uses risk profile and the option of sprinkler system protection to adjust requirements for both structural and internal fire resistance. Typically, internal fire separations between rooms and corridors should have a 30-minute rating A minimum of 60 minutes is typically required for separating of firefighting shafts from lobbies and a total of 120 minutes fire separation between firefighting shafts and risk areas of the building.

In the case of the United States, NFPA 101 (101) provides a table (Table 6.1.14.4.1(a) - Required Separation of Occupancies) covering the fire resistance separations between occupancies based on profile. For example, the fire separation between industrial units and other premises types may be up to 180 minutes. Typically, primary fire separations are required to be around 120 minutes. Internally, the code requires exit routes to incorporate fire separations with a minimum 1-hour (60 min) fire resistance rating, where the exit connects three or fewer floor levels. Otherwise, the separation shall have a minimum 2-hour fire resistance. Half hour fire resisting separations are recognised for lower risks.

Question 4: *What are the key factors for fire detection and alarm systems?*

The Chinese Code (91) use categories of fire detection systems. Siting and spacing requirements are based upon the type of detectors used. Note that typically in China, in the event of an alarm, all parts of the building are evacuated simultaneously.

In the case of India, the relevant standard is IS 2189 (107). On review of this code, it closely covers the requirement of British Standard BS 5839-1 (108). The categories of system, as included within the BS, are not utilised.

Iran can make use of either the UK standard BS 5839-1 (108) or US Code NFPA 72 (109). The categories listed in BS 5839-1 are often specified.

In New Zealand, NZ Standard 4512 (110) for fire detection and alarm systems is the most appropriate for the specification for fire detection and alarm systems. This code categorizes systems into various "types". Note that these classifications are contained in an appendix and are simply provided as information. The types themselves categorize various options including, manual systems with or without automatic signalling to a remote receiving centre, and the inclusion of heat or heat/ smoke detectors. Also included in options is the inclusion of sprinkler systems which are also regarded as heat detection systems. In terms of detector siting and spacing, point type smoke detectors should be sited so that there is a maximum of 10 m between detectors and no point in a room is more than 6 m from a detector (and 5 m from a wall). The criterion for heat detectors is that the max distance between devices is 6 m and can be increased to 9 m in corridors. These should also be installed so that they are within 3 m of a wall (4.5 m in corridors) and a density of 30 m^2 per device. Voice alarm systems are becoming more commonly specified in NZ.

Polish requirements for the use the fire alarm system is regulated by the ordinance of the Ministry of Interior and Administration (105). Use of the fire alarm system, including signalling and alarm devices for automatic detection and alarm transmission, as well as fire alarm receiving devices, is required, for example, in commercial or exhibition buildings (single-story with a fire zone above 5,000 m^2 and multi-storey with a fire zone area over 2,500 m^2); theatres with more than 300 seats, cinemas with more than 600 seats; entertainment and sports halls with more than 1,500 seats; hospitals, except psychiatric, and sanatoriums - with more than 200 beds in the building; high rise public buildings; underground garages, in which the fire zone exceeds 1.500 m^2; metro and underground rail stations, and others. As with many other areas, component standards make use of a range of European standards. The criteria for heat detectors is that the max distance between devices is 5 m and for smoke detectors from 6 to 7.5 m.

United Kingdom utilises BS 5839-1 (108) which is the predominant standard for fire detection and alarm systems for non-residential buildings. It is utilised in many other countries. Key parameters for comparison are the spacing of smoke detectors; a maximum of 7.5 m from any point in the room to the device, which is reduced to 5.3 m for heat detectors. Alarm sound levels are typically stated as 65 dBA or 5 dBA above ambient and 75 dBA at bed heads for sleeping risks. Note that the standard incorporates categories for life safety and property protection.

United States primary code for fire detection and alarm systems is NFPA 72 (109). This Code covers all aspects of detection and signalling system includes requirements for control equipment, cabling, use of alarm sounders and siting and spacing of fire detectors. As an example, NFPA 72 requires that smoke detectors be installed on ceilings at a maximum point to point spacing of 30 ft (9 m) and 15 ft (4.5 m) to walls. It also states that no point should be within 0.7 times the listed spacing (i.e. a max of 21 ft or 7 m). For heat detectors, the spacing is based upon height. For a 10 ft ceiling the spacing should be no more than 12 ft (3.6 m).

Audible signal appliances intended for operation in the public mode shall have a sound level of not less than 75 dBA at 10 ft (3 m). Sleeping areas audible appliances shall have a minimum of 70 dBA or 15 dBA above the average ambient sound level.

Question 5: *Requirements for firefighter response?*

In China, there is no specification for the expected time of response by firefighters. The one provision is that fire hydrants should be available within 30 m of the building.

The Indian Standards do not go into detail regarding firefighter attendance times. There is an Indian Standard – IS 3844 (111) that covers internal fire hydrants and hose reels. The requirement for firefighting provisions is based upon building height and use. Buildings over 15 m in height should have provisions for wet riser systems, with the number of risers required based upon building type and floor area (typically one riser per 500 m^2 to 1,00 m^2. The tank storage requirements increase with building height.

In Iran, actual maximum attendance time by the emergency services is stated as 4.5 minutes in, for example, Tehran. The goal is to reach 2.5 minutes. For firefighting facilities, the limits on access to fire hydrants are set as 75 m from the building for critical areas as like as very high-density residential areas, and commercial / industrial zones. For areas with average population density and low risk commercial areas, this is set at 100m and 150 m for low risk areas with a low population density. For high risk buildings such as warehouses, two to three hydrants shall be installed. For Gas/Gasoline stations, two hydrants are required. Wet and dry risers in buildings should meet NFPA 14 (112).

In the case of New Zealand, there should be access such that the maximum distance from where a fire appliance can park to the inlet into the building at 75 m of any point in any unit contained in the building except if there is a sprinkler system, and 20 m of any inlets to fire sprinkler or building fire hydrant systems. Buildings higher than 10 m should have firefighter lift control features. The NZFS (113) stipulates that response times for fire incidents inside fire districts be monitored for performance against the national service delivery guidelines of 7 min 30 s 90% of the time for permanently manned stations, and 10 min 90% of the time for volunteer stations

Polish regulations typically assume that attendance time of the fire and rescue services will be within 15 min. In some cases, the services ask for a special declaration over expected time to attendance. The requirement for firefighter shafts is based upon building height and profile. For commercial and office buildings, this is set at 25 m. For residential blocks, this increases to 50 m. Note that dry risers are not a specific requirement for provision within firefighter shafts although a form of smoke control is.

United Kingdom offers a range of requirements for fire fighter facilities. Buildings higher than 18 m should typically be fitted with dry riser systems and firefighting shafts. Hydrants should be provided within 90 m of dry fire main inlets on a route suitable for laying hose or, for buildings not provided with fire mains, hydrants should be provided within 90 m of an entry point to the building and not more than 90 m apart. There are other requirements including access to smoke control and ventilation standards do not specify attendance times. Instead these are determined by individual fire and rescue services, who have had autonomy in setting their own response targets and strategies based on local integrated risk management plans (114).

The NFPA (101) covers requirements in buildings for appropriate controls including control of elevators, smoke extract and ventilation systems and other key features. They do have a separate code to cover full firefighting facilities. NFPA 1 (115) provides fire and life safety for the public and first responders as well as property protection by providing a comprehensive, integrated approach to fire code regulation and hazard management. It does reference NFPA 101, as well as many other codes. For example, it is a requirement that the aggregate fire flow capacity of all fire hydrants within 1000 ft (305 m) of a building cannot be less than the required fire flow. A table is then provided to allow calculation of how many fire hydrants will need to be required, together with how far they should be from the building. Note that a recent Code has been produced, NFPA 1710 that covers response times and allows a measurement system from initial alarm through to actual firefighting. NFPA 1710 (116) establishes criteria that provide a good place to start. Those criteria include:

- alarm answering time: 15 seconds for 95% of calls; 40 seconds for 99% of calls;
- alarm processing time: 64 seconds for 90% of calls; 106 seconds for 95% of calls;

- turnout time: 60 seconds for EMS responses; 80 seconds for fire responses;
- first Engine arriving at the scene: 240 sec (4 minutes) for 90% of responses with a minimum staffing of 4 personnel;
- second Engine arrives at the scene: 360 seconds (6 minutes) for 90% of responses with a minimum staffing of 4 personnel;
- initial full alarm (Low and Medium Hazard Assembly Time): 480 seconds (8 minutes) on 90% of responses;
- initial full alarm (High Hazard/High-Rise Assembly Time): 610 seconds (10 minutes 10 seconds) on 90% of responses.

Summary of findings

The idea for a global comparison of standards seemed to be a sensible exercise for research, although a like for like analysis proved more difficult than expected. This was largely due to national code styles and the format for questioning. Nevertheless, some early conclusions can be made:

- the criteria for means of escape did show some variations although the differences were relatively minor;
- the application of fire compartmentation showed a surprising degree of variation, given that construction styles and methodologies should be interchangeable anywhere in the modern world;
- agreements for a global standard for fire detection systems should be straight forward although could be influenced by preference for the UK or US approach;
- the basic facilities for firefighting are clearly similar although some of the detailed requirements may vary.

A more in-depth examination, perhaps by refining the questions, and using an even large cross section of nationalities, could provide more meaningful results.

One of the objectives of a proposed "holistic" fire strategy approach is to provide a single global methodology. It is concluded that the increased use of performance-based fire engineering solutions has more of a globally based level of acceptance. Nevertheless, given that the responses above were mostly based upon nationally prescribed codes, a global approach is still achievable but will probably rely on the willingness of all involved. This will be covered in section 3.2.

3. A review of the current status of the use of fire strategies

The previous chapter examined both national and international fire safety standardisation. The benefits of the flexible performance-based fire engineered solution are acknowledged internationally. Nevertheless, as stated, most countries continue to adopt codes that are largely prescriptive. This is understandable given that fire safety is an area where the risk of changing the main principles of specification may be one that many countries are not ready to accept. Whereas prescription limits flexibility, the flip side is that flexibility allows a greater degree of diversity in approach, in the assumptions made at the outset, and in the methods used to arrive at the final fire strategy. Such solutions often rely upon the experience, knowledge and, most often, opinion of those preparing the fire strategy. This leads to the conclusion that one building could potentially have multiple fire engineered design solutions. Clearly, this may be a factor holding back the embracing of the more flexible fire engineering process.

3.1. Verification of fire strategies

The variability of performance-based fire strategies is not just an issue for those formulating the fire strategy but also those who are tasked with verifying and approving the fire strategies. At least some enforcement authorities (3) have stated problems with respect to the receipt of fire strategy documents. Typically, every submitted fire strategy differs in the degree of detail, as well as format. Some use a pure performance-based solution including CFD modelling. Some tend to bridge the gap between prescription and performance setting. Some are ambiguous about the decisions made. All of this introduces a problem to those tasked with having to ensure that the fire strategies are indeed good enough. It was a simpler task when strategies used prescription. Now the task had become much more difficult.

Building design itself has also become more complex, introducing further frustration for enforcement agencies who typically cannot afford the resource and cost required to properly analyse each fire strategy forwarded to them. The same issues can be found around the world, with enforcement agencies facing similar issues, especially where building projects are increasing at a growing rate.

It has been muted (54) that a methodology that would allow for fire safety engineers to follow a process, would dramatically improve the consistency of approach and of the output. Given that the issue is a global (international) problem, then it would be sensible that the process is also global but acknowledging local national requirements. In the Author’s opinion, built on considerable international engineering experience, contemporary building designs are increasingly much the same around the world. This is a factor incorporated to the holistic approach is detailed in the next section.

3.2. A holistic approach to fire strategy formulation and approval

The issues raised in this chapter could be combined into a singular revised methodology for fire strategy formulation, rather than considered separately. The term *Holistic Fire Strategy* was chosen as an appropriate title for this idea (47). The word *Holistic* is defined here as "relating to the whole of fire engineering subject or to the total fire safety system instead of just to its individual elements and safety measures" (117). This would be most applicable in that the concept is seeking to apply a framework that will deliver a fire strategy that will cover all issues and not those just related to national requirements. Furthermore, the intention is that it is an international, or global, issue rather than a national one. The Holistic fire strategy concept incorporates all three elements as illustrated in Fig. 9. A "holistic" approach to fire safety is necessary. Meacham (118) recognised that a holistic and all-encompassing methodology was necessary when specifying fire safety for buildings, particularly where performance based fire engineering techniques are to be used.

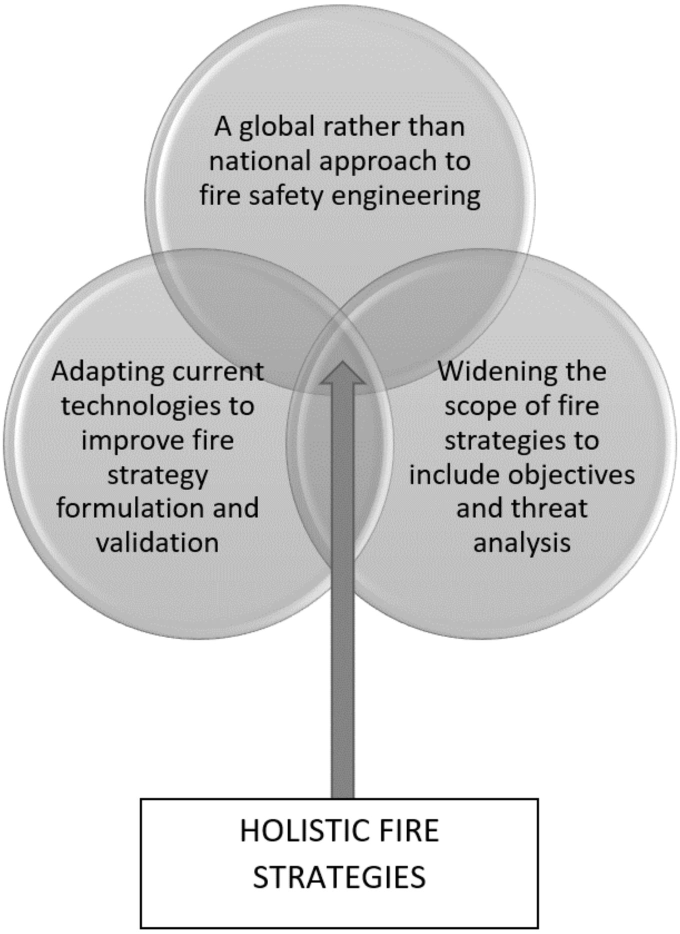


Fig. 9. The holistic fire strategy Venn diagram.

Given the wealth of what is already known about the subject of fire and fire safety, the holistic fire strategy concept is not intended to change fire science, or the application of fire engineering principles. The key principle is to provide a highly auditable framework. The beneficiaries of this would be those enforcement agencies around the world, as this will increase their confidence in holistic fire strategies but, more importantly, improve the efficiency of fire strategy evaluation and approval.

The concept should be available equally across all countries, whether the building design is based in London, Stockholm, Chicago, Dubai, Sydney, etc. The key principles are:

- to ensure that a fire engineered solution properly accounts for the real and perceived threats affecting the building, it occupancy and processes. Extreme events may or may not be included based upon a risk evaluation;
- that all objectives are considered, and not just those applicable to national regulations. Note that comparison with national regulations will need to be included within the process;
- all existing recognised means to develop holistic fire strategies are utilised;
- critical to the holistic fire strategy methodology is that the analysis and design process is controlled by a measurement system to allow full audibility and comparison at any stage of the process. Consequently, third parties can be provided with greater assurance that the solution is compliant with "holistic fire strategy" metrics;
- the process and metrics must be transferable globally such that they will be the same wherever they are applied. Obviously, the concept will need to include assessment of national requirements;
- the framework and process covers feasibility through to delivery of the holistic fire strategy.

This remainder of this Thesis will concentrate on one aspect of this; to improve the auditability of fire strategies. As a technical solution of the proposed *Holistic Fire Strategy* methodology, a semi-quantitative approach is proposed, where the chosen (referred to as actual) fire strategy is compared with a baseline fire strategy, typically taken from national codes. A fire strategy risk indexing system has been developed to cater for this. The method, with practical examples of its use, are described in Chapters 5 and 6.

3.3. Objectives and Threats

The Holistic Fire Strategy concept described introduces two sets of criteria that are not currently automatically incorporated into the fire strategy process (47). These are:

- Enhanced Objectives Setting;
- Threat Analysis.

Enhanced Objectives Setting is one of the conclusions from the fire statistical trends raised earlier, i.e. objectives outside of life safety remain a concern. As previously noted, national legislation tended to focus on life safety, so consequently, fire strategies would be typically bound to life safety requirements. Some strategies would venture out to consider other objectives such a property protection, but normally when specifically required by external stakeholders such as insurers. Preparing a fire strategy for a new building is often a golden opportunity to at least consider other objectives, rather than later down the line (5). Objectives setting may be covered somewhat in fire safety guidance but often not explicitly. Sometimes it may take the input of other stakeholders to initiate a greater level of objective setting. The Fire Offices' Committee (the FOC) (14), an organisation introduced in Chapter 1, can be used as one example. The focus of the FOC was understandably on the use of fire protection to protect insured risks. Predominantly the risk was the building and possibly the stock / assets within that building. The FOC wrote their own set of rules covering automatic sprinkler systems, passive fire protection requirements and fire detection and alarm systems. For those who abided by these rules, and used approved equipment, then the insured would enjoy a substantial discount on the insurance premiums. One outcome was that, in the UK at least, there were two groups of standards. The British Standard set of standards which tended to concentrate on life safety, while the insurance standards concentrated on property protection. Fortunately, over the years, some of the standards came together either via the European Standards Committee – CEN or the International Standards Organization (ISO). Note that, in many ways, the United States have experienced a similar situation with the National Fire Protection Association (NFPA) covering Life Safety and the Underwriters Laboratories (UL) and Factory Mutual (FM) covering other objectives, notably property and asset protection. In some cases, property protection and life safety have been amalgamated into a single standard. For the case of fire detection and alarm systems in the UK, the concepts were combined into the British Standard BS 5839 Section 1 (108) by using categories; the L set of categories cover life safety and the P set cover Property Protection. The Author of this Thesis was directly involved in merging these objectives for the British Standard.

BS PAS 911 (6) identified the primary objectives as life safety, property protection, business protection & continuity and environmental protection. All four primary objectives may be relevant to a specific building, in whatever sector it operates, and in any region of the globe it is located. *Fig. 10* shows the four primary objectives. Each of these objectives is broken down into four sub-objectives, to assist in decision making. It is proposed that every fire strategy should consider all 16 sub-objectives for every building project. This idea is presented as part of the holistic fire strategy process but is not part of the scope of this Thesis.

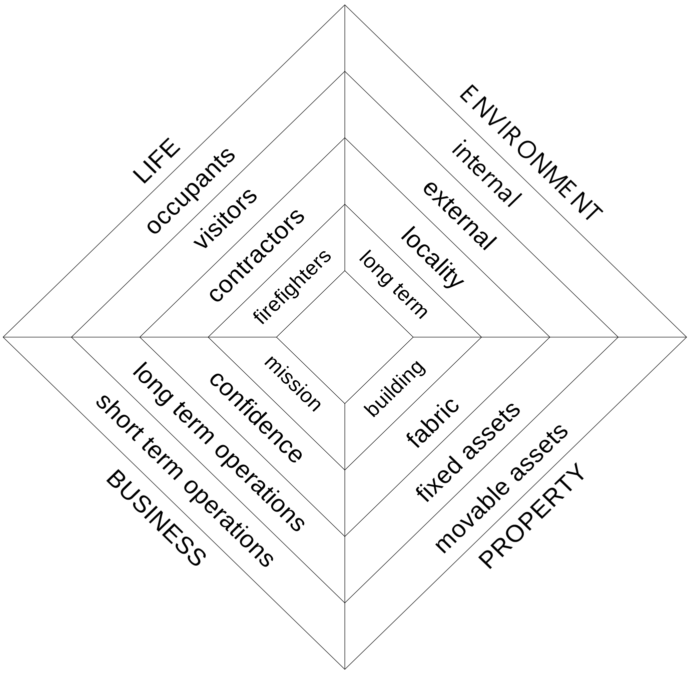


Fig. 10. The fire strategy objectives matrix (6).

The concept of introducing **Threat Analysis** (119) is in recognition that the social environment is changing. New threats could lead to new fire scenarios that may not have been properly considered in the past. A fire safety engineered solution should incorporate a proper consideration of threats that could impact on the building, its occupancy, and its processes. Most fire strategies are based upon the concept of a single fire event at any one time. It is doubted whether most fire safety engineers, when applying their national codes to a new building project, are even aware of that fact. Most standards are based on the idea that anything other than this event is sometimes regarded as an extreme event. In fact, it is not uncommon for fire strategies to state that "extreme events" are not allowed for. Many may believe that an extreme event is something like a major explosion. National Codes mostly regard two simultaneous, independent, fires in different parts of a building as an extreme event. Stakeholders involved in the fire strategy process may not even be aware of such a limitation. Note that the methodology of incorporating threat analysis into a holistic fire strategy is not covered in this Thesis.

3.4. Sustainability in building design and its impact on fire safety decision making

The primary aim of fire safety engineering is to assess the building, its processes and occupancy profiles and to determine the most effective strategy to limit the consequences of a fire, both directly and indirectly. Typically, a key consideration is the protection of life, although, in more recent times, the scope has widened into issues such as protection of assets, business interests and the environment. Collins English Dictionary (120) defines sustainability as the ability (for a scenario) to be maintained at a steady level without exhausting natural resources or causing severe ecological damage. Given that damage control is also a primary objective of fire safety and protection, it could be argued that the objectives of both the sustainability and fire safety industries are aligned. But this is not always the case. Some of the methods used to fight fires have been found to be harmful to the environment. Halons (halogenated hydrocarbons), once prominently used to extinguish fires, were found to be extremely harmful to the ozone layer and were banned for general use in the 1990s. Run-off water from the action of firefighting typically can contain chemical biproducts of combustion, leading to contaminated land, rivers, etc. (121). There are other issues affecting the relationship between sustainability and fire safety / fire engineering (122). One example is the extensive requirement of fire compartmentation in building fire strategies, whilst sustainable building design tends to favour more open building layouts. If sustainability is to become a natural feature of the built environment (123), then the methods used to apply fire safety need to incorporate features that consider issues such as the environment. This must start by reflecting on how fire strategies are both prepared and evaluated. Troisi *et al* (124) refers to enforcement Authorities as one agent in improving a systemic approach to safety systems, with a shift of perspective from single bodies involved with safety performance to interdependence with all agents.

As identified above, despite advancement of the use of fire engineered solutions, most buildings are still required to meet with the prescriptive national building regulations. These have historically been supported by national fire codes which have also been largely prescriptive in nature. Such rules are often seen as restricting advances in building design. The whole focus is on rigid designs to help protect building occupants against the ravages of fire, with little concern for other aspects such as the internal and external environment of the building. This is naturally at odds with the objectives of sustainability. The Society of Fire Protection Engineers (125) stated that performance-based fire engineering design will become increasingly important in ensuring sustainable building design. They recognised the mismatch between fire safety prescription and sustainability issues and point out that, in order to quantifiably reduce a building's resource use, fire engineers need to take into account the resource demands of products necessary to achieve the required fire safety performance. The fire protection industry needs to recognize new materials and products, and adapt the fire safety solutions accordingly (126) (127).

A major manufacturer of fire resisting glazing (128) highlights that fire can have a major impact on the sustainability of communities and the built environment since a building that burns down is fundamentally unsustainable. They point out that fire protection of buildings therefore has an increasing role on the sustainability agenda. Yet, most fire standards and codes rarely explicitly highlight the issue of sustainability (129). It is only by promoting an innovative approach can the subject and objectives of sustainability be specifically incorporated.

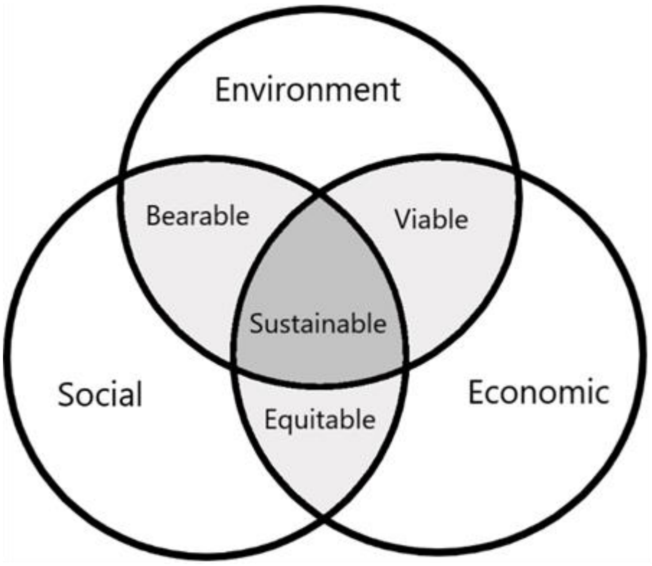


Fig. 11. A sustainability model (170) (129)

Fig. 11 illustrates a model depicting how sustainability relates to the key factors of social (equity), economics, and the environment. The balancing of all three factors will enable true sustainability to be delivered. But could this relate to the objectives of fire engineering? Social factors closely relate to the ethical need to protect life and this is largely delivered by national fire safety regulation as being a fundamental part of all building legislation. The environmental issue is less touched upon by prescriptive fire standards but can be a key consideration and a performance objective for modern fire safety engineering. Economics is a factor that is relevant in both approaches. The added flexibility of fire engineering has also been recognised as delivering benefits by avoiding “overprotection” (6) and applying systems as specifically required. They obvious conclusion is that the adoption of performance-based techniques for the specification of fire safety and protection will assist in developing “sustainable buildings”. However, there are some issues that may prevent the techniques from being globally approved (130). Nevertheless, the drive towards "green" buildings and core sustainability in both building and community design continues. The fire industry will need to adapt.

3.5. Building information modelling (BIM) and fire safety

Building information modelling, or more commonly referred to in its abbreviated form – BIM, is widely regarded as the next inevitable step in building design and construction. Traditionally, the various phases from building concept to handover made use of a variety of disconnected tasks (131) such as drawings (usually numerous versions to cover various elements of the building and services), multiple schedules of materials and assets, specifications for each aspect of the building, externally and internally, and production and construction detail documents. These would normally be supported by method plans and statements for each stage of the building design and construction. Instead, BIM allows the detailed development of the building, virtually and in 3D, to provide a single holistic model. Any documents can then be taken off the master model. A key benefit is that any modifications to the design will influence all aspects of the area affected.

The idea behind BIM can be traced back to 1975 with a concept then referred to a "Building Description System" (132). A leading architect at the time, Charles Eastman, wrote a paper titled "*The Use of Computers Instead of Drawings in Building Design*". He discussed amalgamating different geometric objects for building design to create a single project, allowing viewing a given model from many different angles, combined with databases for the components of the building projects.

It is inevitable that the primary global supplier of computer aided building design software – Autodesk, are playing a lead role in BIM today. Their product is called "Revit". The benefits they cite (133) for BIM are:

- Improves efficiency and accuracy across the building project lifecycle, from concept to construction.
- Allows the automatic updating of floor plans, elevations, and sections.
- Performs routine and repetitive tasks automatically.
- Allows collaboration between the different parties (architects, engineers, project managers, etc) to work together and deliver projects more efficiently and with less errors.
- Allows for specialist analysis of specific aspects of building design. Specifically, the system can allow, for example, structural analysis and performance of materials such as the types and arrangements of timber, concrete and/or steel solutions.
- Provide a complete auditing and information management tool, including automated schedules of components.

There are no doubts benefits in BIM for the application of fire strategies. Strömgren (26) uses the example of the Grenfell Tower Fire in London (2017) and the subsequent review (the Hackitt report) of the UK fire safety building regulations. The report acknowledges that BIM can improve the control and transparency of specifying fire safety and fire protection systems for buildings. In other words, a more robust audit trail, a factor identified as a failure in the Grenfell Inquiry. It is the central management of large amounts of information covering every asset and material used in the building that is so powerful a tool.

Already, specialist software applications for fire safety and protection using BIM are being introduced. One such example is a Swedish company, Briab, who have recognised the need. They have introduced their own suite of software called *BIMfire* (134) to allow designers to allocate fire protection features to 3D CAD models. This will include the specification and location of fire compartments together with relevant ratings, the location of fire detectors with cable routes and the layout and pipework location for sprinkler systems. They also provide, a collaborative platform using the web. It is likely that many similar applications will emerge.

One thing to note here is that BIM is becoming a global tool. A single standard building design methodology that can, at one instant, provided a uniform solution wherever the building is located. Yet when it comes to fire safety, this will need to revert to national requirements. A concept of fire strategy formulation and verification that can neatly tie into the BIM phenomenon is, no doubt, desirable. The aims of this Thesis – to provide a better process of providing fire strategies, on a global basis, is consistent with the aims of BIM.

4. Fire scenario analysis: Determining the most appropriate fire scenario within a public building for further evaluation

4.1. Fire scenarios in public buildings

One of the best ways to evaluate the performance of a fire strategy is to test it. One or more fire scenarios can be chosen and evaluated. To help select appropriate fire scenarios, the following methodology has been developed. It is designed to be of particular use for public buildings, given that they tend to be more complex in nature than many buildings used for non-public use. This complexity can be found in three ways:

- **building design and layout complexity whereby** buildings are designed to accommodate anything from a single use with simple dimensions, through to those intended for a range of uses with the necessary levels of convolution. Buildings intended for use by the public, tend to be at the upper end of the range;
- **occupancy profile complexity** represented by one or more occupancy groups, or profiles, within the building at any one time. This could include significant occupant densities in specific parts of the building, occupancies of different age ranges, occupants of varying degrees of manoeuvrability throughout the building, etc.;
- **process complexity** when it is necessary to accommodate for a range of processes within the building. The type (s) of process can vary from those introducing minimal fire risk to those where extensive fire safety management procedures and sophisticated fire protection systems will be required.

All the above introduce a range of fire risks and, consequently, several possible fire scenarios. These scenarios will need to consider some factors:

- likely location within the building;
- likely means of ignition;
- likely level of direct fire loading;
- likely method of fire spread;
- designated existing control measures.

It would be evident that many complex public buildings could have limitless possible fire scenarios. Consequently, a method to analyse and determine the most important fire scenarios is required. This will follow a fire risk evaluation of each potential fire scenario.

The Author (5) has identified that, in many ways, prediction of how a fire develops and its impact on a building is similar to predicting the weather. As with fire, the key principles and patterns of growth and movement are known. What cannot be predicted with accuracy is in the determination of the end results and the impact of a major event. Nevertheless, a range of risk analysis methodologies are used for evaluation of fire risk. Some are detailed below.

4.2. The global concept of risk assessment

As presented in the chapter 2.4, the International Organization for Standardization (ISO) is a global platform with the intention of unifying national rules. The risk assessment process, as a subset of a risk management process, is described by ISO Standard 31000 (135) and is illustrated in *Fig. 12*.

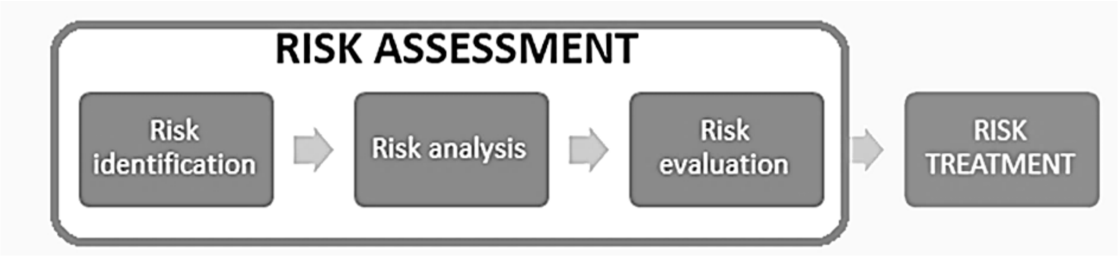


Fig. 12. The ISO risk assessment process (135).

In this Standard, risk management incorporates both risk assessment and risk treatment, Risk assessment is then broken down into three elements:

- Risk identification - the identification of those areas that offer a distinct risk;
- Risk analysis – the analysis of how those areas identified will lead to certain unfavourable risk-based scenarios;
- Risk evaluation – a qualitative or quantitative evaluation of the level of risk found.

From the risk assessment process, appropriate levels of treatment can be applied. The Standard states that it is designed for use by people who create and protect value in organizations by managing risks, making decisions, setting and achieving objectives, and improving performance. It points out that organizations of all types and sizes face external and internal factors and influences that make it uncertain whether they will achieve their objectives. The Standard gives several pointers:

- it is iterative and assists organisations in setting strategy, achieving objectives and making informed decisions;
- it is part of governance and leadership and is fundamental to how the organization is managed at all levels. It contributes to the improvement of management systems;
- it is part of all activities associated with an organization and includes interaction with stakeholders;
- it considers the external and internal context of the organization, including human behaviour and cultural factors.

Note that the ISO Standard is used to evaluate all risks and not those posed by a fire within a building. There are many guidance documents and standards that specifically cover fire risk which will be described shortly. By developing the elements given in *Fig. 12* but relate to the specifics of fire risk assessment, the different stages in fire risk management can be described as:

- *Fire risk identification* is a systematic means to understand how, when, and why fire could happen in each area of a building being assessed. This would typically be a qualitative process;

- *Fire risk analysis* (also known as fire risk assessment) which is the process of estimating magnitudes of consequence and probabilities of the adverse effects resulting from fire in a building. The result of fire risk analysis is expressed either in qualitative, semi-quantitative, or quantitative terms, depending on the type of risk, the purpose of risk analysis, how detailed the analysis is to be, and the information resources available;
- *Fire risk evaluation* follows on from the analysis by judging the risk criteria to determine the appropriate or acceptable level of fire risk;
- *Fire risk treatment* is the implementation of assessing existing risk control measures, and to recommend additional risk control measures and implementing these measures to reduce fire risk.

Although fire risk analysis and assessment is only considered to be one aspect of the ISO risk management process, it has been used as the foundation of regulatory decision-making on whether to take actions to reduce risk or choose appropriate risk treatment measures. The UK fire safety legislation – the Regulatory Reform (Fire Safety) Order, described in the previous chapter, is one example.

There are documents that detail the steps required for the undertaking of fire risk assessments. British Standard PAS 79 (136) suggests the process is divided into 9 steps:

1. obtaining information on the building, the processes carried out in the building and the people present, or likely to be present, in the building;
2. identification of the fire hazards and the means for their elimination or control;
3. assessment of the likelihood of a fire;
4. determination of the fire protection measures in the building;
5. obtaining to the relevant information about fire safety management;
6. assessment of the likely consequences to people in the event of fire;
7. assessment of the fire risk;
8. formulation and documentation of an action plan;
9. definition of the date by which the fire risk assessment should be reviewed.

The above is designed to be a practical guide for those undertaking fire risk assessments. There is a difference between a fire risk assessment for the benefit of legislation and one to assist with the development of a fire strategy, particularly for new constructions (5). In several cases, the former could be described better as a fire compliance assessment where the assessor compares his or her findings with the requirements of building regulations and standards, together with an assessment of the "fire precaution" housekeeping. The latter is likely to be more of a technical exercise where the risks could be quantified and determined by the team.

The use of a risk assessment process in identifying both the likelihood and impact of a fire is sometimes referred to as probabilistic risk assessment (137). Note that probabilistic risk assessments may be much more complex than a simple assessment based on a subjective judgement of two factors, and then multiplying them together. It may be developed using statistical techniques, which could be based upon relevant fire data from historical fires. Assessments may use mathematical techniques such as regression analysis. Sensitivity or event tree analysis can be applied to provide a more robust conclusion by showing how a sequence can lead to certain outcomes.

Probabilistic risk assessments can be as straightforward or as complex as would be appropriate for a building, its occupancy, its process, and the objectives set for the fire strategy. The most advanced standard in this field is that offered by British Standards Institution. BS PD 7974-7 (137) is part of a suite of documents designed to support the performance-based approach described by British Standard BS 7974 (60). It states that a probabilistic risk assessment can add value to traditional deterministic analyses and outlines acceptance criteria for the assessment. It includes data for probabilistic risk assessment, based on fire statistics, building characteristics and reliability of fire protection systems. Deterministic studies can be used to *determine* potential worst-case scenarios. To get to a point where this approach is useful, those undertaking the analysis would need to derive several significant scenarios and ensure that the chosen fire strategy can cope with them. Such a method may make use of fire modelling techniques to evaluate prescribed zones or fields, to show the impact of chosen fire scenarios over time and under specific conditions. Alternatively, deterministic methods could be highly quantitative.

New Zealand uses a form of this approach and is described later in this chapter (98). A comparative study of risk is another approach that, as the term suggests, compares the risk of the building subject to the fire strategy with similar building and occupancy criteria. This is a form of risk profiling and is a suitable method of fire risk analysis for new build projects. Finally, the fire risk profiling can be a useful and quick route to categorising a building and its occupancy. The profile can be based on a single aspect of a building or may cover several factors, such as:

- building size/complexity;
- building use;
- occupancy profile including occupant numbers, age range, mobility, sleeping/non-sleeping risks, etc.;
- average/worst-case potential for ignition;
- average/worst-case fire loading criteria;
- typical fire growth curve.

Risk profiling tends to take a common-sense approach in that, for example, one hospital would have a similar risk profile to another hospital, one petrochemical plant would tend to be similar in risk level to another. British Standard BS 9999 (7) makes use of risk profiling and uses two factors to allow a specific building and its use to be categorized. This is based upon expected fire growth rate as well as the type of occupancy. For example, an office building with occupants aware of the building and a medium growth rate will be classified with one profile. A sleeping risk, also with a medium fire growth rate, will have a higher risk profile. The US Society of Fire Protection Engineering (SFPE) (138) *Handbook of Fire Protection Engineering* (139) has introduced a similar method of identifying risk by using a risk indexing system. Fire risk indexing systems can be described as an empirical model of fire safety and are particularly useful for the insurance application of risk based upon hazard categorisation. The methods constitute various processes of analysing and scoring hazard and other system attributes to produce a rapid and simple estimate of relative fire risk. The system may start with a degree of subjectivity by using professional judgment and experience. Fire risk indexing assigns values to selected variables, representing both positive and negative fire safety features. The selected variables and assigned values are then operated on by some combination of arithmetic function to arrive at a single value, which is then compared to other similar assessments, or to a standard. In a latter chapter, these principles are used to develop a fire strategy risk index system. A risk index is defined as a single number measure of the risk associated with a facility (140). Thus, insurance rates are linked to fire risk indices.

Lapp *et al* (141) provides a graphic view of the relative power and limitations of three broad levels of risk quantification as illustrated in *Fig. 13*. Curves A, B, and C do not represent actual data points but are used for relative illustration.

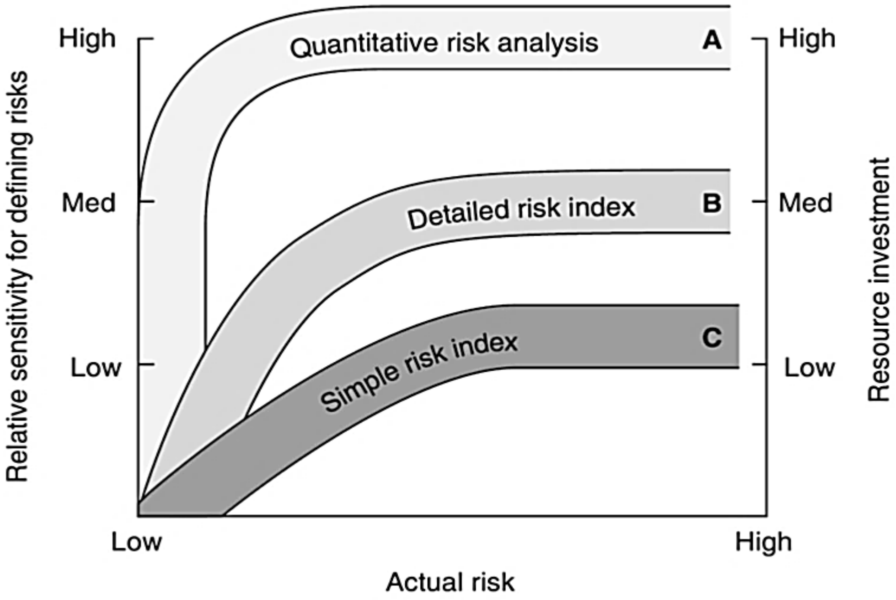


Fig. 13. Risk indexing system and relative sensitivity (141).

Curve A represents a probabilistic risk analysis using quantitative analysis of the hazards and statistics for exposure (or severity). This analysis is described as the most accurate approach to defining risks, especially where the risk is low. It is also clear that a large resource investment is necessary to accomplish this task. Curve B, as being central to the above curves, represents a method that may be usable for normal circumstances. Curve C is a more simplistic fire risk indexing. This is most useful for high-risk worst-case loss situations where the analysis is consequence oriented. This is not so good for evaluating small differences in risk level. On-site fire risk assessments would probably be best represented by this curve.

A more complex and accurate assessment model will provide greater differentiation between lesser risks and an improved overall accuracy. The trade-off for this approach is increased time and resources expended for model development, implementation, and data collection. Another approach, not dissimilar from the above, was introduced by BS PAS 911 (6). This also considers the resource commitment required to maintain a certain level of risk. Similarly, the same level of resources applied to two different risk profiles will leave different levels of residual risk. It is pointed out that risk vs resource commitment can be illustrated by curves, not dissimilar to the supply and demand curves from economics theory. This idea is shown in *Fig. 14*. The *x, y* coordinates are “cost” and “risk level”. Taking one risk profile as an example, the idea is that with minimal cost associated with applying fire safety and protection resources, there will be an understood level of risk. As resources are purchased and brought into the strategy, the level of risk will gradually be reduced until an optimum level of risk versus cost is reached. As more cost is invested into further risk mitigation provisions, the level of additional risk reduction will reduce until it reaches a stage where there will always be a residual level of risk.

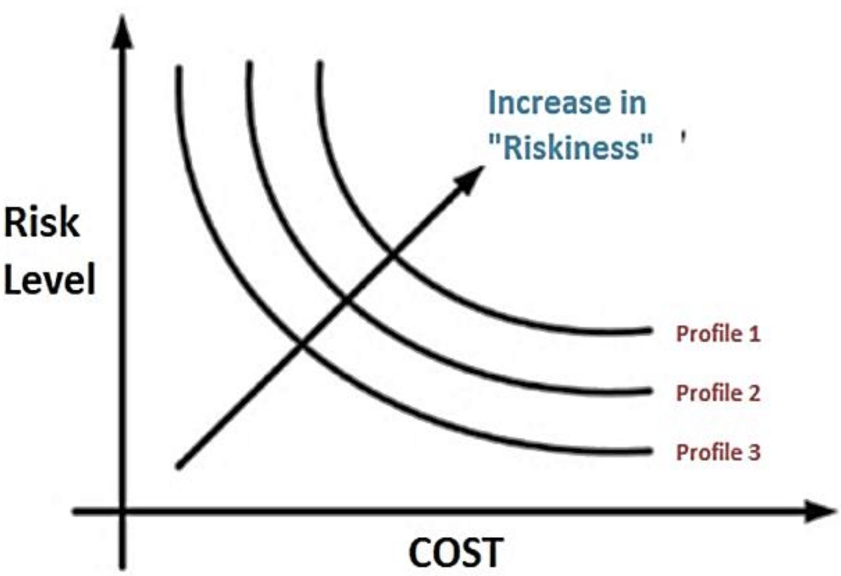


Fig. 14. Risk/Resource profile curves (6).

Note that buildings of a certain type and use will inherently have different risk profiles, so the risk/cost curve will be on a different plane—the riskier the profile, the more the curve moves to the right. The purpose of the curve analogy is to promote an alternative way to think about risk, particularly when cost of the fire strategy is a measure.

At this point, it is worth mentioning the term ALARP which many risk assessment practitioners use, or at least have heard of. "ALARP" (142) is the abbreviated form of "*as low as reasonably practicable*". There is another similar term of "SFAIRP" for "*so far as is reasonably practicable*". The two terms consider the practicality of risk management. The concept of "reasonably practicable" involves weighing a risk against the logistics, time and resource required to provide ultimate levels of risk control. ALARP describes the level to which realistic measures are taken for risk control. Using "reasonably practicable" allows us to set realistic goals. This therefore allows some flexibility over prescriptive requirements. It does require subjectivity by requiring risk assessors to exercise judgement. The term 'good practice' is probably appropriate if ALARP is used. For high hazards, complex or novel situations, more formal decision-making techniques, including cost-benefit analysis, should be considered.

The SFPE Handbook (139) defines fire risk as the product of the probability of fire occurrence and the consequence or extent of damage to be expected on the occurrence of fire. As identified above, there are three key factors comprising:

1. loss of or harm to something that is valued (e.g., life, property, business continuity, heritage, the environment, or some combination of these);
2. the scenario that may induce the loss or harm;
3. a judgment about the probability that the loss or harm will occur.

Fire risk is described as a weighted average of the risk values of each scenario, and it can be presented with the following formula:

$$FR = \sum_{i=1}^{n} P_{f_i} C_{f_i} \tag{4.1}$$

where:
FR – fire risk,
P_{fi} – probability of occurrence of fire scenario i (per year),
C_{fi} – consequences of scenario i;
n – the total number of scenarios.

It could be said that the more scenarios that are chosen (n) the more accurate will be the determination of fire risk. Similarly, the Fire Risk can be applied to several different objectives such as the risk of occupancy deaths, the risk to the property itself, the risk to business and also to the environment. Of course, determination of one or more scenarios for further assessment, will be a key factor behind a performance-based approach when used with fire engineering.

ISO/TS 16733 (143) introduces one approach in the identification and development of appropriate fire scenarios. Ten steps are to be followed from the location of a fire through to event tree analysis to final selection based upon probability, consequences, and the appropriate risk ranking (*Table* 2). In a real sense, the number of potential fire scenarios is unlimited, particularly when complex building environments are assessed. If the ten step ISO approach is followed, then the more likely fire scenarios can be established.

Table 2. ISO recommended steps for determining fire scenarios (143).

STEPS OF ISO/TS16733	**COMMENTS**
1.Location of fire	Characterize the space in which fire begins as well as the specific location within the space.
2.Type of fire	Characterize the ignition, initial intensity, and growth of potential fires.
3.Potential fire hazards	Identify fire scenarios that could arise from fire hazards associated with the intended use of the property or the design.
4.Systems impacting on fire	Identify the fire safety systems and features that are likely to have a significant impact on the course of the fire development of untenable conditions.
5.Occupant response	Identify actions that people take that can have significant impact, favourable or otherwise, on the course of the fire or the movement of smoke.
6.Event tree	Construct an event tree that represents alternative event sequences from fire ignition to outcome associated with fire scenarios.
7.Consideration of probability	Estimate the probability of occurrence of each event using available data and/or engineering judgement.
8.Consideration of consequence	Estimate the consequence of each scenario using available loss data and/or engineering judgement.
9.Risk rating	Rank the scenarios in order of relative risk. The relative risk can be evaluated by multiplying steps 7 and 8.
10.Final selection and documentation	For each fire safety objective, select the highest ranked fire scenario for quantitative analysis. Selected scenarios should represent the major portion of the cumulative risk (sum of the risk of all scenarios).

The SFPE (144) utilises the ISO methodology and recognises that large numbers of scenarios can be prohibitive to most projects so that a selection process using event trees, together with probability and consequence analysis, is the best way forward. It also highlights the use of a model developed by the National Research Council of Canada that uses a fire risk and cost assessment process. The model is called *FiRECAM* (144) and calculates the expected risk to life as well as the cost of a fire using hazard analysis of chosen fire scenarios.

The *FiRECAM* model reduces the number of potential fires into three basic types:

1. smouldering fires where smoke only is generated;
2. non-flashover flaming fires – generation of relatively small amounts of heat and smoke;
3. flashover fires involving significant amounts of heat and smoke with the potential for fire spread throughout the building.

Interestingly, the model utilises data from the USA, Canada, and Australia to consider the relative expectation of each type of fire. In this case, for apartment buildings. This is shown in *Table 3*.

Table 3. probability of fire types in apartment buildings (145).

FIRE TYPE	**AUS (%)**	**USA (%)**	**CAN (%)**
SMOULDERING FIRE	24.5	18.7	19.1
NON-FLASHOVER FIRE	60.0	63.0	62.6
FLASHOVER FIRE	15.5	18.3	18.3

Perhaps not surprisingly, non-flashover fires are the most common and seem to compare well over the three countries. The other fire types are also relatively consistent as a percentage. This points to the fact that fire statistics show a degree of consistency in different continents. Possibly, given the statistics are from first world countries, this uniformity could be attributed to those countries with similarly well controlled fire safety regulation. A more useful analysis would include a range of countries from all parts of the world. This simple evaluation does point to the fact that a global methodology for fire strategy formulation would make sense.

The New Zealand government has adopted an interesting approach to the subject of fire scenarios. In its standard C/VM2 (98) it is recommended that, for a performance-based solution, there are ten identified fire scenarios that any fire engineered design should be assessed against. If any aspect of the design does not cater for these scenarios, then additional control measures will be required. The ten scenarios are:

- Blocked Exit (BE) considers whether a single escape route is acceptable or not. This is based upon the identified number of persons in a specific section of the building (room or floor). The figure of 50 persons is given as the maximum parameter where additional routes may be required. This is raised to 250 persons for sprinklered multi-storey buildings;
- Unknown Threat in unoccupied room (UT) looks at a threat to occupied areas from a fire that may start in an unoccupied area. Again, occupant loading of 50 is used as a benchmark. Other factors for consideration are the use of automatic sprinkler

systems, fire detection systems and fire separation. One of the checks recommended is an ASET/RSET evaluation;

- Concealed Space (CS) in which the 50-person parameter is used to determine whether such spaces, such as floor and ceiling voids, could create adverse conditions for evacuation. The dimensions and fire loading of the spaces are identified as defining criteria, together with the use of active and passive fire protection;
- Smouldering Fire (SF) considers whether a smouldering fire could adversely impact on sleeping persons. The key control measure here is the use of fire detection and alarm systems;
- Horizontal Spread of fire (HS) considers spread of fire horizontally from one building to the next. The premise here is whether the building is sprinklered or not. If not, it considers the dimensions of an “enclosing rectangle” boundary conditions of the building based upon fire loading per unit area, as well as radiant flux;
- Vertical Spread of fire (VS) allows assessment of how a fire could spread vertically via external walls. Of relevance here are whether there are sleeping occupants in upper levels, building height (10 m criteria) and the use of façade materials;
- Surface finishes and rapid-fire spread involving internal surface linings (IS) looks at the impact of internal linings and points to relevant NZ standards for flammability;
- Firefighting Operations (FO) considers firefighters access and provisions. Key parameters for decision making include sprinkler protection, building boundary conditions, floor area, fire loading, expected radiation flux on arrival of the fire service, etc.;
- Challenging Fire (CF) looks at potential worst-case scenarios in a normally occupied building. This requires detailed consideration of ASET and RSET conditions to determine if the building has a suitable safety margin to allow evacuation before conditions become untenable. The “challenge” is included in that it should be considered whether the fire could create potentially challenging conditions for the building’s fire safety systems;
- Robustness Check (RC) considers how failure of a key fire safety system could impact on life safety. Once again, this scenario is based upon numbers of people affected (150 or 50 sleeping persons). The scenario should consider how any system could impact on the ASET/RSET calculations and whether these will need to be revised.

Another interesting way of reviewing fire scenarios is to consider a fire scenario cluster approach, as presented by Jing Xin *et al* (146). A 'fire scenario cluster' is a subset of fire scenarios that resembles each other. It could group the universe of possible fires into a manageable number of scenario subsets so that all the elements are present. As observed in the examples above, a fire scenario is a sequential set of fire events that are linked together by the success or failure of certain fire protection systems or actions. A fire event is an occurrence that is related to fire initiation and growth, and may be impacted by existing control measures, occupant behaviour, and firefighter response. In the process of understanding fire risk analysis, a few fire scenario clusters can be considered important to support calculations of frequency and consequence: a fire scenario cluster, a fire automatic suppression scenario cluster, a fire behaviour cluster, and so on.

The clustering of similar fire scenarios is recognised by the NFPA in their guide NFPA 501 (147). This document divides fire risk assessments into four methodologies: qualitative, semi-quantitative (likelihood) - where "likelihood" only is quantitatively assessed, semi-quantitative (consequences) - where "consequences" only is quantitatively assessed and fully quantitative. The document re-introduces equation 4.1 (in a slightly modified form) but also introduces a derivative equation (Eq. 4.2) where multiple objectives may need to be considered such as the inclusion of business risks. The equation applies the summation of scenarios for one objective (j to m) with a secondary objective (i to n).

$$R_i = \sum_{j=1}^{m} . \sum_{i=1}^{n} F_i C_{ij} \tag{4.2}$$

where:
R_i – total risk,
C_{ij} – consequence of multiple losses,
F_i – sequence frequency.

This is an interesting idea, which points to the conclusion as how the total risk can become convoluted and complex, especially when multiple objectives are considered. In section 4.3 an alternative suggestion for evaluating risks for specific fire scenarios is given.

4.3. An alternative methodology for assessing fire risks scenario in fire strategy evaluation

Even with the wealth of information available, it is questioned whether a succinct methodology could be provided that may assist in scenario determination in a globally consistent manner. Some of the concepts introduced above are used but in a modified form. The premise assumed is that the varied probability/consequence formulas described are tried and trusted but may have certain flaws. Is it possible to fully understand the single factor of probability of a fire event, by treating it as a single variable? By separating the probability of fire ignition from that of fire spread, then a much more realistic probability factor can be created. The reasons for this are that:

- fire ignition and spread require consideration of a different set of variables;
- fire ignition requires a more fundamental assessment of a small number of limiting conditions, namely local fuel and heat sources in oxygen;
- if fire prevention techniques are particularly good, such that the probability of ignition is negligible, or very low, then further assessment of growth conditions is less important;
- assessment of the probability of fire growth will typically be more complex and require consideration of a range of factors including potential routes for smoke and fire and existing limiting features and control measures.

Following on from the above, there are two probability factors: P_i - Fire ignition and P_g – Fire growth

To understand the Probability factor of fire ignition (P_i), requires returning to the fundamental elements of the fire triangle, namely, fuel, heat and oxygen, if any one of these three parameters are non-existent then, de-facto, there will be no fire. In the real world, all three parameters exist to a lesser or greater extent. Accordingly, the probability of ignition is not likely to be absolute zero but could often be described as being negligible. Therefore, the scenario fire risk is simply proportional to an ignition (with a varying degree of probability) or non-ignition condition. The consequence, or impact, of a fire is only relevant should the fire grow after ignition. This can be represented by:

$$SFR_i \sim P_i \tag{4.3}$$

where:
SFR_i – Scenario Fire Risk (ignition),
P_i – probability of fire ignition.

Analysing and quantifying fire hazards has been a key component of fire risk analysis for decades (148). The book "Fire strategies – strategic thinking" (6), describes that the risk or hazards associated within an enclosure will exist in one of two ways: the local environment of the enclosure (covering the static elements of the enclosure such as the structure, fabric and fixtures/fittings) and the process (covering the dynamic environment of people, equipment, operations, and so on). To understand this better, a matrix (*Fig. 15*) with coordinates separately depicting the environmental hazards and process hazards is introduced, thus allowing every enclosure or area of the building to be subjectively judged independently.

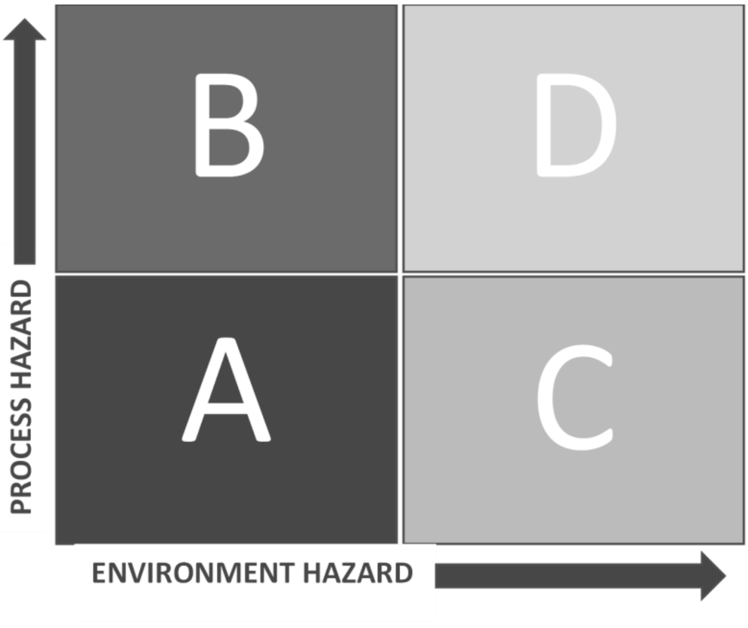


Fig. 15. Hazard matrix (6).

The hazard matrix is primarily designed to assess how a set of hazardous conditions could lead to fire ignition and is not completely relevant to fire growth when another set of conditions will be at play. The quadrants are as follows:

- Quadrant A (Low Environment Hazard / Low Process Hazard) existing in an ideal situation presenting little risk to the building;
- Quadrant B (Low Environment Hazard/High Process Hazard) which will be in a situation where processes are necessary, so a low environmental hazard is appropriate. Such a situations will be found in hotels, restaurants, and schools where the main process is people and our behaviours;
- Quadrant C (High Environment Hazard/Low Process Hazard) existing when a hazard is present, but the process within the area is controlled, possibly by good levels of fire safety management. Examples include heritage buildings, where the inclusion of drapes, bookcases full of books, and so on, are the key risks;
- Quadrant D (High Environment Hazard/High Process Hazard) represented by situations when a fire is more likely to be an inevitability than a possibility.

By plotting each area, enclosure, or room on the matrix, a "hazard profile" can be prepared, rather like a hazard fingerprint for a building. In this way, fire engineers can focus on key areas and devise a solution accordingly. *Fig. 16* gives an example of this in use.

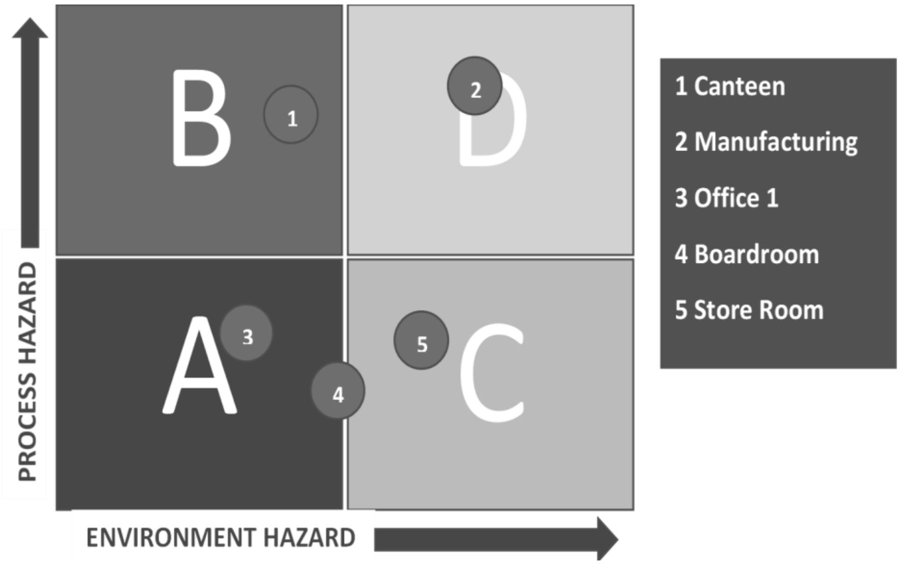


Fig. 16. Use of hazard matrix (6).

This methodology illustrates another thought, and that is what is that the probability of a fire ignition event should be considered from both the perspectives of the environment, and processes. Consequently, equation 4.3 could be further modified as follows:

$$\mathrm{SFR_i} = \frac{(\mathrm{P_{ie}} + \mathrm{P_{ip}})}{2} \tag{4.4}$$

where:
SFR_i – Scenario Fire Risk (ignition),
P_{ie} – probability of fire ignition due to the environment,
P_{ip} – probability of fire ignition due to the processes.

The Scenario Fire Risk (for ignition) is the mean sum of the two probabilities given that, even if one of the hazard categories is near zero, the possibility of the other leading to a fire ignition is still there. The formula also supports the hazard matrix in that the highest probability will be where both the process and environment hazards are high.

Probability factor of fire growth (P_g) follows factor of fire ignition and assumes that the fire may grow but this growth may be limited by both the local conditions and the forms of fire prevention and protection applied. Ideally, it is preferred that a fire is contained within the enclosure of origin or, better still, is eliminated before any threat is manifested to people, property, the environment, etc. It is at this point that the consequences due to fire and smoke spreads around a building require consideration. A secondary formula is required to develop this idea as:

$$\mathrm{SFR_g} = \mathrm{P_g C_g} \tag{4.5}$$

where:
SFR_g – Scenario Fire Risk (growth),
P_g – Probability of fire growth,
C_g – The consequences of fire growth.

If both the ignition and growth phases are considered, the following combined formula can help to determine the overall scenario fire risk. Note that, in this case. It will be the product of the two probability variables given that, without ignition, there will be no fire spread:

$$\mathrm{SFR} = \mathrm{P_g C_g} \frac{(\mathrm{P_{ie}} + \mathrm{P_{ip}})}{2} \tag{4.6}$$

Equation 4.6 shows that every fire scenario, in terms of probability of ignition, and the probability of fire growth and spread, and how that growth impacts on the consequences, can be assessed to provide a thorough and detailed solution.

If several scenarios (n) are analysed, then equation 4.1 can be adapted as:

$$SFR_n = \sum_{i=1}^{n} P_g C_g \frac{(P_{ie} + P_{ip})}{2} \tag{4.7}$$

Note that most quantitative risk factors use a maximum scoring of both 5 for probability and consequences providing a maximum score of 25 (4). For the SFR equation (4.7) to be comparable, it will need to be divided further, by 5. Therefore, the adjusted SFR equation will be:

$$SFR = P_g C_g \frac{(P_{ie} + P_{ip})}{10} \tag{4.8}$$

Similarly, a range of risk scenarios using a scoring system of 0 to 5 can be described as:

$$SFR_n = \sum_{i=1}^{n} P_g C_g \frac{(P_{ie} + P_{ip})}{10} \tag{4.9}$$

Given that one of the objectives of Holistic Fire Strategies is to provide consistency in approach, this could be an opportunity to provide a guide for the scoring of the SFR. *Table 4* provides a suggested scoring methodology for scores ranging from 0 to 5. *Table 4* provides a suggested table format.

Table 4. Suggested scoring system for SFR analysis.

Factor	**Scoring Criteria**
P_{ie}	No environmental ignition hazard within the enclosure = 0; Some environmental hazard (such as use of partial low flammability linings, multiple electrical sockets, etc) = 3; High environmental hazard (use of drapes, low quality electrical systems, hanging fabrics, etc) = 5
P_{ip}	No processes within the enclosure = 0; Some process hazard (such as computer installations, small level fabrication, etc) = 3; High process hazard (factories, processing, etc.) = 5
P_g	Fire contained at source = 1; Fire contained within enclosure of origin = 2; Fire contained within fire zone = 3; Fire spread unrestricted within a section of the building = 4; Fire spread unrestricted throughout building = 5
C_g	Consequences of a fire v. low (minimal human presence, low value assets, etc) = 1; Consequences of a fire serious = 3 (some numbers of people present; high value assets, some business interruption risk, some environmental risk, etc.) Consequences of a fire devastating (large numbers of people who may not know the building and/ or may be sleeping and/or low mobility, major asset risk, full business loss, and/or devastation to local environment) = 5.

Table 5. Suggested scoring table format for SFR calculation.

Location	Pie	Pip	Pg	SFR	Commentary
Scenario 1					Explanation
Scenario 2					Explanation
Scenario 3					Explanation
Scenario 4					Explanation

The method of calculation will be shown for use in three cases in Chapter 6.

5. A Fire Strategy value indexing system

The development of a fire strategy can be a time consuming and lengthy process, especially for complex building arrangements found for most types of public building. It may require detailed evaluation, a thorough understanding of relevant codes, detailed assumptions, agreement on performance criteria and the possible use of fire and evacuation modelling. Sometimes the level of detail required may hide the overall intentions of the fire strategy as discussed in previous chapters.

Chapter 1 of this Thesis highlighted how business models were developed to "picture" the competitive nature of businesses within the sphere they operate. This simple expression of business compactivity provides a much easier method to allow an instant appraisal of the business without delving into detailed reports. In the same way, it is believed that a pictorial representation of a fire strategy can help deliver the key message of the strategy without the necessity of great levels of detail. This will provide a better understanding to all stakeholders, particularly those who are not professional fire engineers.

Chapter 3 introduced the concept of holistic fire strategies and suggests that a streamlined and consistent methodology will bring benefits in both the formulation and evaluation of fire strategies. It is suggested that visually based techniques can support the aims of the holistic approach.

A "spider" diagram was originally formulated by the Author for use in British Standard PAS 911 in 2007 (6). The purpose of this diagram was to allow a pictorial representation of the eight primary factors for any fire strategy. and the diagram is described in section 5.2.

The second iteration was a modified version of the original diagram and is based upon a published Polish book (4) in 2018. This was also used as a test case for two Polish power stations (149) and was transformed into a practical tool, validated in years 2018 – 2020 in a selection of complex Polish buildings. This is covered in Section 5.3 and in Section 6, where the exemplar case studies are presented.

5.1. The first iteration: The fire strategy value grid

One of the ideas specifically developed for BS PAS 911 (6) was a method of allowing a quick and easy way of "picturing" a fire strategy. Ideally the picture should be apparent using one side of A4 paper. This method is captured in a spider diagram (*Fig. 2 – Page 16*) and has been designed to identify the main elements of a fire strategy. It is intended to allow the user of the diagram to identify how they believe each element contributes to the overall fire strategy. The original title of the diagram as given in PAS 911 was the "Strategy Value Grid," as it allowed identification of the relative value of each of eight elements appropriate for every fire strategy.

As well as allowing the visualization of a fire strategy, it also allows for value analysis as the strategy develops. It all starts with eight key strategic factors:

1. **Control of ignition sources**, which may be found throughout any building. They could be a fundamental part of those processes within or around the building or may be brought in by occupants or any other groups of persons who use the building. What a fire engineer

needs to understand is the possible and probable main sources of ignition and how they could combine with potential fuel sources. This was considered in the previous chapters when determining the scenario fire risk.

2. **Control of combustibles** being the fuel sources for fire, which predominantly exist in fixtures and fittings and possibly within the processes of the building. Furthermore, it is quite possible that fire loading would be introduced by some, or all, of the occupancy groups working in, or visiting, the building. As with control of ignition sources, control of combustibles relies on proper fire safety management, and, as with ignition sources, the scoring will largely be dependent on the fire safety management process.

3. **Fire compartmentation,** also known also as passive fire protection, was probably the original form of fire protection. The two key reasons for compartmenting one area from another are (i) to contain or control a fire for long enough to allow evacuation of persons from the building and (ii) to contain or control a fire for long enough to allow for time to suppress or extinguish the fire by automatic and/or manual means.

4. **Smoke control systems** aims to protect the escape routes and to allow for firefighting (in this case, manual firefighting). The simplest method of controlling smoke is by opening a window or a vent. This may provide some relief, but in most cases, and with most modern buildings, this will not be enough. Even though smoke control systems for life safety purposes are designed to maintain tenability of escape routes, this does not mean that all smoke will need to be extracted for the required period but just enough to ensure that there is visibility to allow escape, that is, the smoke and the associated other products of combustion should be above head height. This would often require powered automatic smoke extract systems.

5. **Automatic fire detection** is often considered a cornerstone of any fire strategy as a fire-monitoring system. It is responsible of fire detection, initiation of warning systems and/or fire protection systems control. A further requirement is to be able to discriminate between fire and other non-fire or unwanted phenomena.

6. **Automatic fire suppression** needs to be appropriate for the likely fire loading. In many buildings, an automatic fire sprinkler system, when properly designed, will always be effective. Today's choice of fire suppression extends from a number of water-based options including fog/mist systems, deluge systems, foam systems and other specialist systems. There are a range of gas extinguishing systems, air volume inerting systems, powder-based systems, and systems that react with the free radicals of flame.

7. **Fire service intervention** covers the time from communicating to the fire brigade to the time they attend site and commence firefighting operations. Initial considerations include the attendance time and the strategy for meeting and guiding firefighters as they arrive. Then there are access considerations into the building, including upper and basement areas. Furthermore, the firefighting infrastructure and facilities must be available and appropriate for the firefighters to utilise. In some cases, based on the complexity of the building(s), it may be appropriate to set up an in-house professional firefighting teams.

8. **First aid firefighting** covers the fire control and equipment available to fight fires in their early stages. This will include portable fire extinguishers. Suitable training goes hand in hand with this item.

Note that these are primary strategic factors. Secondary factors such as alarm sounder systems, fire doors, extract systems, and fire prevention policies will follow from the primary factors. The idea of the diagram is to allow each of the eight factors to be separately considered and scored from zero to five, based on their relative importance to the strategy. The diagram was designed to be used as a first round of analysis, although the book "Fire strategies - strategic thinking" (5) points its real benefit is in regular revisiting it as the strategy preparation progresses. The diagram was designed to allow a team of stakeholders to sit around the table and consider each of the eight elements and, based on their judgement, to mark each of the elements (zero to five) on the relevant node. Once all eight fire safety factors have been scored, straight lines should join the marks, and a pattern will emerge. This pattern can be quite revealing. An example of a completed diagram is shown in *Fig. 17*. The area within the pattern provides an idea of the resources and costs associated with the provisions required by the strategy. For instance, if each element is scored as five, the pattern will form the whole outer core of the diagram, with the maximum area taken up. Consequently, the fire safety and protection provisions are likely to be costly to implement and extremely resource hungry. Conversely, a shape with a much smaller footprint will be much more affordable. However, it must still be effective and answer all the issues from the earlier objectives setting.

The way the pattern sits on the diagram also can tell something about the type of strategy. For a pattern predominantly in the upper quadrant, the strategy will place greater reliance on fire safety management, whilst a pattern towards the lower quadrant will place greater reliance on active fire protection. A shape on the left-hand side of the graph used to indicate that the strategy will rely on suppression of a fire, whilst a shape to the right places greater reliance on containment and control of a fire and the products of combustion by structural means. If the diagram has been prepared following a full prior evaluation, and by a team rather than a single person, then it is likely to be the precursor to the final written strategy. An item scoring highly in the diagram is likely to be an important feature of the final written strategy.

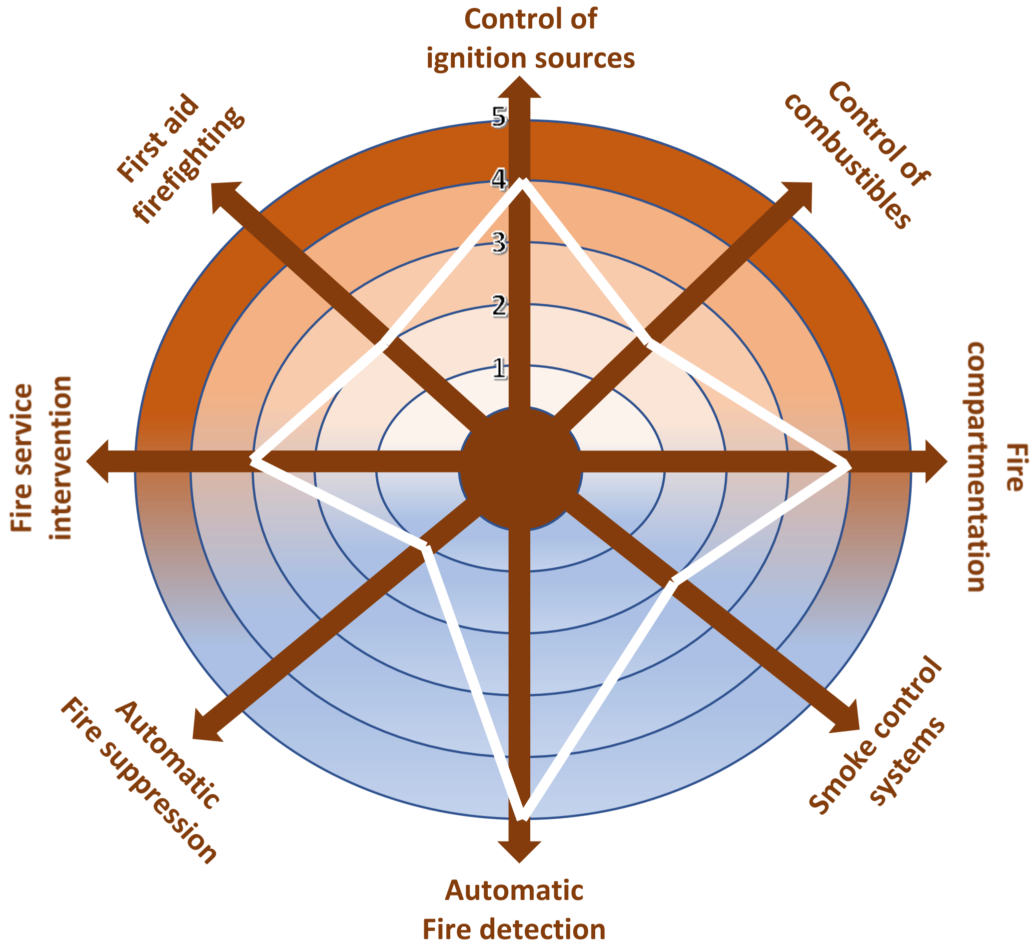


Fig. 17. Use of fire strategy value grid (6).

5.2. The second iteration: The semi-quantitative variation of the methodology

A book covering an assessment method using a modified version of the above diagram, was published in 2018 (4). The purpose of this was to adapt the pictorial concept to form a semi-quantitative method of assessing fire strategies. The modified version is shown below for comparison in *Fig. 18*. The following can be noted here:

- the nodes covering fire compartmentation, fire detection, smoke control, fire suppression and fire service intervention remain the same, albeit the wording has been modified. They have also been moved to other nodes;
- control of ignition sources and combustibles has been amalgamated into a single node;
- the node "First aid firefighting" has been removed;
- new nodes "organisation and management" and "maintenance of fire precautions and systems "have been included";
- the scoring has been increased from 5 to 25.

The quoted reasons for the update (4) were based on the need to make the methodology more applicable to issues surrounding fire strategies, especially for complex buildings and those for non-residential purposes, such as public buildings, where the range of risk will be greater.

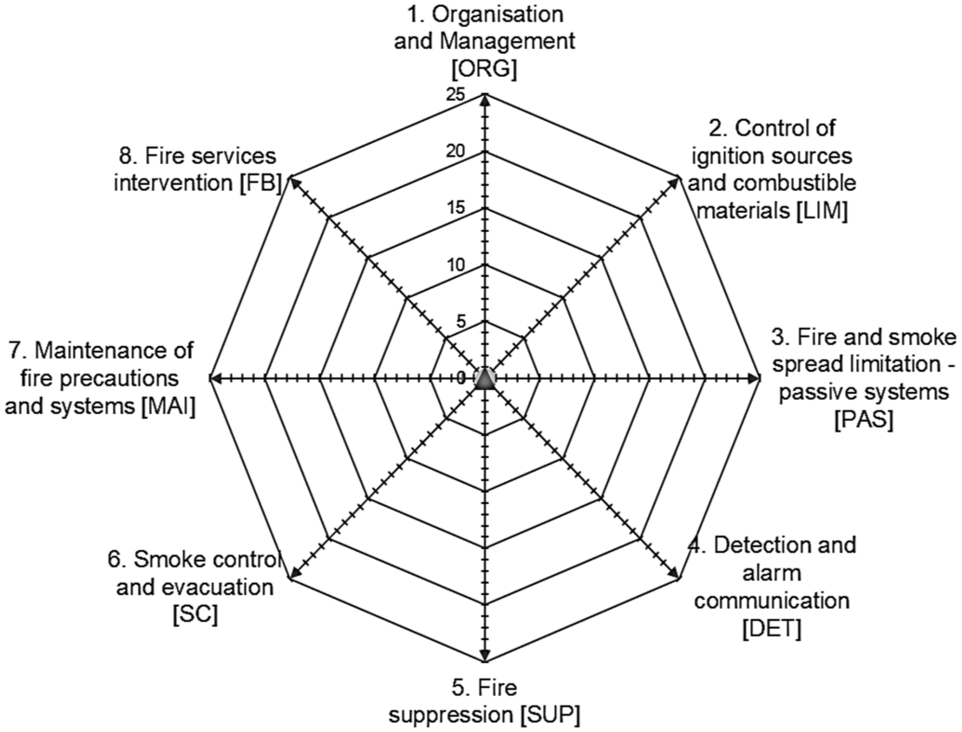


Fig. 18. Fire strategy value grid for semi-quantitative variation of the methodology (4).

5.3. The development of a semi-quantitative approach to assess and score fire strategies

The assessment technique makes use of a risk assessment methodology that was developed in Poland prior to this Thesis and was presented in the book Strategies of Buildings Fire Protection" (4), separate journal articles (150) (151) and national fire conferences. This iteration seeks to make use of a simple risk assessment process.

Simplistic fire risk index methodologies had already been proposed by, for example, the Gretener Method or Dow's Fire and Explosion Index (139). The Gretener Method, originally developed in Switzerland for risk assessment by insurers, is used here as a basis for a novel evaluation method of fire strategies (152). It was deemed a relevant method, in that it uses empirical figures, estimated individually for the building, based on the level of its fire protection, instead of theoretical numbers of failure, used in traditional risk calculation. The method used for the Polish variation also uses current fire engineering analysis concepts, for demonstration of the level of fire protection against a baseline fire strategy. One method of supporting improvements to an actual fire strategy is to make use of computational fluid dynamic (CFD) analysis. There are commercially available software packages available for this and are described earlier in this Thesis. Such analysis can evaluate the following:

- how fire and smoke growth will develop within a room or area;
- what would be the potential response time of fire detection systems;
- what would be the impact on the tenability of evacuation routes by smoke and heat development including the use of smoke control systems;

- what would be the effect of fire suppression systems on the control of heat and smoke;
- what would be the impact of fire compartmentation on smoke and heat movement.

The fire strategy evaluation should ideally be undertaken by a team of engineering specialist stakeholders. This may consist of:

- independent fire strategist consulting engineers;
- internal fire and technical experts from the industrial plant;
- persons responsible for fire safety including explosion risk;
- persons responsible for housekeeping and building management;
- representatives of the insurance company involved with the risk.

The methodology can be used both at the project stage of construction or applied to existing infrastructure.

5.3.1. Fire Strategy Evaluation

The following method for fire strategy evaluation is based upon the fire strategies methodology (5) (4) described above. The method assumes scoring of eight fire safety factors onto the fire strategy value grid.

Under the evolution of the original method, for the purpose of this Thesis, for each evaluated building (or part, e.g. a fire zone), the methodology is comparative. It compares two fire strategies: the baseline strategy (default, based on the building risk profile or determined individually) and the actual strategy (real, realized for a new build project or for existing building). *Fig. 19* illustrates the flow chart of the evaluation sequence.

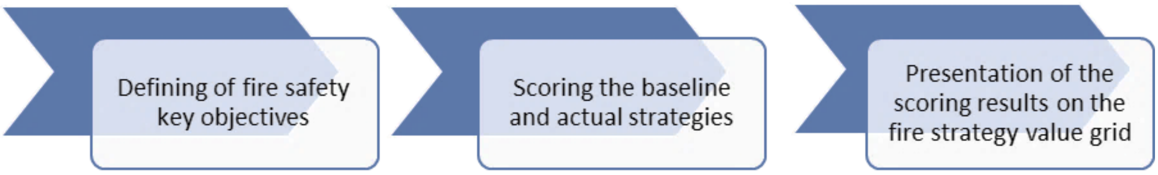


Fig. 19. Fire strategy evaluation sequence.

The baseline and actual fire strategies can be defined as:

- **Baseline Fire Strategy** is the strategy which represents fire prevention and protection solutions acceptable as a minimum for the risk profile of a specific building type, or form of infrastructure.
- **Actual Fire Strategy** which is the adopted or utilised strategy for a building project, or as applied for an existing building. The methodology requires the individual assessment and scoring of each fire safety factor, making use of typically the most relevant fire safety elements (4) (150).

5.3.2. Fire Safety Factors

The eight fire safety factors (FSF) represent three fundamental layers of fire protection: fire prevention (including the limitation of fire spread organizational safety rules, ignition sources and combustible materials limitations), fire protection measures (the use compartmentation and using of automatic fire protection measures and systems) and fire service intervention. Each layer of fire protection is represented by appropriate fire safety factors. During the fire strategy evaluation process, the level (relevance) of each fire safety factor is scored from zero to twenty-five (*Table 6*). The scoring is realised separately for the baseline and the actual fire strategies and is helped with special questions list (4) (150).

Table 6. Fire safety factors for a fire strategy.

Layer of fire protection	Fire safety factor (FSF)	Symbol	Score
Fire prevention and fire spread limitation	1. Organisation and Management [ORG]	ORG	0-25
	2. Control of ignition sources and combustible materials [LIM]	LIM	0-25
Fire protection measures	3. Fire and smoke spread limitation - passive systems [PAS]	PAS	0-25
	4. Detection and alarm communication [DET]	DET	0-25
	5. Fire suppression [SUP]	SUP	0-25
	6. Smoke control and evacuation [SC]	SC	0-25
	7. Maintenance of fire precautions and systems [MAI	MAI	0-25
Fire fighting	8. Fire services intervention [FB]	FB	0-25

5.3.3. Scoring of Fire Strategies

In order to make all fire strategies uniform, the building profile specific list of questions, representative for each of the fire safety factors were created and are presented in *Table 7* (4) (150).

Table 7. Detailed questions for the Fire Strategy Risk Index scoring method.

Fire safety factor	No.	Fire safety element	Max
1. Organisation and Management [ORG]	1	Fire strategy: not developed (0) / has been developed for selected aspects (1) / has been developed and documented in all aspects necessary for the pre-defined strategy objectives (4)	4
	2	Documented fire safety procedures for the building (1) + implementation of the procedures (1) + regularly controlled updates (1) + documented evacuation plans for all floors (1)	4
	3	Central building security personnel for the building (1) + trained fire wardens on all floors/in zones (3) + regular evacuation drills with specific staff participation (2) / regular evacuation drills involving all building occupants (3)	7
	4	Fire safety training: only key staff (2) / all staff (4)	4
	5	Independent certification and audit system for fire safety management: only mandatory checks (1) + full regular fire safety audits, undertaken by specialist bodies (1)	2
	6	Management commitment to fire safety including fire safety management review meetings and training of personnel in the key aspects of the management, operation and maintenance of fire protection systems, and the principles of fire strategy, evacuation strategy awareness, etc. (0 to 4)	4

Fire safety factor	No.	Fire safety element	Max
		Total	25
2. Control of ignition sources and combustible materials [LIM]	1	Fire load density [MJ/m^2] (>4000) (0) / (>2000, ≤4000) (1) / (>1000, ≤2000) (2) / (>500, ≤1000) (4) / (≤ 500) (5) + High hazard ignition sources Y (0) / N (2)	7
	2	Expected fire growth: ultrafast (0), fast (1), medium (4), slow (5)	5
	3	High risk areas of the building are separated from other parts of the building by suitable fire resisting construction Y (2) / N (0) + high levels of combustible materials stored in the building - Y (0) / N (2)	4
	4	Smoke production from construction products and fixed equipment (the worst case): S3 and products of reaction to fire class ≤E (0) / S2 (1) / S1 and products of reaction to fire class A1 (2)	2
	5	Reaction to fire class of construction products (claddings/coverings) (the worst case) ≤E (0) / D i C (1) / B (2) ≥A2 (3)	3
	6	Reaction to fire class of the building insulation products (external walls, roof) (the worst case): ≤E (0) / D i C (1) / B (2) ≥A2 (4)	4
		Total	25
3. Fire and smoke spread limitation - passive systems [PAS]	1	Fire resistance of structural elements: <15 min (0), 15 min (1), 30 min (2), 60 min (3), 90 min (4), ≥120 min (6),	6
	2	Maximum fire resistance of internal subdivisions: 30 min (1), 60 min (2), 120 min (3), 240 min (4)	4
	3	Fire resistance of doors and shutters: No resistance rating (0) / 30 min (1), 60 min (2), 120 min (3), 240 min (4)	4
	4	Distance from neighbouring buildings: Not in accordance with regulations (0) / in accordance with regulations (2) / fire wall used as separation (2) / the heat flux density on adjacent object walls < 12,5 kW/m^2 (2)	2
	5	Compartmentation - fire zones [m^2] (>20000) (0) / (>10000, ≤20000) (1) / (>5000, ≤10000) (2) / (>2000, ≤5000) (3) / (>1000, ≤2000) (4) / (≤1000) (5)	5
	6	Activation of fire shutters, doors, dampers etc. with fusible links (1), manual activation via control panel (2) / automatic after verification (3) / automatic (4)	4
		Total	25
4. Detection and alarm communication [DET]	1	Full monitoring, i.e. detection in all risk areas (5) / partial monitoring (1) + detection in evacuation routes (1) / manual system (1) / no detection (0)	5
	2	Expected detection response time (>420 s) (0) / (>300 s, ≤ 420 s) (2) / (>180 s, ≤ 300 s) (3) / (≤180 s) (5)?	5
	3	All detection devices are appropriate for the risk (0 to 4)	4
	4	Sufficient and suitable control and indicating equipment in the building, including power supplies and cables (2) + certified systems (1)	3
	5	False alarms controlling procedures: No (0) / Yes (4)	4
	6	Alarm warning systems: sounders (1) / voice alarm (2) / Voice alarm with public address (3) + active visual support signage (1)	4
		Total	25
5. Fire suppression [SUP]	1	Fire suppression systems covering all risk areas (3) / partial coverage only (2) / no suppression systems (0) + fast response sprinklers (1)	4
	2	Fire suppression response time index (RTI): standard B (>200, ≤ 300) (1)/ standard A (>80, ≤ 200) (2)/ special (>50, ≤ 80) (3) / fast (≤ 50) (4)?	4
	3	Expected activation time: (s): >300 (0)/ (>200, ≤ 300) (1) / (>150, ≤ 200) (2)/ (>120, ≤ 150) (3) / (≤ 120) (4)?	4
	4	Fire suppression systems appropriate to: the height of storage (2) + type of combustible material (2) + storage method (2)	6

Fire safety factor	No.	Fire safety element	Max
	5	Reliability of suppression installation: system monitoring (1), independent power supply and water suppression systems (1) operation + dual water supply (1) + double source water supply (1)	4
	6	Hose reels covering all parts of the building Y (1) / N (0) + portable fire extinguishers (pfe) with rated extinguishing efficiency provided sited to standard accepted densities (1) or enhanced densities (2).	3
		Total	25
6. Smoke control and evacuation [SC]	1	Stair core smoke control: Non-existent (0) / in place but effectiveness not specified (1) / assured protection of means of escape (2) + assured support for firefighting operations (1) + monitored for all system failures (1)	4
	2	Horizontal evacuation routes smoke control system: Non-existent (0) / in place but effectiveness not specified (1) / assured protection of means of escape (2) + assured support for firefighting operations (1) + monitored for all system failures (1)	4
	3	Smoke enclosure control system: Non-existent (0) / in place but effectiveness not specified (1) / assured protection of means of escape (2) + assured support for firefighting operations (1) + monitored for all system failures (1)	4
	4	Aspects of the construction of the means of escape could potentially lead to uncontrolled smoke production (0) / Suitable control of combustible materials on horizontal evacuation routes (1) + vertical evacuation routes (2)	3
	5	Dimensions of stair cores and horizontal evacuation routes relevant to the amount and profile of occupants (0 to 2) + at least two stair cores (2) + at least two directions of travel from each area (2).	6
	6	Evacuation signage: Passive signage correctly selected and arranged (1) / illuminated signage systems (2) / dynamic illuminated signage systems to control movement of occupants (4)	4
		Total	25
7. Maintenance of fire precautions and systems [MAI]	1	Has the design, installation and commissioning of fire-fighting and fire protection systems been carried out in accordance with the manufacturer's instructions and standards? Y (2) / N (0) + by certified contractors Y (2) / partly (1) / N (0)	4
	2	Is there a suitable inventory of fire-fighting and fire protection systems (1) + operation and maintenance information (2)?	3
	3	Maintenance procedures and inspections in accordance with minimum national regulations (1) + manufacturer's instructions (2) + national standards (2)?	5
	4	Functional testing (over and above minimum requirements) of fire-fighting and fire protection systems to ensure maximum levels of availability and reliability: Y (6) / partly (3) / N (0)?	6
	5	Systems used to monitor in real time the availability and reliability of fire-fighting and fire protection systems: Y (3) / partly (1) / N (0)?	3
	6	Modifications to fire fighting and protection system recorded (1) + monitored (1) + audited (2)	4
		Total	25
8. Fire services intervention [FB]	1	Method of communication with fire-fighters: Manual means by building user (e.g. no automatic fire detection) (0) / manual means by building user in the case of fire detection operation (1) / automatic, via alarm receiving centre with alarm confirmed by external staff (2) / automatic, via alarm receiving centre with alarm confirmed by staff on site (4).	4
	2	Availability of on-site fire safety personnel to assist (2) / nominal or part time availability (1) / no availability (0)	2
	3	Fire brigade arrival time [s] (>900) (0) / (>600, ≤900) (2) / (>300, ≤600) (4) / (≤300) (6)	6
	4	Access to the building: No direct access (0) / limited access to the building (1) / direct access to at least 50% or two sides of building (2) / direct access to all parts of building perimeter (3)	3

Fire safety factor	No.	Fire safety element	Max
	5	Internal communication for fire-fighting purposes within the building: difficult (0) / easy (1) + easy access to the fire control panel (1) + graphic display showing fire locations (1) + lighting of evacuation routes suitable for firefighting effort (1) + at least 2 staircases (1) + fire-fighters lifts with lobbies (1)	6
	6	Fire service facilities: No firefighting facilities (0) / suitable fire-fighting hose reels or dry /wet risers on each level (2) + smoke ventilation controls available (1) + fire pump provisions on site (1)	4
		Total	25

5.3.4. Fire Strategy Risk Index calculation

The last step of fire strategy evaluation is a Fire Strategy Risk Index (FSRI) calculation. The purpose of this calculation is to amalgamate each of the individual scores for both the baseline and actual conditions.

Risk Profile

The application of risk profiles allows the grading of buildings and other infrastructure in terms of fire risk. The profile makes use of a combination of occupancy characteristics and fire growth rate. It is possible that a building, especially a complex one, may comprise multiple risk profiles throughout the whole of the premises. Ancillary accommodation can contain different fire growth rates or occupant profiles to that of the main building and mixed-use buildings are also likely to have a variety of occupancy types. Risk profiles used in the methodology should be determined in accordance with British Standard BS 9999 (7) based on the expected occupancy characteristics and fire growth rate (*Table 8*).

Table 8. Risk profiles (BS 9999) (7).

OCCUPANCY CHARACTERISTIC	FIRE GROWTH RATE		RISK PROFILE
A (OCCUPANTS WHO ARE AWAKE AND FAMILIAR WITH THE BUILDING)	1	Slow	A1
	2	Medium	A2
	3	Fast	A3
	4	Ultrafast	A4 [A]
B (OCCUPANTS WHO ARE AWAKE AND UNFAMILIAR WITH THE BUILDING)	1	Slow	B1
	2	Medium	B2
	3	Fast	B3
	4	Ultrafast	B4 [A]
C (OCCUPANTS WHO ARE LIKELY TO BE ASLEEP)	1	Slow	C1 [B]
	2	Medium	C2 [B]
	3	Fast	C3 [B], [C]
	4	Ultrafast	C4 [B], [A]

[A] these categories are unacceptable within the scope of bs 9999. Addition of an effective localized suppression system or sprinklers will reduce the fire growth rate and consequently change the category.

[B] risk profile c has sub-categories.

[C] risk profile c3 is unacceptable under many circumstances unless special precautions are taken.

Baseline Fire Strategy

The baseline fire strategy is the strategy which represents fire prevention and protection solutions acceptable as minimum for the risk profile of a specific building type, or form of infrastructure. It is up to the fire engineer, together with other relevant stakeholders, to determine the baseline conditions for each of the nodes. These could be based upon national codes, or could be the result of a stakeholder assessment, possibly using performance-based objectives. In the following case, the risk profiles have been taken from BS 9999 (7). However, the assessment criteria were taken from Polish Regulations.

The methodology used for explanation in this Thesis has been prepared specifically for the subsequent evaluation of the Polish test cases as given in Chapter 6.

The suggested, default scores for baseline fire strategies are presented in *Table 9* as previously published in the book "Strategies of Buildings Fire Protection" (4). A formal breakdown of each of the series of questions included in the Fire Strategy Risk Index questionnaire has been carefully prepared against Polish Regulations (99) for each risk profile. This detailed breakdown is given in Appendix D. A summary of the values is provided in Table 7.

Table 9. Baseline scoring based upon risk profile (4).

	Profile											
Risk Profile/ Fire safety factor	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
E_{ORG}	3	3	10	20	6	8	12	17	4	3	9	16
E_{LIM}	21	19	13	9	21	19	13	9	21	19	13	9
E_{PAS}	8	9	17	19	9	11	18	24	10	12	19	24
E_{DET}	1	5	13	23	1	7	16	25	5	10	18	25
E_{SUP}	1	1	14	21	1	3	18	23	3	3	19	25
E_{SC}	2	2	10	19	2	8	12	19	14	14	18	19
E_{MAI}	1	7	13	19	1	7	13	19	3	7	13	19
E_{FB}	1	3	14	23	1	6	14	23	4	7	14	23

Actual Fire Strategy

The actual fire strategy is scored on the site findings for an existing building or the design proposals for a building. Each fire safety factor (node) is scored separately, and the scores are then adjusted by a weighting factor and the summed to provide a single score to determine the protective measures applied. This is explained later in this section. Note also that it may be decided to calculate more than one actual fire strategy using different options for one or more of the fire safety factors (nodes).

Basis of calculation method

Various methods could be used with the information obtained for the fire strategy value grid (153). It is the Gretener Method, that was developed by Swiss engineer Max Gretener (152) that was chosen as a basis for the wider assessment of fire strategies. The reason for this is that this method promotes the calculation of potential hazard and protective measures values, which are used for the final fire hazard index calculation. The method uses empirical figures, estimated individually for the building, based on the level of its fire protection, and in comparison, with solutions either generic, or required by national legislation. This idea follows most probability type risk assessments, where fire risk was assumed as a product of hazard severity and loss expectation represented by the fire frequency of ignition and here is presented in Eq. 5.1.

The purpose of the Fire Strategy Risk Index (*FSRI*) is to provide a single score for both the baseline and actual fire strategies based upon the product of the Fire Hazard Index (*FHI*) and the Frequency of Ignition (*Fi*) both of which are found by analysis and existing codes as described below In a comparison between the two scores, the overall efficacy of the fire strategy can be evaluated. The fire strategy risk index assesses the residual risk for a fire strategy. Ideally, the actual risk index score is equal to, or lower than the score for the baseline. Where it is higher, then the fire strategy should be re-evaluated.

$$Fire\ strategy\ risk\ index\ (FSRI) =$$

$$= Fire\ hazard\ index\ (FHI) \cdot\ Frequency\ of\ ignition\ (Fi) \tag{5.1}$$

Frequency of ignition

The Frequency of Ignition is one of the key parameters of most probabilistic risk assessments and is specifically covered in British Standard PD 7974-7 (137). A table taken from the standard is shown in *Table 10*. The numbers shown in the table assume 1000 m^2 area of the building. For another areas individual calculations have to be prepared.

Table 10. Frequency of ignition table (137).

Occupancy	Probability of fire (y^{-1})
Industrial	$1.43\cdot10^{-2}$
Offices	$2.96\cdot10^{-2}$
Hospitals	$1.24\cdot10^{-1}$
Schools	$3.56\cdot10^{-2}$
Food and drinks premises, hotels, hostels, communal	$8.00\cdot10^{-2}$
Other public buildings and services	$6.60\cdot10^{-2}$

Fire hazard index

The hazard severity from equation (5.1) is proportional to the potential hazard and reduced by protective measures (Eq. 5.2).

$$Fire\ Hazard\ Index\ (FHI) = \frac{Potential\ Hazard\ (PH)}{Protective\ Measures\ (PM)} \tag{5.2}$$

The original Gretener formula expressed empirically derived numerical factors for fire initiation and spread, with factors for fire protection. The idea used in the method presented here is based upon the values achieved from scoring of each fire safety factor in accordance with *Table 7* for the baseline and actual strategies, respectively.

Introducing a weighting system

A weighting system is used to adjust the Protective Measures value. This is based upon the relative importance of each of the fire safety factors (nodes) and can be taken from the values attributed to the baseline fire strategy, divided by an integer which, in this case, is 5. The values of *Table 9* are suitably adjusted and contained in *Table 11*.

Table 11. Weighting factors appropriate for building risk profiles.

Objective	**Profile**											
Risk Profile/ Weighting Factor	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
W_{ORG}	0.6	0.6	2.0	4.0	1.2	1.6	2.4	3.4	0.8	0.6	1.8	3.2
W_{LIM}	4.2	3.8	2.6	1.8	4.2	3.8	2.6	1.8	4.2	3.8	2.6	1.8
W_{PAS}	1.6	1.8	3.4	3.8	1.8	2.2	3.6	4.8	2.0	2.4	3.8	4.8
W_{DET}	0.2	1.0	2.6	4.6	0.2	1.4	3.2	5.0	1.0	2.0	3.6	5.0
W_{SUP}	0.2	0.2	2.8	4.2	0.2	0.6	3.6	4.6	0.6	0.6	3.8	5.0
W_{SC}	0.4	0.4	2.0	3.8	0.4	1.6	2.4	3.8	2.8	2.8	3.6	3.8
W_{MAI}	0.2	1.4	2.6	3.8	0.2	1.4	2.6	3.8	0.6	1.4	2.6	3.8
W_{FB}	0.2	0.6	2.8	4.6	0.2	1.2	2.8	4.6	0.8	1.4	2.8	4.6

Calculation of protective measures

A total scoring for protective measures (PM) is obtained from the formula (Eq. 5.3) by aggregating the points obtained from the assessment of each fire safety factor adjusted by the appropriate weighting factors.

$$\begin{aligned} \mathrm{PM} = {} & W_{ORG} \cdot E_{ORG} + W_{LIM} \cdot E_{LIM} + W_{PAS} \cdot E_{PAS} + W_{DET} \cdot E_{DET} + W_{SUP} \cdot E_{SUP} \\ & + W_{SC} \cdot E_{SC} + W_{MAI} \cdot E_{MAI} + W_{FB} \cdot E_{FB} \end{aligned} \tag{5.3}$$

where:

EORG, ELIM, EPAS, EDET, ESUP, ESC, EMAI, EFB – actual score of each fire safety factor. The corresponding weighting factor is represented by W.

Calculation of fire hazard index

The value of the fire hazard index FHI, for both baseline and actual fire strategies, is be calculated from the formula (Eq. 5.4).

$$\mathrm{FHI} = \frac{\mathrm{PH}}{\mathrm{PM}} \cdot 100 \tag{5.4}$$

where:

FHI – fire hazard index,
PH – potential hazard,
PM – protective measures.

The potential hazard is applied, respectively, to the building risk profile (4). The final step of the fire strategy assessment is the determination of the fire risk index from (Eq. 5.5).

$$\mathrm{FSRI} = \mathrm{FHI}\ \cdot \mathrm{Fi} \tag{5.5}$$

where:

FRI – fire risk index,
FHI – fire hazard index,
Fi – frequency of ignition.

The Potential Hazard (PH) can be determined by assuming that, for the case where baseline conditions are exactly met, in an optimal fire strategy, it will be assumed that PH = PM, thus the FHI will be exactly unity. Therefore, by using Equation 2, PH = PM /100.

As it was stated above, the presented methodology was created in early 2018 and has been validated by testing with stakeholders of a Polish Power Station (149). Chapter 6 illustrates the use of the methodology for actual cases of non-standard public buildings.

5.4. Using the Fire Strategy Risk Index (FSRI) calculation as part of the building design and construction process

The presented methodology is intended to be used both for the assessment of existing buildings as well as guiding the design of new build projects. As an example, and referring to the UK's accepted "RIBA" design stages (154) in building design, the use of the concept is explained:

Stage 0 - Strategic Definition: This is the point at which a business case is made for the proposed building project. At this stage it would be too early for consideration of the fire engineering involvement.

Stage 1 - Preparation and Briefing: This is where project objectives are determined. This should include the base requirements for the fire strategy. At this stage, an early version of the baseline fire strategy can be drawn up using national codes and or the main requirements and objectives of the stakeholders.

Stage 3 – Concept Design: This will include outline proposals for the structural design of the building, its size, height, use(s), etc. The additional information can help provide a more detailed baseline fire strategy, more closely attuned to the dimensions, stability requirements and risk profile proposed for the building. It is also at this stage, the practical, logistical and technical constraints may be known, allowing a mock-up of one or more "actual" fire strategies.

Stage 4 – Spatial Coordination /Developed Design: By this time, the baseline conditions for the building should be established. At this stage, one or more "actual" fire strategies can be assessed and scored. Alternative fire strategies can be tested. For instance, structural and fire resistance ratings can be evaluated with or without the use of sprinkler systems. Travel distances to emergency exit routes can be re-evaluated with and without smoke control systems for the escape routes, etc.

Stage 5 – Technical Design: At this point, the designs will have been converted to the pre-construction drawings and specifications. However, it is quite normal that last minute amendments to the design are proposed. The FSRI method will allow swift evaluation of options and adjustments to the fire strategy can be made.

Consequently, there are potential benefits of the assessment method at every design stage.

6. Applying the methodology: Three test cases

In order to test the methodology, three varied public building types, whose management were agreeable to be the subject of the testing, were chosen. The analysis presented below represent examples of operational non-standard public buildings in which the new semi-quantitative method of fire strategy evaluation was used within the last two years, when the method was validated. These were:

- EC1 Łódź - City of Culture, Poland (155) (156) (157);
- A Castle converted to a hotel, Ryn, Poland (158) (159) (160);
- A Hospital located in Chelsea, London, UK (161).

In two of the cases, the EC1 centre and the Ryn Castle Hotel, the buildings were chosen because they posed additional challenges by renovating older historical buildings into complex contemporary structures with new uses. For the case of the Hospital in Chelsea, London, the original use of the building was intended as a shopping mall but this was changed after the design process into a Hospital. Consequently, the building has a number of rare features not typically found with purpose-built Hospitals.

The two Polish examples had previously been the subject of fire safety evaluation in 2018 and some of the results taken were used for this analysis. The London Hospital chosen is supported by a fire strategy that was prepared by the Author of this Thesis.

Each example follows the given 7 step process (*Fig. 20*) from the methodologies detailed in Chapters 4 and 5.

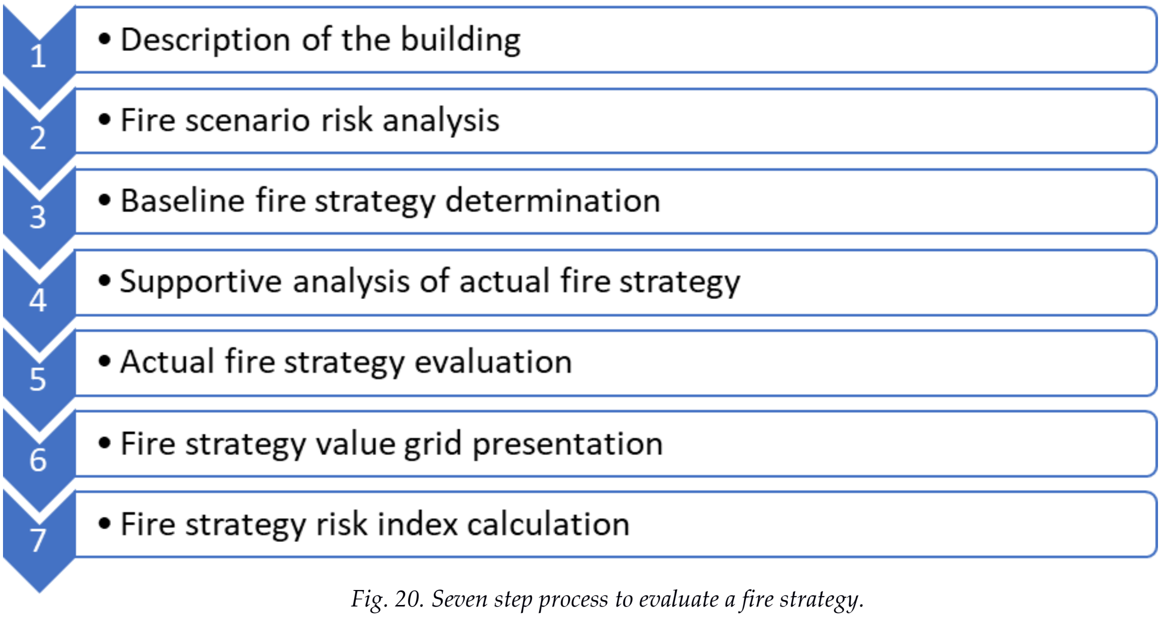


Fig. 20. Seven step process to evaluate a fire strategy.

Step 1 provides an overview of the building and any pertinent factors impacting on the fire safety and protection of the building. Occupancy profiles and use of the building are also relevant to the analysis;

Step 2 makes use of the fire scenario analysis method proposed in chapter 4. A few fire scenarios for each of the buildings are chosen for further evaluation. The choice is based upon judgement of the Author of this Thesis together with assistance by others who are knowledgeable of the buildings in question. The chosen fire scenario taken from the scoring system is further evaluated;

Step 3 corresponds to the baseline fire strategy which is taken from the national guidance or regulations relevant to that building profile and specifically concentrating on the chosen fire scenario;

Step 4 uses Computational Fluid Dynamic (CFD) model relevant to the worst-case fire scenario chosen for further examination. The key parameters for agreement are:

- determination of the appropriate fire size heat release rate;
- placement of the source of ignition within the fire scenario;
- monitoring of how fire and smoke growth will impact on tenability of escape routes in terms of smoke obscuration and rate of heat increase over time;

Step 5 is the point when the fire strategy questions can be re-assessed based upon the actual conditions known in the building as well as any findings found in Step 4. An "actual" table will then be created for one or more conditions (such as with and without fire suppression);

Step 6 involves preparing of the fire strategy value grid comparing baseline and actual conditions. This can be used to demonstrate to some stakeholders how the fire strategies can be visualised;

Step 7 assumes the fire strategy value grid preparation based upon the table of Step 6. From this, the Fire Strategy Index Risk (FSRI) can be established. If the FSRI is shown to be higher for the actual strategy than the baseline strategy, then this is an indicator that the residual risk within the fire strategy is unacceptable. If the FSRI is equal or less than the baseline fire strategy, then this should be acceptable.

The following actual building examples follow the above methodology.

6.1. EC1 Łódź - City of Culture, Poland

EC1 Łódź is a power station of which construction commenced in May 1906. The generation of power began on 18 September 1907. The plant was extended in 1928-30. From 1953 it was adapted to produce process steam for some factories in Łódź. Operations ceased completely in 2001.

The power station has since been renovated into a contemporary building and the whole complex is now a cultural centre. The Art Nouveau machine hall is used for exhibitions and concerts, while other buildings accommodate the National Centre for Film Culture, a Planetarium and a Centre for Science and Technology.

6.1.1. Description of the building

The subject of the analysis is the EC1 City of Culture Centre based in Łódź. It is described (162) as the most important art and cultural centre in Poland. The property has 3 buildings:

- Building "N" located in the northern part of the area has 2 underground floors and 7 storeys above ground with functions of recording, exhibition and office studies;
- Building S1 is located to the east side of building "N" and consists of 1 underground storey and 6 storeys above ground, which houses offices, a restaurant and a residential apartment;
- Building S2 is a former machinery hall and is located to the south side of building "N". It consists of 1 underground storey and 3 aboveground.

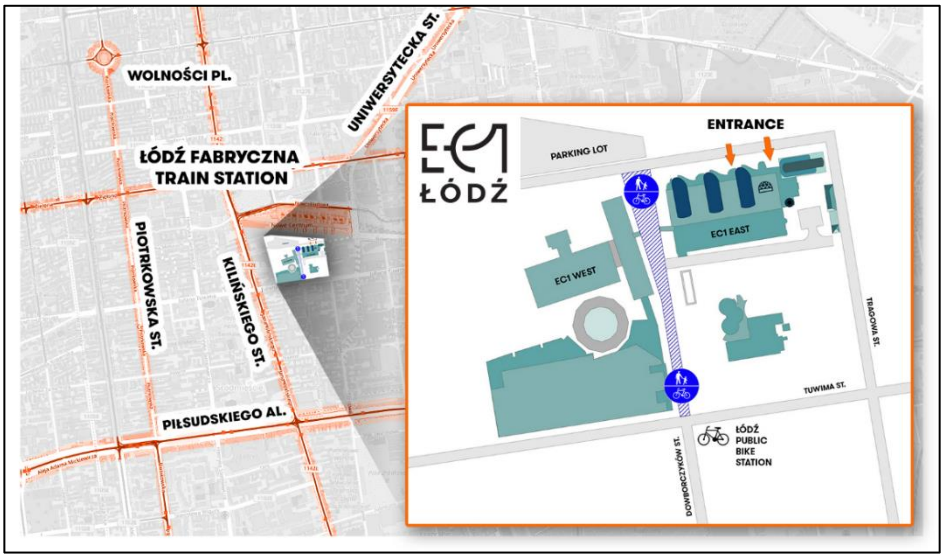


Fig. 21. EC1 Building location in Łódź (163) .

Fig. 21 and 22 provide a location and pictorial view of the building. Due to the purpose and size of the individual spaces, the fire strategy covers the Building "N" incorporating a seven-storey atrium, where up to 1,200 people can stay and some exhibitions could be organized. This building is an independent fire zone, divided from Buildings S1 and S2 with fire resistance walls.

Fig. 22. EC1 Building - Photo view (162).

6.1.2. Fire scenario risk analysis

Based upon the above description and judgement of the varying risks, the following fire scenarios are deemed as most likely in terms of fire risk, based upon professional judgement:

1. fire in the central atrium;
2. fire in the Planetarium;
3. fire in the Exhibition hall;
4. fire in an office.

Based on the method of determining the most appropriate fire scenario within a public building, described in Chapter 4, (Eq. 4.8) was used for the several scenarios probability determination:

$$SFR = P_g C_g \frac{(P_{ie} + P_{ip})}{10}$$

The following probability scores were proposed an on-site hazard survey. In terms of a consequence C_g, the rating should be regarded as suitably high in all parts of the building, including the exhibition halls etc. (e.g. 4). This gave appropriate calculus as follows:

Table 12 provides the scenario fire risk calculation for the EC1 Building "N", Łódź. Note that *SFR* = Scenario Fire Risk, P_{ie} = Probability of fire ignition due to the environment and P_{ip} = Probability of fire ignition due to the processes. and P_g = Probability of fire growth.

Table 12. EC1 Building - Scenario fire risk calculation.

Location	P_{ie}	P_{ip}	P_g	SFR	Commentary
The central atrium	4	4	3	9.6	This is a 8 storey central atrium (from -2 to + 5 floors). Given the range of processes and people within a large area including retail units, cafeteria, etc., It is also noted that exhibitions will be held in the atrium. It is judged that the probability of ignition is fairly high as well as the dedicated halls. with both high environmental and process factors. However, the probability of growth
Planetarium	3	3	2	4.8	Located at a lower ground level. Maximum capacity around 40 persons. The area is enclosed with a measurable amount of ignitable fire loading in both the environment and the processes. However, the area is within its own compartment zone so that growth is limited.
Exhibition Hall	3	3	3	7.2	As with the Planetarium, a typical Exhibition Hall has a similar environment and processes, however, there are a number of openings whereby the possibility of fire growth is not negligible.
Offices	1	4	2	3	Office environments are typically sterile all the range of processes, from computer equipment use to storage of combustibles is judged to be relatively high. However, they are compartmented from other parts of the building such that the possibility of fire growth is relatively low.

From the above calaculation, the area with the largest risk factor is the central atrium. The following section describes the analysis of this area using computational fluid dynamic (CFD) simulations. The analysis considers how the impact of specific control measures such as smoke control systems (Scenario F2A) and water fog systems (Scenario F2B) can vary the risk results.

6.1.3. The baseline fire strategy

The baseline fire strategy was in accordance with the *Polish regulations for buildings and their location* (99), in accordance to the B3 risk profile. This was supported by British Standards (some of which are regulated as European standards) (7) as well as relevant NFPA (101) guidance together with BS and NFPA codes as performance-based tools (60) (147).

A detailed analysis of the questionnaire with respect to the baseline strategy is given in Appendix A. This provide details relevant to each of the questions. However, the key fire safety factors (nodes) are summarised within Table 13.

Table 13. EC1 Building - Baseline scoring detail.

Fire safety factor	B/L	Commentary
ORG	12	Fire safety management requirements at a base level cover the main considerations such but not higher-level systems such as certification of systems. Polish regulations require a fire strategy document or at least a document covering all fire precautions and systems. Only fire wardens are a requirement. Aspects such as certification and enhanced training are not required.
LIM	13	Polish regulations cover the basic elements of ignition control and combustible materials only. A medium sized fire loading (between 500 and 1,000 Mj/m^2) is considered with a fast growth fire. High risk areas are required to be separated from other areas. A class S2 smoke production rating together with Category B reaction to fire size is specified.
PAS	18	The regulations cover detailed specifications for fire and smoke control for primarily life safety and firefighter response but do not cover higher levels of specification. Tables 1 and 2 provide details of the classification. In this case, Category B is required. Compartment zones should be within 5,000 m^3.
DET	16	Minimum requirements are for monitoring of evacuation routes. Detection response limits are based upon relatively early detection within 300 seconds. False alarm prevention is nominally covered.
SUP	18	Fire suppression systems are recommended on a risk basis and based upon typical response expectations. The RTI response / expected activation time should be within 200 seconds. Systems should be chosen based upon local conditions.
SC	12	Nominal levels of smoke control are recommended and these concentrate on escape routes and firefighting access. Minimum smoke control is related to means of escape both vertically and horizontally. Passive evacuation signage is acceptable.
MAI	13	Basic levels of maintenance are prescribed by the Regulations. Heightened requirements are based upon the requirements of all stakeholders.
FB	14	Nominal requirements are made for firefighter access and facilities. The Regulations require automatic connection with fire services with recommended arrival times within 300 seconds. Minimum requirements such as access to dry risers and firefighting lifts are recommended.

6.1.4. Supportive analysis for the actual fire strategy

Before preparing the actual fire strategy evaluation, it is necessary to undertake supportive performance-based analysis. This will help assess the conditions found, making use of fire protection systems provided.

The effectiveness of the smoke control system was verified on the base of CFD simulations. The second level basement of the EC1 atrium is effectively the lowest level and thus is chosen to determine fire growth under specified conditions. A drawing showing the chosen location of a fire (F2) for simulation is given in *Fig. 23.* The existing smoke ventilation system provides a mechanical smoke extract from the smoke zone "SD N/1" (shown in *Figs. 23 to 26*), using a smoke-burning system with a minimum of 13 exhaust points and a total capacity of

67,320 m³/h. Supply air is supplied by an open exterior door to the "A" facility with a total active area of not less than 8.54 m². A second smoke extract zone “SD N/2” is also shown in *Figs. 24 to 28* at all levels. *Fig. 29* show a vertical view of the building.

Note that the standard recommendation is for a form of fire suppression in areas such as this. The CFD model considers both the instance without (Scenario F2A) and with (Scenario F2B) a form of main space fire suppression. In this case, a water fog system was used.

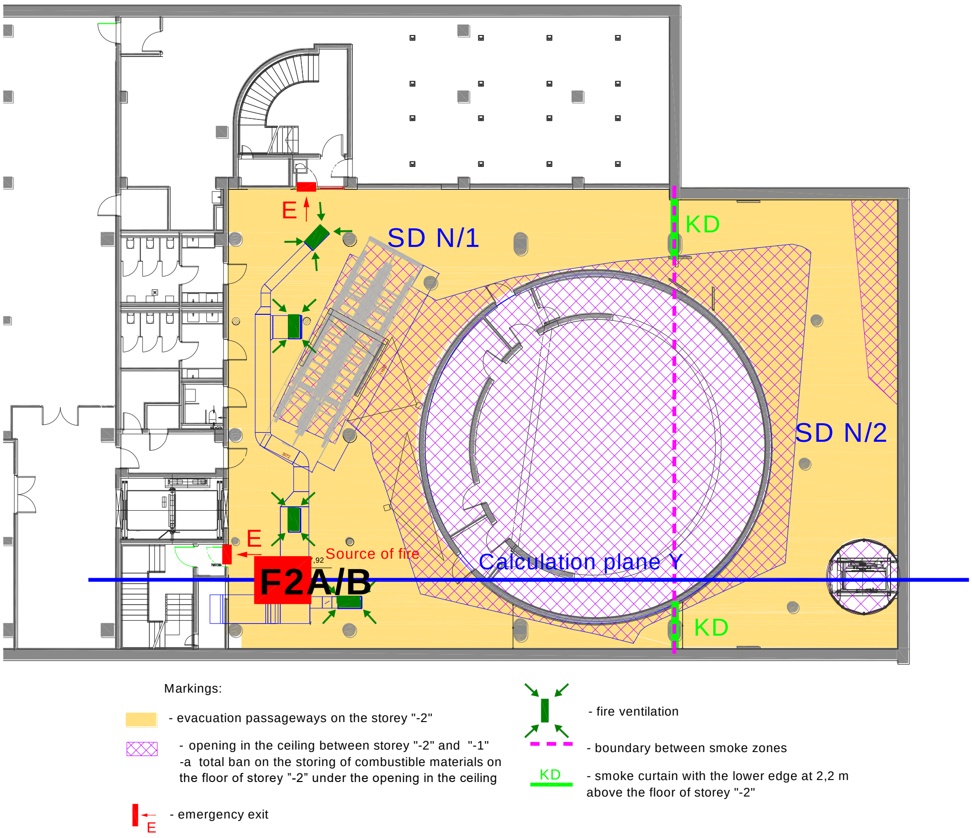


Fig. 23: EC1 Building N - chosen fire scenario at 2nd level basement.

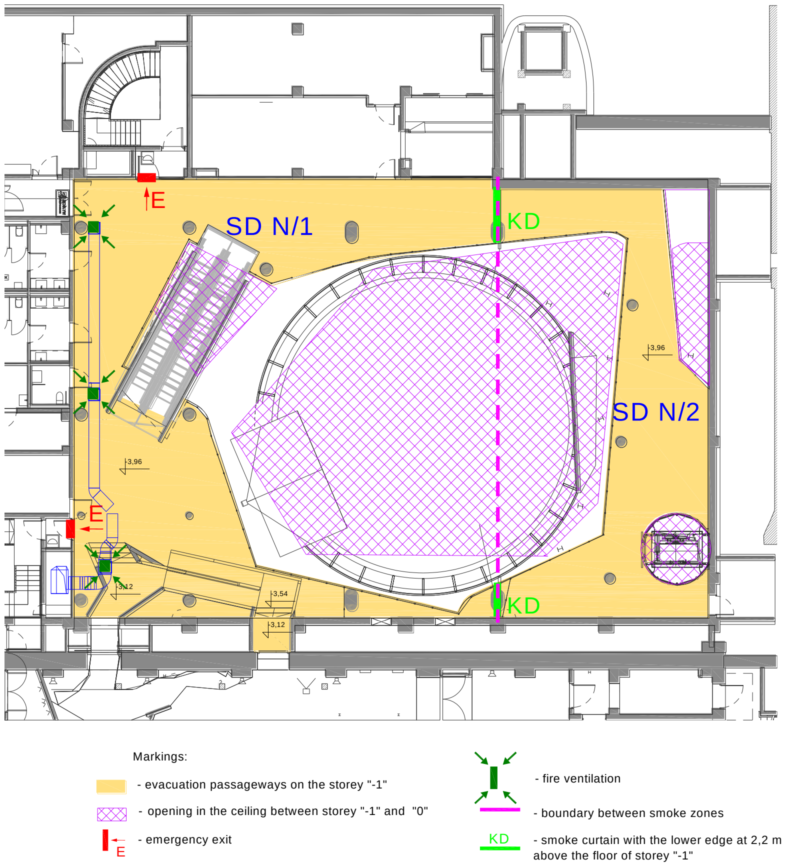


Fig. 24: EC1 Building N – 1st level basement.

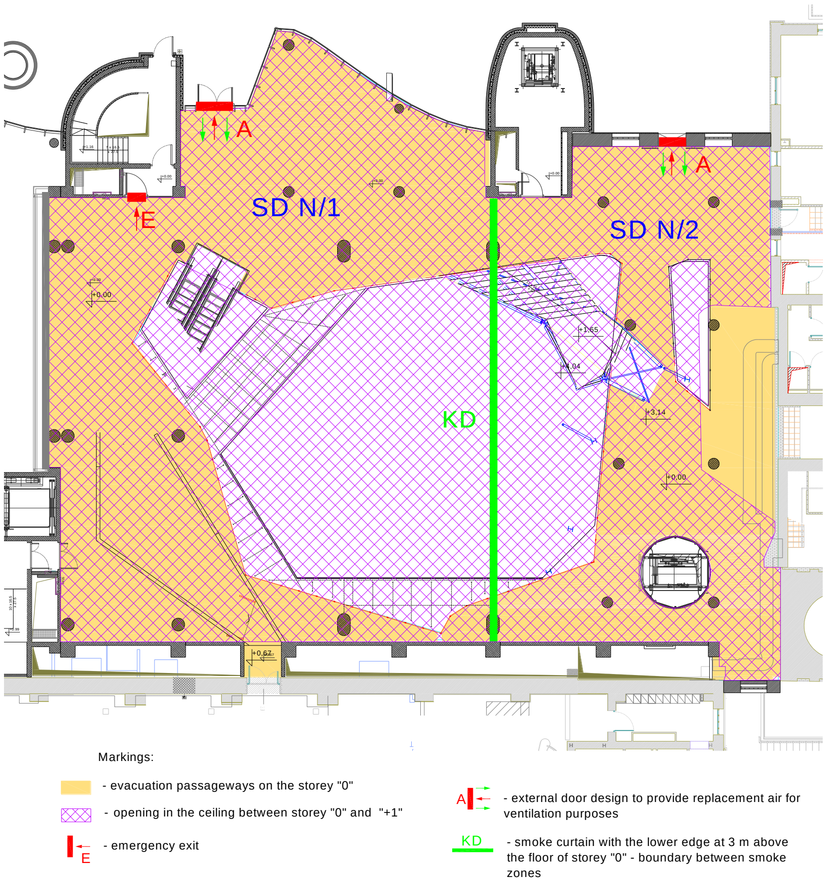


Fig. 25. EC1 Building N - Ground Floor.

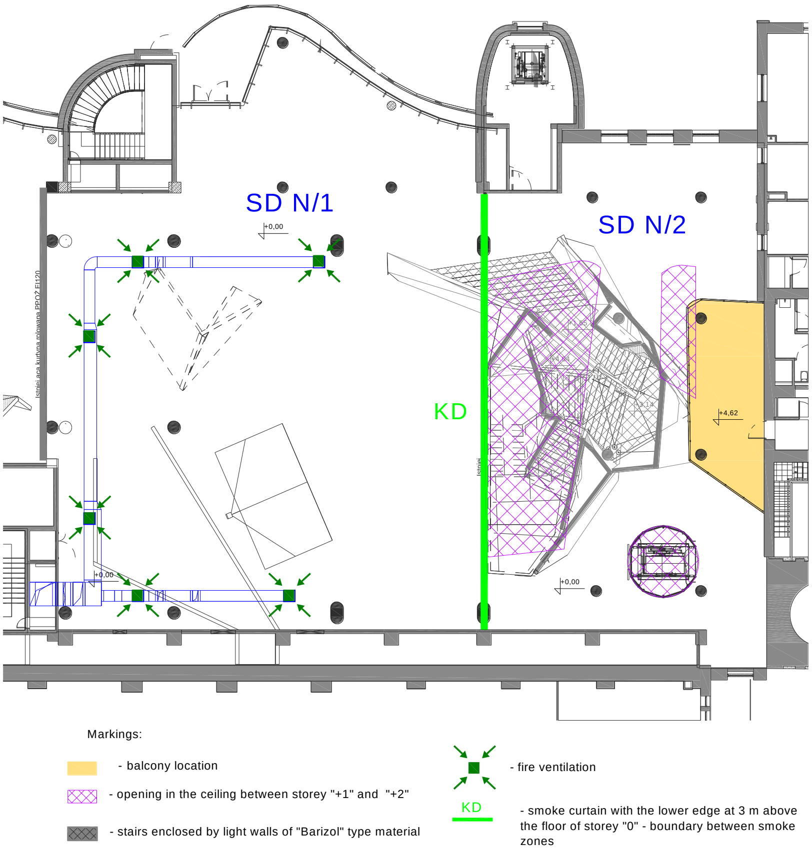


Fig. 26. EC1 Building N - 1st Floor.

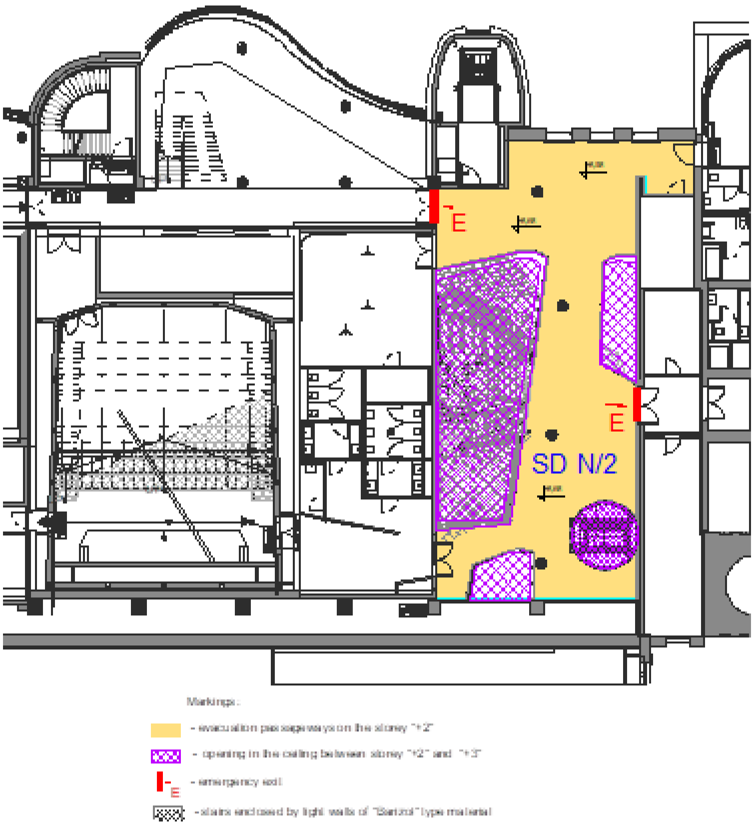


Fig. 27. EC1 Building N – Floors 1 to 4

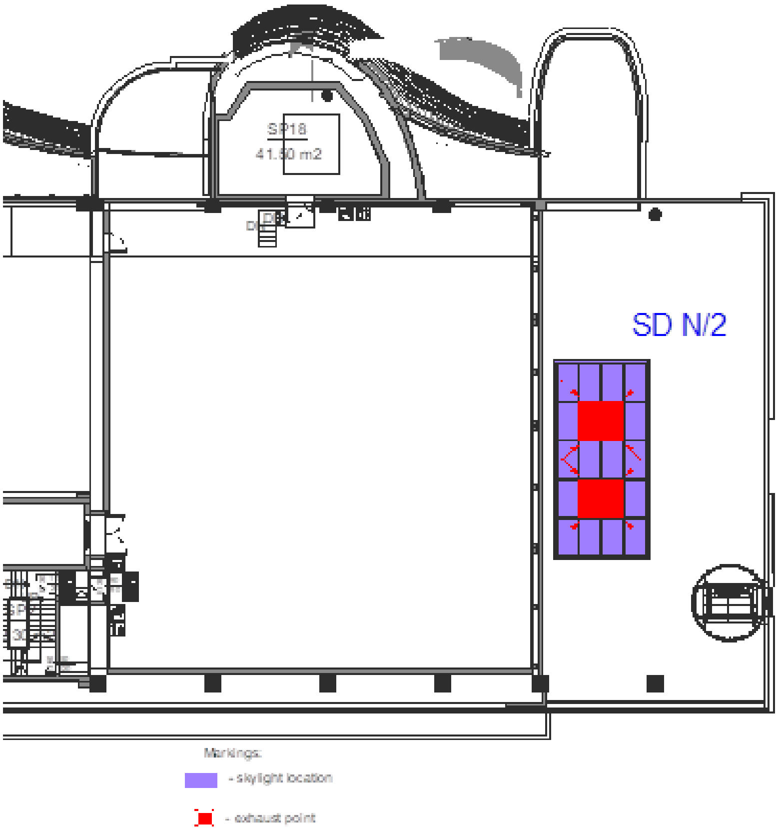


Fig. 28. EC1 Building N - Floor 5

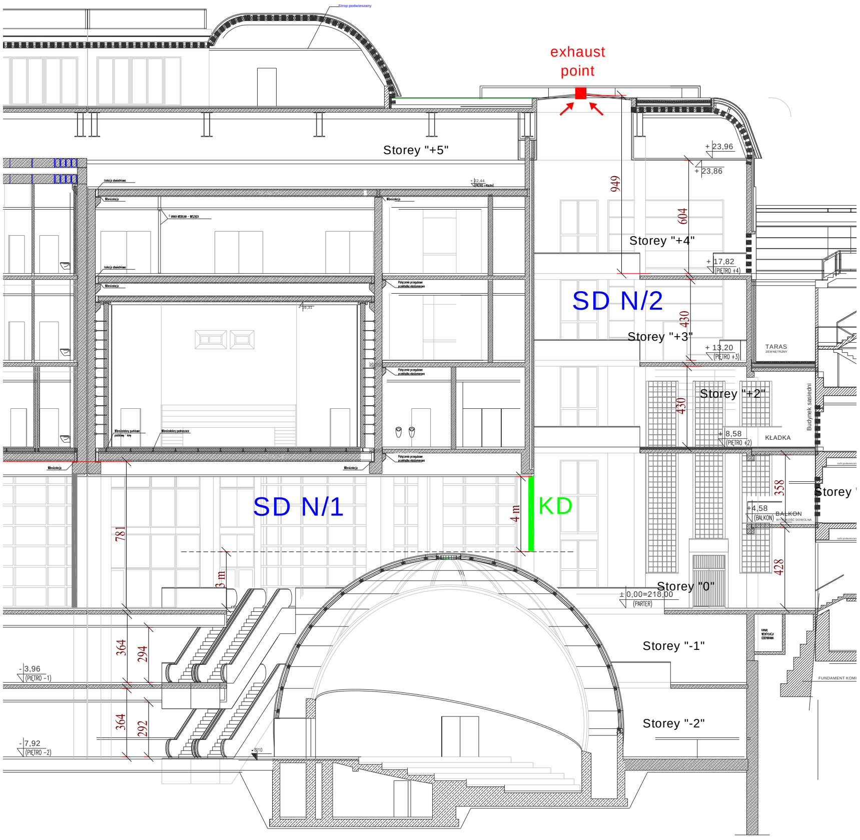


Fig. 29. EC1 Building N - cross section.

Fire Brigade intervention time

The intervention time of the local fire brigade determines one point of fire growth analysis. It can be assumed that firefighting operations will begin to manually extinguish a fire. The nearest fire brigade station is at a distance of 1.8 km (Tamka street 10, Łódź). A map of the route is given in Fig. 30. The expected time of arrival of rescue crews to the site of the fire, from the moment of receipt of alarm information can be taken as up to 7 minutes (based on a distance assessment) with a further 2 minutes to locate the fire. The expected fire detection time is taken as 80 s from fire ignition (the time is determined by the simulation). It is assumed that automatic alerting time once the alarm is detected is negligible. Based upon this, the time from ignition to firefighting operations can be taken as 620 s (80 s detection + 420 s fire brigade travel time + 120 s fire location).

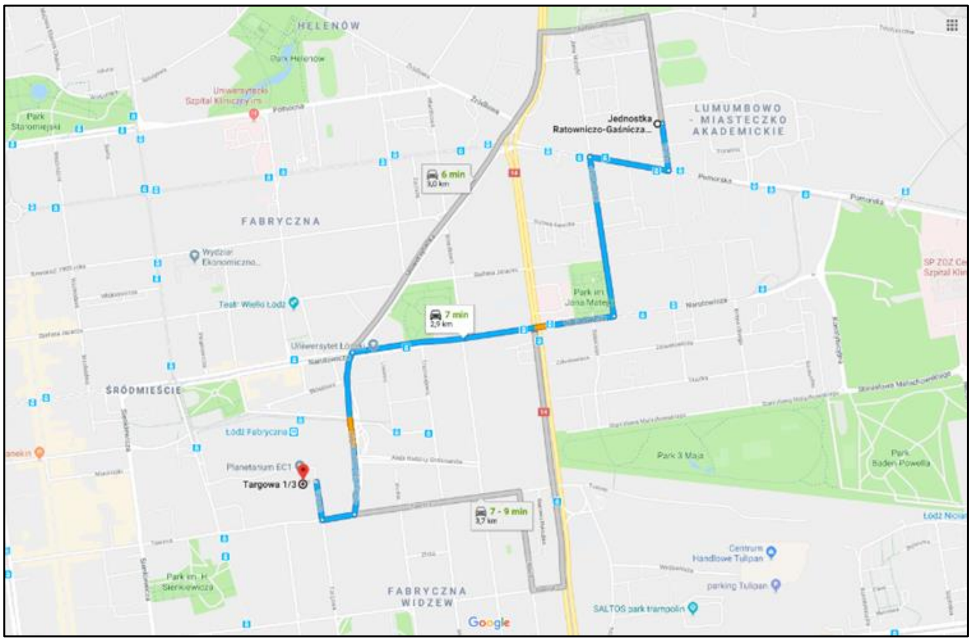


Fig. 30. EC1 Building - Anticipated route taken by fire brigade.

Determination of the required safe escape time (RSET)

The analysis of the assumed evacuation time is based on British Standard Published Document PD 7974-6: 2004 (66). When determining the evacuation times, the existing fire strategy elements were considered, including:

- a fire detection system monitoring all parts of the building;
- the use of a voice alarm system;
- the use of fire hose reels and fire extinguishers;
- there is an alternative, independent, power source to power fire protection systems;
- emergency lighting and escape illuminated signage throughout.

The following categories from the PD were assumed:

- occupant behaviour category B (awake and unfamiliar);

- fire detection and alarm system category A2 (automatic fire detection and activation via the use of coincidence connection of devices, i.e. two devices are required to operate before the alarm is activated);
- influence of the building complexity on the evacuation time –multi-storey structure – uncomplicated orientation (in this respect, only the evacuation from the atrium space is considered) = Category B2;
- the building management level – Category M2 (Security personnel are not expected at the car park level).

For the above categories (B, A2, B2 and M2), the pre-movement time for the first occupants (close to the fire) shall be $\Delta t_{pre(1st\ percentile)} = 60$ s, and for the last persons, $\Delta t_{pre(99th\ percentile)} = 240$ s.

It is assumed, that in case of fire, the evacuating occupants will use the designated evacuation routes to the nearest evacuation exits in directions away from the fire. The longest travel distance in the car park is about 70 m. The walking speed of people along the evacuation routes is taken as 1.2 m/s. Therefore, for the worst-case condition, the travel time to the nearest evacuation exit is $\Delta t_{trav} = 70$ m x 1.2 m/s = 84 s

Based on accepted analysis it is assumed that the fire detection system will within 80 s from the start of the fire. It is also assumed that the fire alarm will be activated immediately ($\Delta t_a = 0$ s) after the detection of a fire ($\Delta t_{det} = 80$ s).

Accordingly, the Required Safe Escape Time (RSET) is:

For the first occupants from smoke zone covered by fire:

RSET (1%) = $\Delta t_{det} + \Delta t_a + \Delta t_{pre,1\%} + \Delta t_{trav}$ = 80 s + 0 s + 60 s + 84 s = 224 s

For the last “99% occupants” from all areas of the car park:

RSET = $\Delta t_{det} + \Delta t_a + \Delta t_{pre,99\%} + \Delta t_{trav}$ = 80 s + 0 s + 240 s + 84 s = 404 s.

On the basis of the above calculations, it is assumed that the time required to leave the specified area is assumed to be 404 s.

Boundary and Initial Conditions for CFD simulations

Initial conditions of external and internal air parameters in simulation was assumed as: the air temperature: 20°C, ambient pressure: 1013 hPa, relative air humidity: 40%. Building partitions were assumed to be made of concrete with a density of 2,100 kg/m^3, a thermal conductivity of 1.0 W/mK and a specific heat of 0.88 kJ/kgK. A mixture of polystyrene and wood was taken as the combustion material, which could represent combustible materials potentially present in the room for which simulations were carried out. The SOOT_YIELD coefficient, i.e. the mass fraction of the fuel, which is converted into soot, was 0.07 kg/kg, the SOOT_YIELD coefficient, the heat of combustion: 20,000 kJ/kg. A computational grid with a density of 0.3 m in the X, Y and Z directions in simulation was adopted.

Fire spread scenario; NFPA 92 (164), recommends that the analysis of computational fire development is in accordance with the standard fire development curve given in NFPA 204 (165), as described as a model:

$$Q = \alpha t^2 \tag{6.1}$$

where:
Q – heat release rate [kW],
α – fire growth coefficient of 0.047 [kW/s^2] (a fast growth fire),
t – time [s].

Fire scenarios analysis considers appropriate fire size with and without a fire suppression system (water fog system) providing for fire in the absence of protection of the firefighting system, it was assumed that due to the limited number of combustible materials, the maximum fire size HRR will not exceed 5 MW (with a perimeter of 12 m), as shown in *Fig. 31*. In the case of fire scenarios providing for fire simulation F2B, a water fog system is utilized with RTI≤50 fog nozzles and a 68°C operating temperature. The nozzles are located at a height of not more than 3.6 m from the floor of each level. VDI Standard 6019-1:2006 "Engineering methods for the dimensioning of systems for the removal of smoke from building" states that the activation of the fog nozzle should not exceed 329 s. This figure is used for analysis, in order to reach a fire load HRR of 1,300 kW, before being controlled, as shown *Fig. 32*.

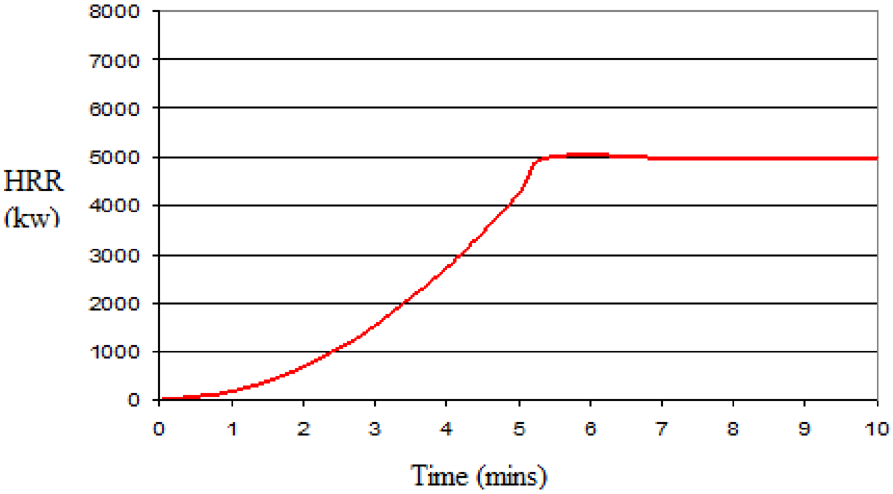


Fig. 31. Fire development curve adopted in fire scenario F2A, in the absence of the fire fog extinguishing system.

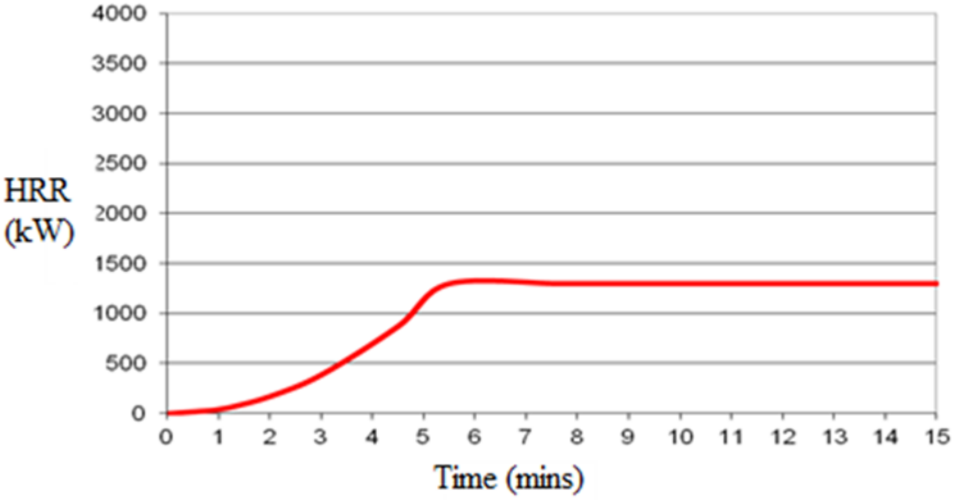


Fig. 32. Fire development curve adopted in fire scenario F2B, in the presence of the water fog extinguishing system.

Fire parameters analysed

Temperature distribution and visibility range at an altitude of up to 1.8 m from the floor were modelled using FDS. According to the literature data, the limits of the values of the individual parameters should be:

- the maximum tenable temperature for escape is 60°C. Note that, to take into account a suitable margin of error for the simulation, the actual temperature requires that the tenable temperature should be reduced to 52°C;
- the visibility range is taken as 10 m for non-lit areas, and 30 m with illuminated evacuation signs.

CFD simulations results

Fig. 33 and 34 provide graphical representation of the results over a number of time periods. In this case, the progression of fire in terms of both obscuration and temperature distribution is considered for two scenarios – with and without a water fog system protecting the main space. The time periods chosen for analysis and based on the prior calculations are:

1. 140 s: this period represents the commencement of the evacuation from the immediate effects of fire. Of relevance in this case is the tenability and visibility of escape routes;
2. 300 s: this represents the start of the evacuation of the last occupants from the immediate effects of fire. Similarly, it is the visibility range that is of interest;
3. 404 s: this represents the completion of the evacuation from the immediate effects of fire. The visibility range that is of interest;
4. 620 s: this is the time calculated as when the fire brigade will arrive on site. Note that the visibility range and temperature distribution are of interest at this point;
5. 900 s: this is completion of the simulation period.

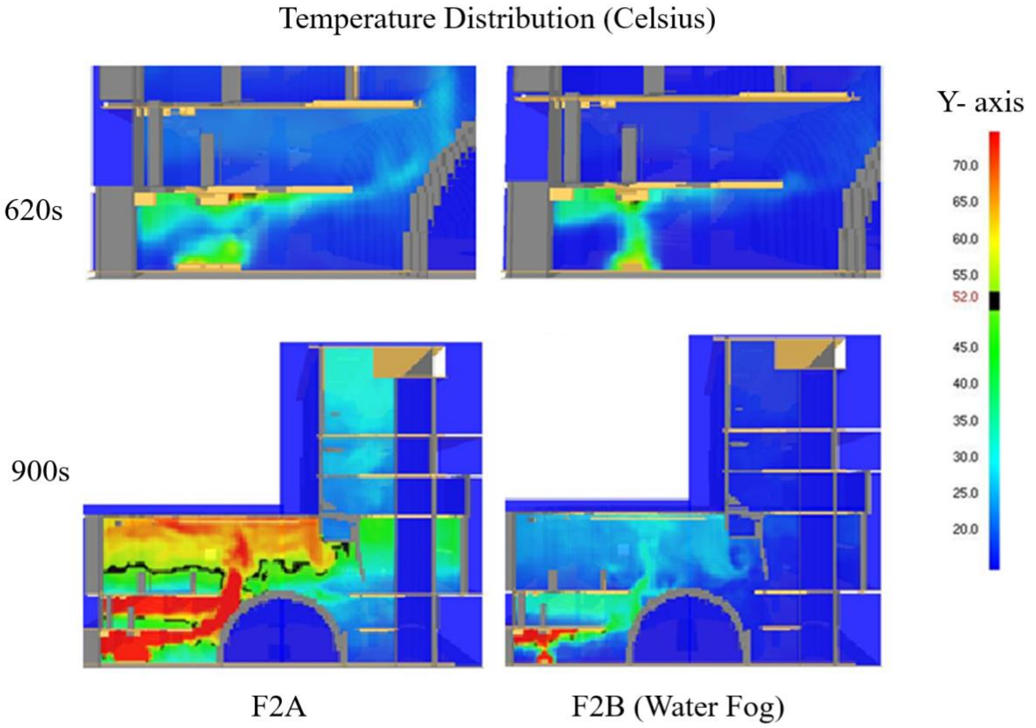


Fig. 33. EC1 Building: Fire at 2nd level basement - temperature distribution

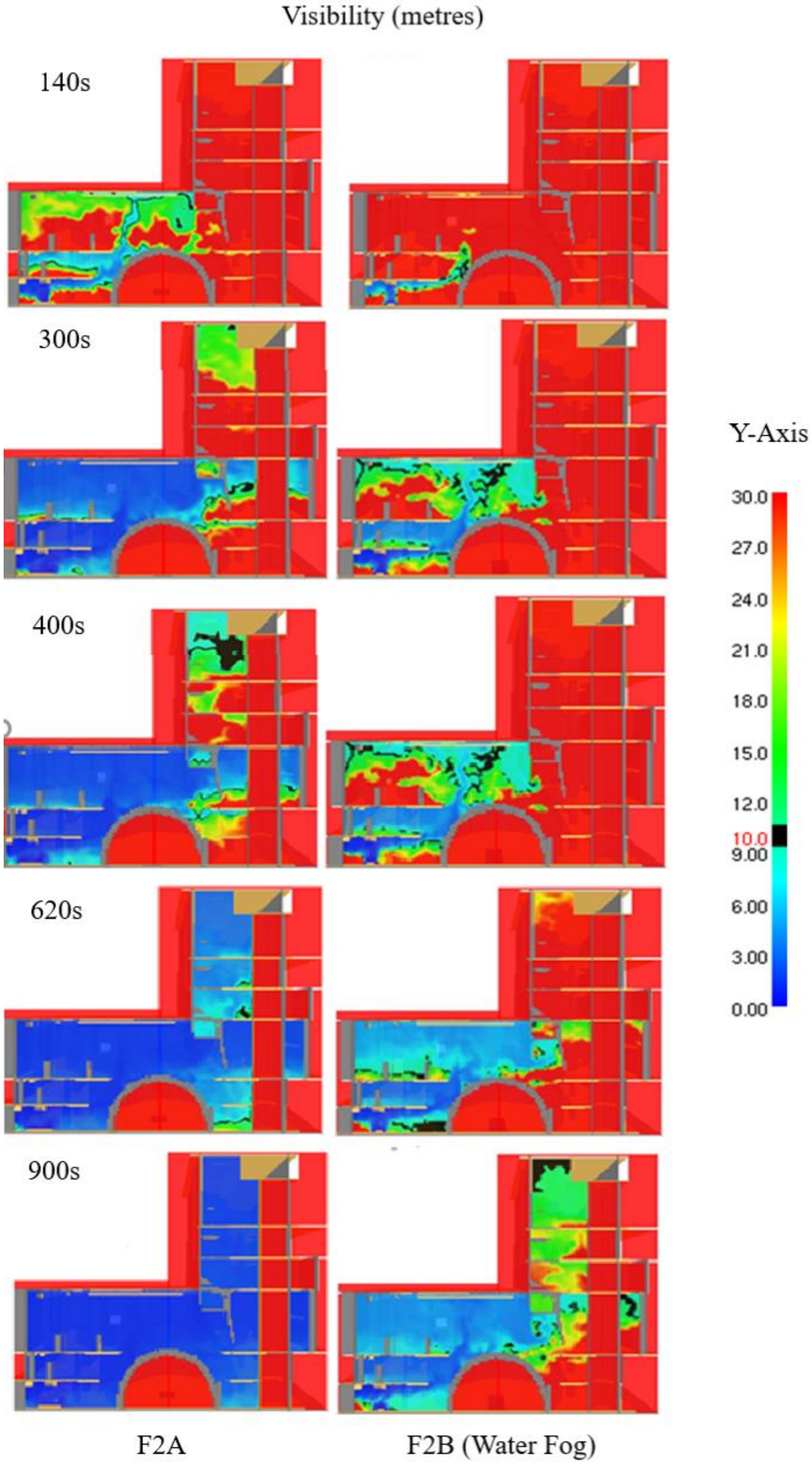


Fig. 34. EC1 Building: Fire at 2nd level basement –visibility.

Conclusions from the CFD analysis

In the fire scenario F2A, when only the smoke control system was operating, it can be seen that, at a head height of 1.8 m over several floors, the visibility range falls below the required 10 m before the calculated evacuation time has been reached in this area. This is somewhat improved by the operation of the water fog system, with near tenable conditions for the full evacuation period. However, the smoke control and ventilation conditions would need to be reviewed for both cases.

At the time of arrival of the Fire Brigade, the temperature limit value of 60°C (adjusted to 52°C to allow for a margin of error) has been exceeded without the water fog system. Furthermore, should the fire brigade still be setting up for firefighting by 900s, the high smoke temperature could introduce a risk of ignition of materials constituting the stairwell housing. With the water fog system, heat build-up is largely prevented, providing better conditions for firefighting.

6.1.5. Actual fire strategy evaluation

The actual fire strategy evaluation was prepared based on the project of the building renovation and supportive performance-based analysis described in Section 6.1.4. Following on from the CFD simulation, the conclusion is that a water fog system would clearly provide benefits in terms of evacuation as well as firefighter access. *Table 14* provides an actual building description taking into account findings from the supportive analysis described in the next chapter. scoring based upon the actual fire strategy adopted. A detailed breakdown on the scoring is given in Appendix A.

Table 14. EC1 Building - Scoring of actual fire strategy.

Fire safety factor	Building description	Actual score
ORG	A full fire strategy has been developed and documented for the building under consideration, providing fire protection solutions aimed at the main objective of protecting people's lives. A fire safety manual for the building was also developed, and implemented, updated regularly. Security personnel are available, trained in the event of a fire, and present during the working hours of the facility on the floor of the ground of the building. Evacuation drills are carried out regularly, with the participation of representatives of the management staff. Mandatory checks are carried out by eligible supervisory Authorities, but no external audits are used.	11
LIM	Combustible materials and a variety of equipment are found in individual workshops. There are no highly combustible materials stored throughout the centre. The development of the fire is assumed in accordance with the standard curve for the development of a "medium growth" fire. Fire protection systems are employed as control measures as described below. Wall and ceiling linings and roof covering are non-spread of fire rated. The roof lining construction is sheet metal and asphalt. The outer façade is of original brick construction. All equipment and materials used, as construction products used for fire protection purposes, have up-to-date certificates, approvals or certificates from Polish Scientific and Research Institutes and have declarations of conformity of the producer product. The installation of these devices complies with current technical approvals and requirements of manufacturers.	9

Fire safety factor	Building description	Actual score
PAS	The building is designed in accordance with Polish fire resistance class B. The building is divided into fire zones up to 4,164.52 m^2 in accordance with local technical regulations. Fire doors and dampers are used to maintain the fire compartment lines. Ventilation ducts are made of non-combustible materials, and their combustible thermal and acoustic insulation and other combustible linings of ventilation ducts are used only on the outer surface of their surface, in such a way as to ensure non-spread of fire. The building borders directly a main road belonging to the city. To the north is a green belt of about 39 min width. To the west is a neighbouring building at a distance of approximately 25 m distance. The adjoining S2 Building is fire separated with a rating of REI 120 and rated at EI 60. To the east, the neighbouring building is located at a distance of 16.5 m. The external fire separation of the building meets with the requirements of the Polish regulations.	10
DET	The fire alarm system is designed to ensure full monitoring of all parts of the building. The system is certificated, and equipment have declarations of conformity. The assumed fire detection time is taken as between 180 s and 300 s based upon the use of smoke detectors. Power and monitoring cables meet the appropriate fire resistance class and are CNBOP certified. A two-stage alarm (coincidence connection) arrangement is used to minimise false alarms. An automatic / manual fire warning system is deployed throughout the facility to broadcast voice messages for the purpose of evacuation. In automatic mode, this is signalled via the fire detection system automatically after receiving a signal from the signalling system and by the operator (firefighter). This system is in accordance with the Polish Standard PN-EN 60849. The audible warning system covers the entire building. The devices used are certified to comply with the relevant standards. A fire alarm signal from two smoke detectors indicates an immediate Grade II alarm.	18
SUP	The building does contain some fire suppression systems but not currently a water fog system in the atrium, although this is planned to protect selected parts of the facility (indicated in the computer simulation described above). The system will significantly reduce the maximum HRR in areas such as the atrium. The building is also fitted with portable fire extinguishers and internal hydrants.	11
SC	The property is equipped with smoke forms of smoke ventilation and extract. Ventilation is designed in according with ITB No. 378/2002 – "Designing fire ventilation systems for evacuation routes in tall and altitude buildings". On the escape route from the "PLANETARIUM" room and the room itself (designed for a maximum of 160 occupants), there is a mechanical smoke extract system. The lower levels from the second level basement to the 1st floor use smoke curtains on each storey, which will prevent smoke from entering the atrium (from the second level basement to the 6th floor). Escape route distances in the ZL zones are generally 10 m in the atrium up to a maximum of 40 m. The total width of the evacuation passage and the door from the room and on the evacuation, route was calculated at a rate of 0.6 m per 100 people but not less than 0.9 m. The figure of 160 persons was used. The building is equipped with standard emergency lighting and evacuation directional lighting.	12
MAI	The installation of all fire systems was carried out in accordance with the instructions of the manufacturers, by the contractor without certification. After the systems were commissioned, an inventory was drawn up with list of planned inspections and maintenance. Documentation has been prepared confirming the availability of most firefighting equipment. Significant changes made to firefighting systems are recorded and constantly supervised.	16
FB	The detection system connects with the rescue and fire ighting unit of the State Fire Brigade, in accordance with the local Municipal Commander. The building has facilities for firefighting. Due to the distance from the nearest JRG, the expected journey time from the moment of notification is up to 10 minutes (although up to 15 minutes was used in earlier analysis). Access for the fire brigade appliiances is provided with paved internal road with entry and departure from ul. Fair. The fire road runs around a set of buildings and meets all the requirements contained in the IAS Regulation of 24 July 2009. for firefighting water supplies and fire roads.	10

6.1.6. The fire strategy value grid

The following fire strategy value grid (*Fig. 35)* can be established from the information of previous steps. Both the actual and baseline strategies line up well with the actual strategy scoring better than the baseline based upon national standards for the building.

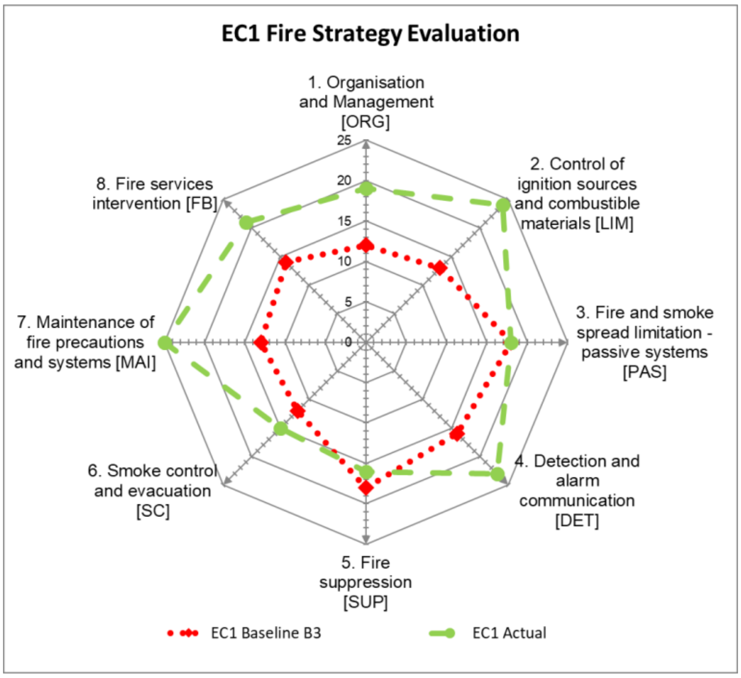


Fig. 35. EC1 Building - Fire strategy value grid.

6.1.7. The fire strategy risk index

A summary of the calculated weighting and scoring is based on the equations 5.1 to 5.5 given in Chapter 5, and is given below (the baseline strategy is based on *Table 14* for the risk profile B3). The details of the scoring are provided in the Table Appendix A.

Table 15. EC1 Building - PM Calculation.

EC1 Centre Lodz - *PM* Calculation					
Fire safety factor (FSF)	**B/L**	**ACT**	***W***	***PM* (B/L)**	***PM* (Act)**
ORG	12	19	2.4	28.8	45.6
LIM	13	24	2.6	33.8	62.4
PAS	18	18	3.6	64.8	64.8
DET	16	23	3.2	51.2	73.6
SUP	18	16	3.6	64.8	57.6
SC	12	15	2.4	28.8	36
MAI	13	25	2.6	33.8	65
FB	14	21	2.8	39.2	58.8
			Totals:	**345.2**	**463.8**

A summary of the calculated weighting and scoring is given below:

Baseline strategy: PM = 345.2

Actual strategy: PM = 463.8

PH (in both cases) = 345.2 / 100 = 3.452

Actual strategy: FHI = PH/PM × 100 = (3.452/463.8) × 100 = 0.744

(Note that for the baseline strategy: FHI = 1)

The value of Fi for public buildings is given as Fi of $6.6 \cdot 10^{-2}$ as given by PD 7974-7 (Table 10), what for the actual area A = 1226 m^2, gives Fi = **8.09×10^{-2}.**

Therefore, the Fire Strategy Risk Index (FSRI) for both strategies is:

Baseline strategy: FSRI = FHI·Fi =1 × 8.09×10^{-2} = 8.09×10^{-2}

Actual strategy: FSRI = FHI·Fi = 0.744 × 8.09×10^{-2} = 6.02×10^{-2}

In this case, the FSRI for the actual fire strategy is substantially lower than the baseline. This concludes that the risk in the actual case is satisfactory. The areas in which the strategy exceeds the expectations of the baseline requirement are areas concerned with fire safety management including organisation, control of ignition and materials, controls for maintenance of systems and facilities for the fire services. This follows from the same conclusions from the fire strategy value grid given in *Fig. 35*.

6.2. A Castle converted to a hotel, Ryn, Poland

Ryn Castle Hotel dates back to the 14th century and was the subject of rebuilding and renovation over the centuries. In the 19th century it was converted for use as a prison. Most recently, the castle has been updated and converted into an upmarket hotel with conference and banqueting facilities. The hotel's full title is the "Masurian Congress Center - Leisure Castle Ryn" (*Fig. 36*).

6.2.1. Description of the building

The hotel provides for around 350 bedrooms and apartments. These are located in each the four wings of the Castle, named the Commander's, the Knight's, the Prison's and the Hunter's. The restaurant can seat up to 180 persons and there is a separate wine bar. The hotel includes a swimming pool, gym and sauna.

A key feature of this hotel is the central covered hall that was once the central courtyard, this can accommodate up to 1,200 people for both banquets and exhibitions

Fig. 36. Ryn Castle Hotel - showing central covered courtyard (166).

6.2.2. Fire scenario risk analysis

Based upon a site risk assessment and judgement of the varying risks, the following fire scenarios are deemed as most likely in terms of fire risk:

1. fire in the central banquet hall;
2. a fire in a hotel apartment;
3. a fire in the restaurant.

The following equation will be used as developed in the chapter 4 (Equation 4.8):

$$SFR = P_g C_g \frac{(P_{ie} + P_{ip})}{10}$$

In terms of a consequence C_g, the rating should be regarded as medium for the hotel rooms and apartments (e.g. 3) and slightly higher for the communal areas (a rating of 4).

Table 16. Ryn Castle Hotel: Suggested scoring system for SFR.

Location	P_{ie}	P_{ip}	P_g	SFR	Commentary
The central banquet hall	4	4	4	12.8	This is an extremely large central space, such that fire growth can reach sizeable values. This space is treated as a single fire and smoke zone. Given its use for exhibitions, both the probability of ignition in both the environment and process will be relatively high.
Hotel room or apartment	3	3	2	4.8	Dur to the strong passive fire protection, a fire within an enclosure will likely be contained until it can be extinguished. Ignition from the room environment and processes will be medium.
Restaurant	1	4	2	3	The restaurant is fire separated from the rest of the building. This includes the kitchen. Fire growth beyond the restaurant is unlikely. The restaurant environment is well controlled although the process of the restaurant would be higher.

From the above, the fire scenario that should be further analysed is that of a fire in the central banquet hall. The hall has an B3 risk profile in accordance with BS 9999.

6.2.3. The baseline fire strategy

The baseline fire strategy was in accordance with the *Polish regulations for buildings and their location* (99), in accordance with the A2 risk profile. As with the first example of the EC1 Centre, this was supported by British Standards (some of which are regulated as European standards) (7) as well as relevant NFPA (101) guidance together with BS and NFPA codes as performance-based tools (60) (147).

A detailed analysis of the questionnaire with respect to the baseline strategy is given in Appendix B. This provide details relevant to each of the questions. However, the key fire safety factors (nodes) are summarised in *Table 17*.

Table 17. Ryn Castle Hotel – Scoring of baseline conditions.

Fire safety factor	Building description	Actual score
ORG	The hotel's fire safety design will follow Polish Regulations which does not automatically require a written fire strategy. Fire safety management requirements at a base level cover the main considerations such as the availability of evacuation plans but not higher-level systems such as certification of systems. Only fire wardens are a requirement. Aspects such as certification and enhanced training are not required.	15
LIM	Polish regulations cover the basic elements of ignition control and combustible materials only and do not restrict the hazard level. Expected fire growth is low. High risk areas are required to be separated from other areas. A class S1 smoke production rating together with Category A2 reaction to fire size is specified.	17
PAS	Structural elements must have a fire resistance of 60 mins. Internal areas and fire doors will have a maximum fire resistance from 30 minutes to 120 minutes. Fire doors will close automatically after verification.Compartment zones should be within 5,000 m^3.	17
DET	Minimum requirements are for monitoring of evacuation routes by automatic fire detectors with manual callpoints. Detection response limits are based upon relatively early detection within 300 seconds. False alarm prevention is nominally covered.	17
SUP	Fire suppression systems are recommended on a risk basis and based upon typical response expectations. The RTI response / expected activation time should be within 200 seconds. Systems should be chosen based upon local conditions.	3
SC	Nominal levels of smoke control are recommended and these concentrate on escape routes and firefighting access. Minimum smoke control is related to vertical means of escape. There are no requirements for smoke control for horizontal means of escape. Passive evacuation signage is acceptable.	15
MAI	High levels of maintenance and system management are prescribed by the Regulations.	24
FB	Nominal requirements are made for firefighter access and facilities. The Regulations require automatic connection with fire services and some availability recommendations for on-site staff. There are no limits set on attendance time. Minimum requirements such as access to dry risers and firefighting lifts are recommended. Equipment maintenance should meet recommended and manufacturer;s instructions.	12

6.2.4. Supportive analysis of actual fire strategy

Before the actual fire strategy evaluation it is necessary to prepare supportive performance based analysis, which allow to know the effectiveness of the action of protective measures planned for installation in the building. The analysis is based upon Published Document PD

7974-6: 2004 (66). When determining the evacuation times, the existing fire strategy provisions are considered:

- a fire detection and alarm system throughout using a voice alarm system;
- the building is equipped with fire hose reels and fire extinguishers;
- the building is equipped with an alternative, independent power source;
- emergency lighting and escape illuminated signage are used throughout.

The following categories are used based upon Polish regulations for buildings and their location (99) (99).

- Occupant behaviour category – B (Awake and unfamiliar). Note that part of the hotel is graded as sleeping and unfamiliar.
- Alarm system quality - A2 (automatic fire detection where an alarm signal is derived from two smoke detectors in the same smoke detection zone)
- Influence of the building complexity on the evacuation time – B2 (non-complex multi-storey structure).
- Note that, only the evacuation from the atrium space is considered. Building management level - M2 (security personnel are not utilised).

For the above categories (B, A2, B2 and M2), the pre-movement time for the first occupants (close to the fire) shall be taken as:

Δt_{pre} (1st percentile) = 60 s or 1 min , and for the final evacuating occupants,

Δt_{pre} (99th percentile) = 240 s or 4 min.

The exception to the above is the hotel accommodation area directly adjacent to the covered courtyard. From which, there is no possibility of direct evacuation but only through the covered courtyard. In this case, it is anticipated that, taking into account sleeping persons, the figures for Δt_{pre} (1st percentile) and Δt_{pre} (99th percentile) are 20 min (1,200 s) and 40 min (2,400 s) respectively. The time needed to find the right escape route is 0.5 min.

It is assumed, that in case of fire, the evacuating occupants shall use the designated evacuation routes to the nearest evacuation exits in directions other than the location of the fire.

Based upon the layout of the building, the maximum length of the evacuation passage in a given fire zone to the emergency exit (to the staircase and in the covered courtyard) is 50 m and the length of the passage from the staircase on the top floor to the outside of the building is 60 m. The walking speed of evacuating persons is taken as 1.2 m/s horizontally, and 0.8 m/s down staircases and ramps. The maximum evacuation time is therefore:

Time required to overcome the path to the staircase and into the covered courtyard:

50 m / 1.2 m/s = 42 s.

Time required to leave the building (down the staircase to the ground floor and exit from the building) is:

60 m / 0.8 m/s = 75 s.

Based on the initial analyses carried out for the fire safety criteria, it was assumed that the time needed to activate the fire detection and alarm system in the building shall not exceed

80 s from ignition. It is assumed that the fire alarm will be activated immediately, Δt_a=0s, after the detection of a fire Δt_{det} = 80 s.

In accordance with the Polish regulations, the number of exits from the building is such that an exit width of 0.6 m per every 100 persons should be assumed. However, each exit width shall not be less than 0.9 m. Taking into account the velocity of people moving through the evacuation doors = 1.3 persons/m of the active door opening width, with the minimum width of any evacuation door being 0.9 m (which equates to 150 persons)> Therefore, the maximum time of exiting for this number of people is:

150 persons / (0.9 m x 1.3 persons/m) = 128 s.

Accordingly, the Required Safe Escape Time (RSET) to evacuate people from the **covered courtyard**:

For the first occupants:

RSET(1%) = Δt_{det} + Δt_a + Δt_{pre},1% + Δt_{trav} + Δt_{pass} = 80 s + 0 s + 60 s + 42 s + 128 s = 310 s (or 5.2 min)

For the remainder of the occupants:

RSET = Δt_{det} + Δt_a + $\Delta t_{pre,99\%}$ + Δt_{trav} = 80 s + 0 s + 240 s + 42 s = 362 s (or 6 min).

The Required Safe Escape Time (RSET) to evacuate people from the **hotel accommodation** area:

For the first occupants:

RSET(1%) = Δt_{det} + Δt_a + $\Delta t_{pre,1\%}$ + Δt_{trav} + Δt_{pass} = 80 s + 0 s + 1,200 s + 42 s + 30 s + 75 s + 128 s = 1,555 s or 26 min.

For the remaining occupants:

RSET = Δt_{det} + Δt_a + $\Delta t_{pre,99\%}$ + Δt_{trav} + Δt_{find} + Δt_{trav} = 80 s + 0 s + 2,400 s + 42 s + 30 s + 75 s = 2,627 s or 44 min.

Based on the above calculations, it is assumed that the time required to evacuate people from the covered courtyard is 6.0 minutes, while from the hotel accommodation time is 44 minutes.

Fire brigade intervention time

The Hotel is located at ul. Freedom Square 2 in Ryn, 0.2 km from the nearest TSO unit (Volunteer Fire Brigade, ul. Green 1, 11-520 Ryn, *Fig. 37*).

The expected time of arrival of the TSO rescue teams to the scene of the fire, from the moment of receipt of information about the fire, is up to 2 min. The nearest PSP unit that will automatically receive communication of a fire alarm (State Fire Department District Command, ul. Białostocka 2, Giżycko, *Fig. 38*), are 23.0 km away, with an expected time of arrival, from the moment of receipt of information, at up to 26 min.

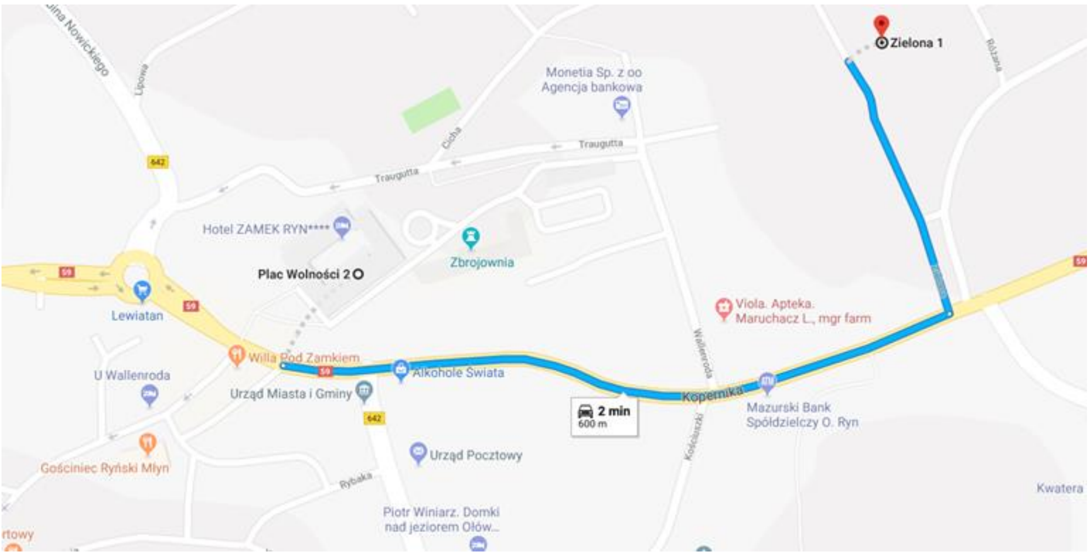


Fig. 37. Ryn Castle Hotel - Location of the Volunteer Fire Brigade unit in Ryn.

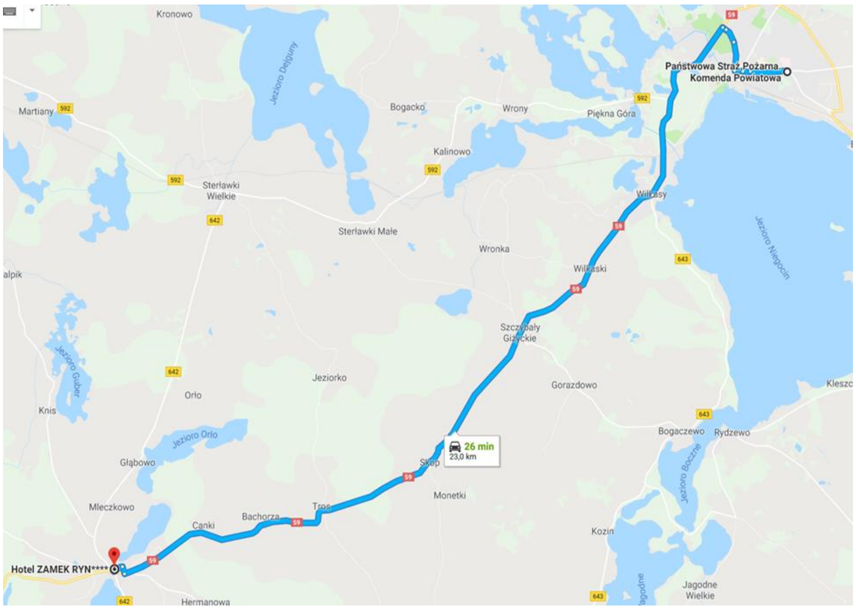


Fig. 38. Ryn Castle Hotel - Location of State Fire Dept.

Boundary and Initial Conditions for CFD simulations

Initial conditions of external and internal air parameters for the simulation were assumed as: air temperature: 20^{o}C, ambient pressure: 1013 hPa, relative air humidity: 40%. It was assumed that building partitions are constructed of concrete with a density of 2,100 kg/m^3, a thermal conductivity of 1.0 W/mK and a specific heat of 0.88 kJ/kgK. A mixture of polystyrene and wood was taken as the combustion material, which could represent combustible materials potentially present in the room for which simulations were carried out. The SOOT_YIELD coefficient, i.e. the mass fraction of the fuel, which is converted into soot, was 0.07 kg/kg, the SOOT_YIELD coefficient, , the heat of combustion: 20,000 kJ/kg. A computational grid with a density of 0.3 m in the X, Y and Z directions in simulation was adopted.

Based on NFPA 92 (164) , recommends that the analysis of computational fire development is in accordance with the standard medium fire development curve given in NFPA 204 (165), as described as a formula:

$$Q = \alpha t^2 \tag{6.1}$$

where:
Q – heat release rate [kW],
α – fire growth coefficient of 0.012 [kW/s^2] (a medium growth fire),
t – time [s].

It was assumed that due to the limited amount of combustible materials in the covered courtyard (simulation F1), the maximum power of the fire following the average fire development curve will not exceed 5000 kW, as shown in *Fig. 39*.

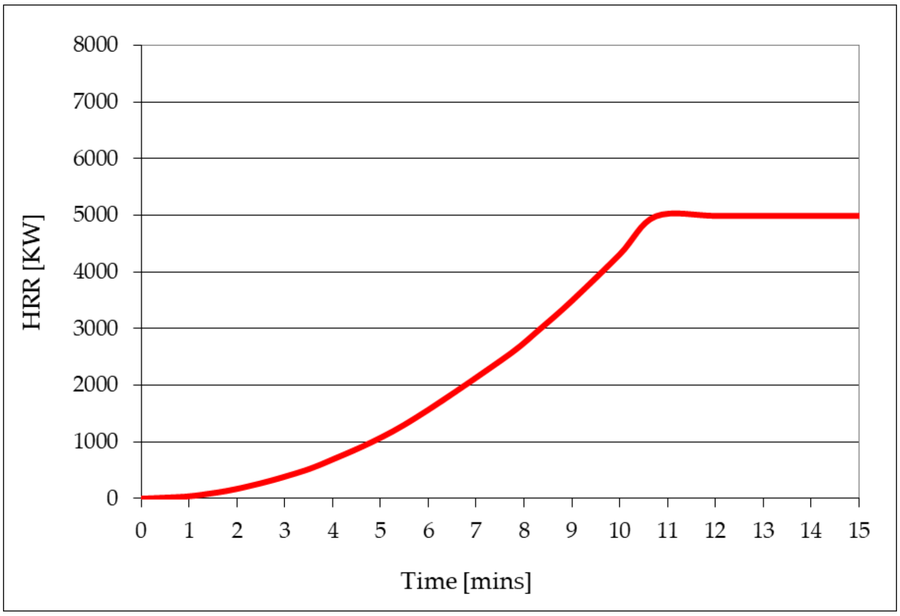


Fig. 39. Fire development curve adopted in fire scenario F1.

Fire parameters analysed: Temperature distribution and visibility range at an altitude of up to 1.8 m from the floor were modelled simulation using FDS. According to the literature data, the limits of the values of the individual parameters should be:

- the maximum tenable temperature for escape is 60°C. Note that, to take into account a suitable margin of error for the simulation and the actual temperature means that the tenable temperature should be reduced to 52°C);
- the visibility range is taken as 10 m for non-lit areas elements, and 30 m with illuminated evacuation signs.

CFD simulations results

The time periods chosen for analysis and based on the prior calculations are:

1. 362 s: this represents completion of evacuation from the hall;
2. 780 s: this represents the commencement of firefighting by the TSO Unit;
3. 1,555 s: This represents the commencement of evacuation from the hotel accommodation;
4. 1,760 s: this represents the commencement of firefighting by the main FB;
5. 2,627 s: this is completion of the evacuation from the Hotel.

Two simulations were run using two different positions at ground floor level. Position F1 (by main entrance) and F2 were located as shown in *Fig. 40*. *Fig. 41* illustrates the roof area directly above the simulations. *Fig. 42, 43 and 44* provide graphical representation of the results over a number of time periods. In this case, the progression of fire in terms of both obscuration and temperature distribution is considered for two scenarios – with and without a water fog system protecting the main space.

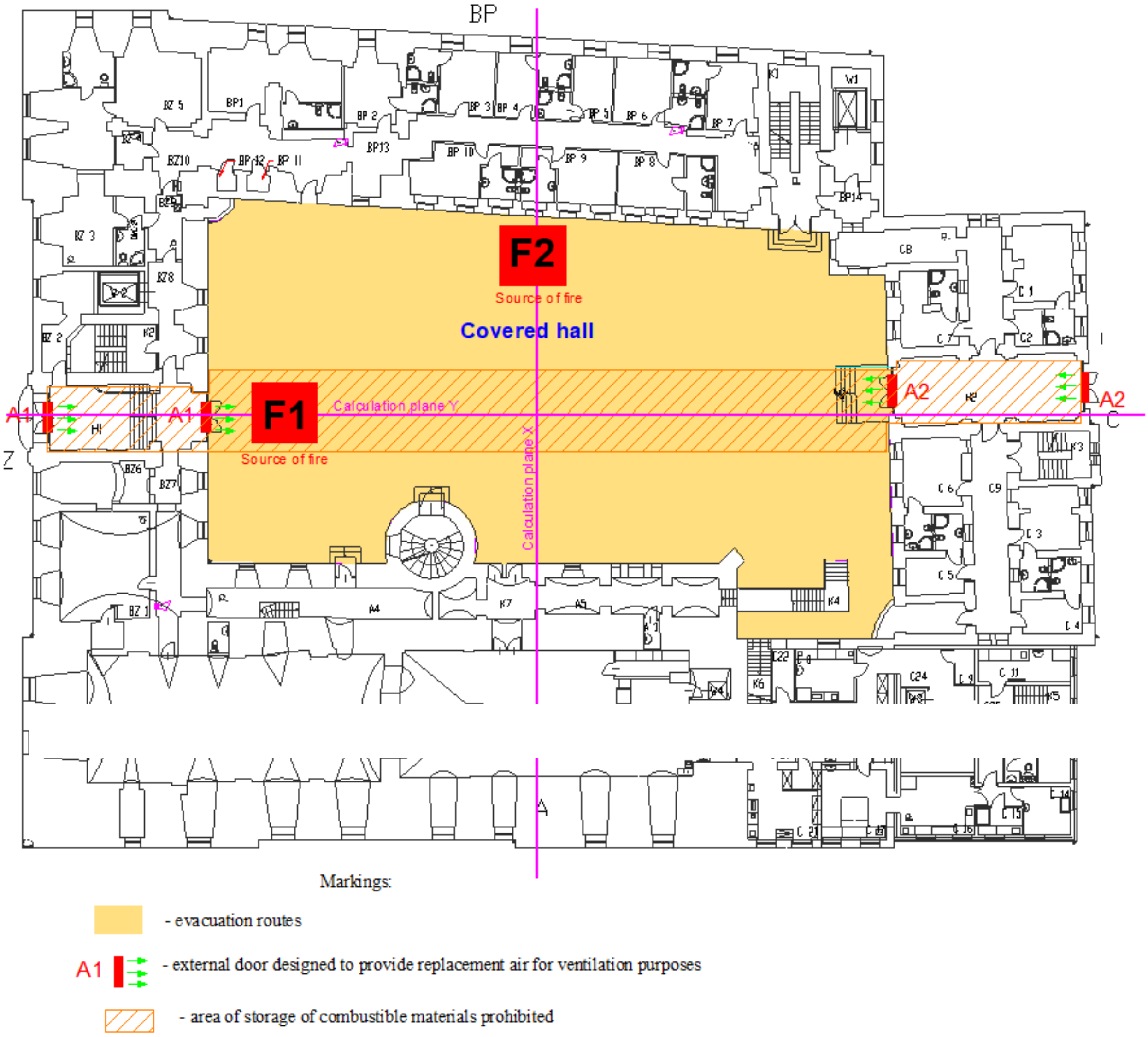
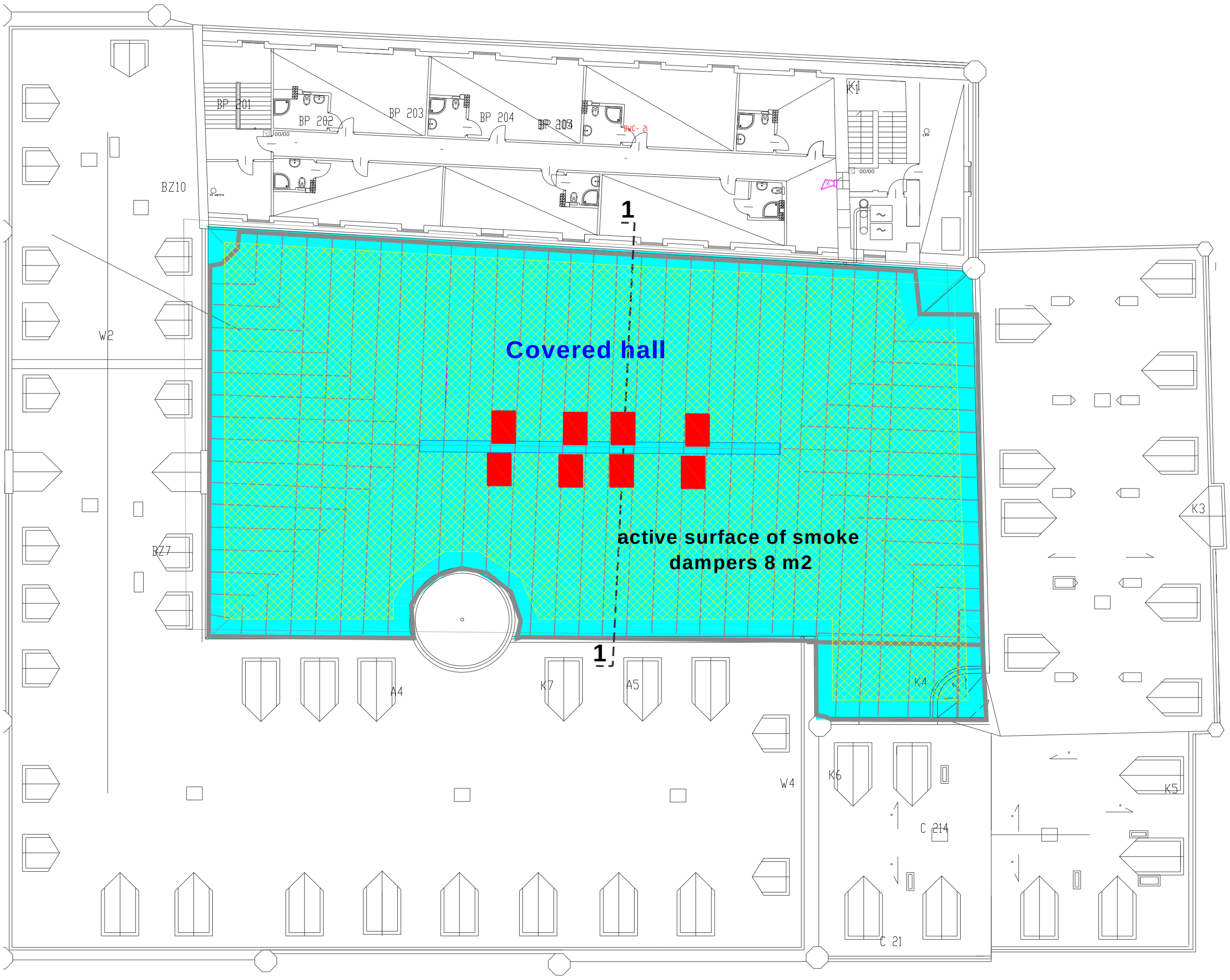


Fig. 40. Ryn Castle Hotel - Location of fires for simulation purposes.



Markings:

🟦 - roofing of the covered courtyard

🟥 - smoke damper

▨ -location of the material attached to the bottom edge of the truss

Fig. 41. Ryn Castle Hotel – roof.

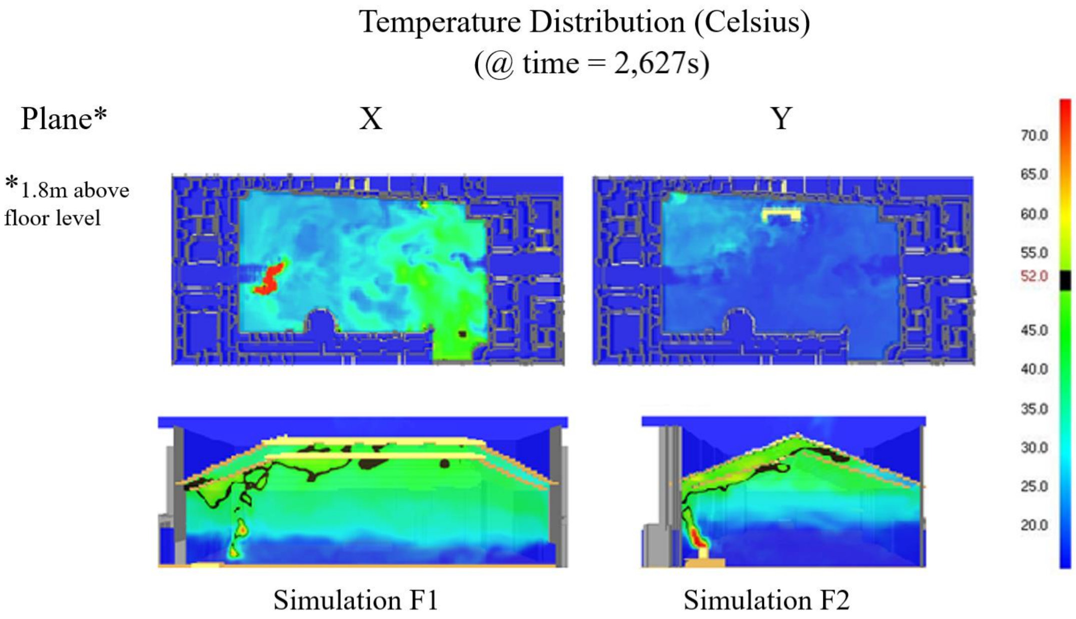


Fig. 42. Ryn Castle Hotel - Simulation (temperature distribution).

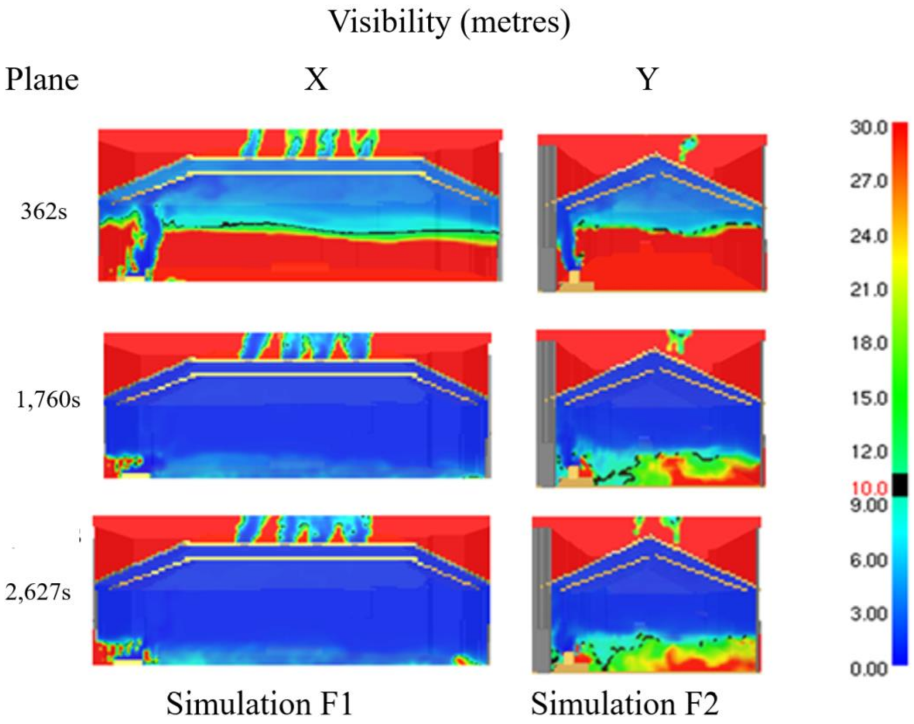


Fig. 43. Ryn Castle Hotel - Simulation (Visibility).

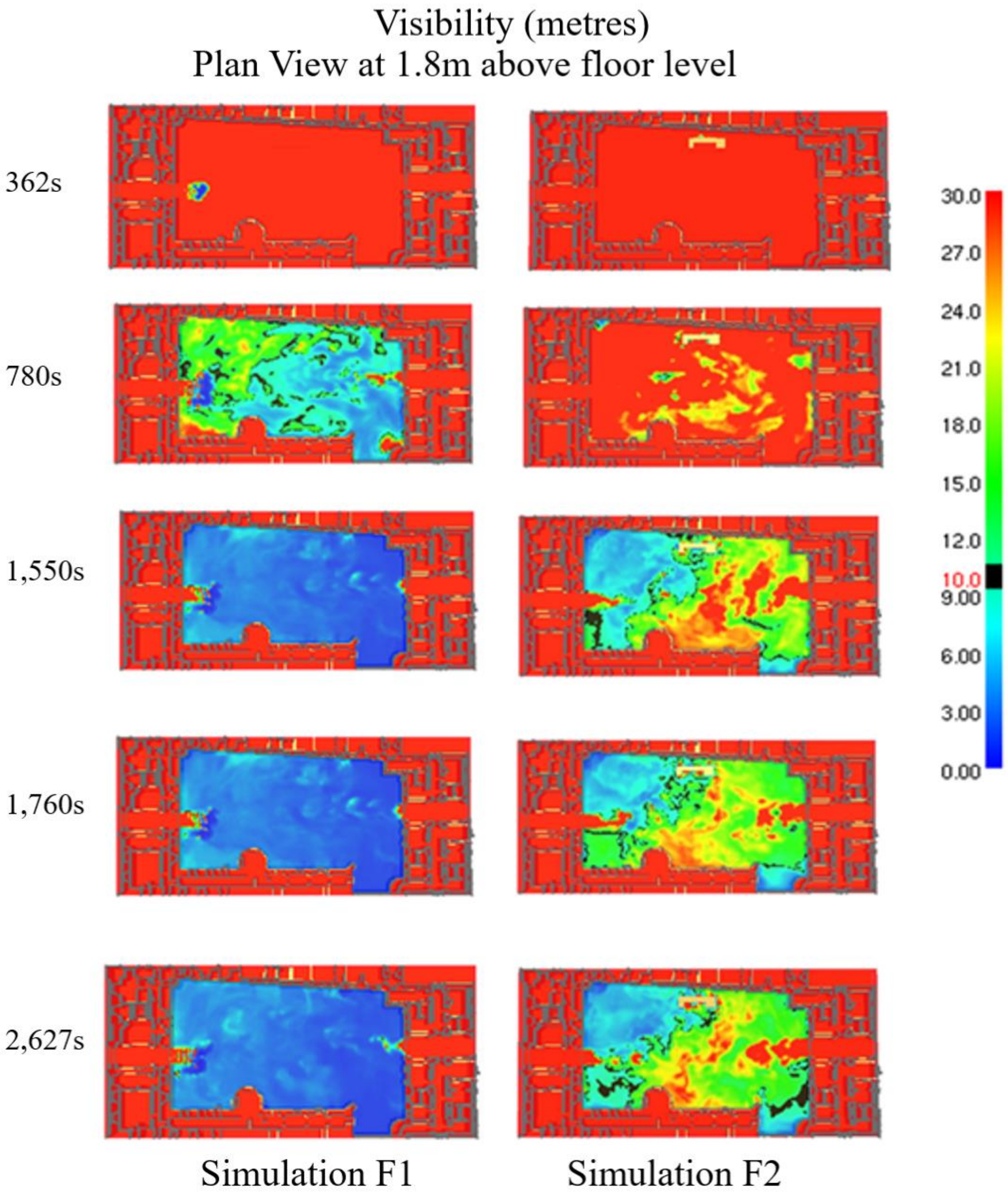


Fig. 44. Hotel - Simulation (Visibility)- 1.8m above floor level.

Conclusions from the CFD analysis

Analysis of the temperature distribution and visibility for the both fire scenarios (simulations F1 and F2), on the evacuation routes, at height of 1.8 m from floor level, has shown that the limit value of 60°C (52°C for the simulation) was exceeded and the decrease in visibility range fallen below the accepted 10 m occurred after 362 s, when the last occupants of the Covered hall completed the evacuation, which means that the fire ventilation system adopted by the assumptions does provide adequate local evacuation conditions. However, a comparison of the F1 and F2 scenarios results over time, demonstrates a significant difference between the simulations. In the case of the F1 scenario, the smoke control system appears to not be efficient, and the tenability limits of visibility for the evacuation of the sleeping occupants as well as fire brigade arriving, are exceeded.

The main conclusion from the CFD is that the proposed fire strategy (actual strategy 1) needs to be corrected and the fire load at the area by the main entrances, which allows for fresh air supply via the opening, should be limited. Consequently, areas where the convective smoke column can spread without any interruptions would be the appropriate location for furnishings and fixtures that have a degree of combustibility. This would be considered for the "actual strategy 2".

6.2.5. Actual fire strategy evaluation

Table 18 provides a description of the specific issues, based upon the eight designated fire safety factors (nodes), as found in the central atrium. The supportive analysis results and conclusions from previous section were taken into account here. Detailed scoring is given in Appendix B.

Table 18. Ryn Castle Hotel - Scoring of actual fire strategy conditions.

Fire safety factor	Building description	Actual score 1	Actual score 2
ORG	A full fire strategy has been developed with the main objective of protecting life. A fire safety manual for the building was also developed, and implemented, which will be updated regularly. Organizational solutions provide for the presence in the building of permanent security personnel, trained in the event of a fire, present during the working hours of the facility on the floor of the ground of the building. Evacuation attempts are carried out regularly, with the participation of representatives of the management staff. Mandatory checks are carried out by eligible supervisory Authorities, but no external audits are provided. Note for the "actual 2" strategy, management controls will be further improved.	18	22
LIM	The hall is used to house major events, which create the biggest fire hazard. The location of hospitality greeting areas, that were situated near the entrance to the hall will be relocated to one side, as deduced for the "actual 2" strategy.	17	20
PAS	All constructions meet the requirements for fire resistance, except for the roof over the courtyard, which has a wooden structure and is covered with cellular polycarbonate. The roof is, however, protected to a level of low flammability (manufacturer's declaration of conformity) with the help of the Fobos M-4 immunization agent (immersion method). The cellular polycarbonate roof covering is in accordance with technical approval AT-15-4764 / 2004 and does not contribute to the spread of fire. The covering will not drip or fall off when exposed to fire. All structural materials as well as those supporting the courtyard roof covering are non-flammable. The canopy under the structural roof, is made of polyester fabric according to the manufacturer's declaration is difficult to ignite and its properties are in accordance with PN-EN 13501-1. Flammable materials whose decomposition products are very toxic or intensely smoking, will not be used to finish the interior of the building - rooms.	10	13

Fire safety factor	Building description	Actual score 1	Actual score 2
	Furthermore, no flammable materials will be used in public corridors used for evacuation. These latter factors have been deuced based upon the fire simulations.		
DET	The fire alarm system is designed to ensure full protection of the building including all rooms and areas escape routes. All basic components of the installation are certificated. The expected fire detection time is 180 s – 300 s. The detectors used are suitable for potential threats. Power and monitoring cables have an appropriate fire resistance class and are CNBOP certified. Two detectors are required to operate before an alarm is given to control false alarms in accordance with ROP type B. Automatic and manual fire warning (PA system) is used throughout the building to broadcast voice messages to coordinate evacuation. This system is in accordance with the Polish Standard PN-EN 60849. The system includes the monitoring system of the State Fire Service in Giżycko. The results of the simulations have resulted in a review of spacing.	20	21
SUP	The building is equipped with portable fire extinguishers in accordance with applicable regulations - 2kg (3 dm^3) for every 100 m^2 of usable area. The simulations have strengthened the need to ensure full conformance. Note that there is no automatic suppression, such as a sprinkler system, throughout the building.	1	3
SC	The covered hall is equipped natural smoke vents in accordance with ITB No. 378/2002 – "Designing fire ventilation systems for evacuation routes in tall and altitude buildings". The fresh air supply is provided through doors in the building's external facade. The system is activated automatically, upon the activation of the fire detection system, with the option of manual control. Due to the presence of the system the travel distance in an emergency increases to 40 m. The total width of the evacuation passage and the door from the room and on the evacuation route was calculated at a rate of 0.6 m per 100 people but not less than 0.9 m. The width of the walk and escape passages was selected according to the number of evacuated persons. The building is equipped with standard emergency lighting as well as evacuation directional lighting and signage. The results of the simulations point to modifications to the evacuation and tenability parameters.	9	18
MAI	The design and installation of all fire systems was carried out in accordance with manufacturer's standards, although not certificated. This will be improved for the revised conditions. An inventory is kept of all systems and a list of planned inspections and maintenance is followed. In the building, recurring tests and functional tests of the most important elements of fire systems are performed, confirmed by entries in the service documentation. Documentation has been drawn up confirming the availability of most fire fighting equipment. Significant changes made to firefighting systems will be recorded and constantly supervised. These additional measures are incorporated into Actual 2 fire strategy.	15	23
FB	There is an automatic fire signalling system were connected to the rescue and firefighting unit of the State Fire Brigade, in a manner agreed with the Psp Municipal Commander. The alarm to the unit shall be transmitted as soon as the grade II alarm is checked	15	15

6.2.6. The fire strategy value grid

The following fire strategy value grid (*Fig. 45*) can be established from the information of previous steps . It can be seen that all shapes follow a similar pattern. However "Actual 1" falls short in some areas. This is largely rectified by "Actual 2".

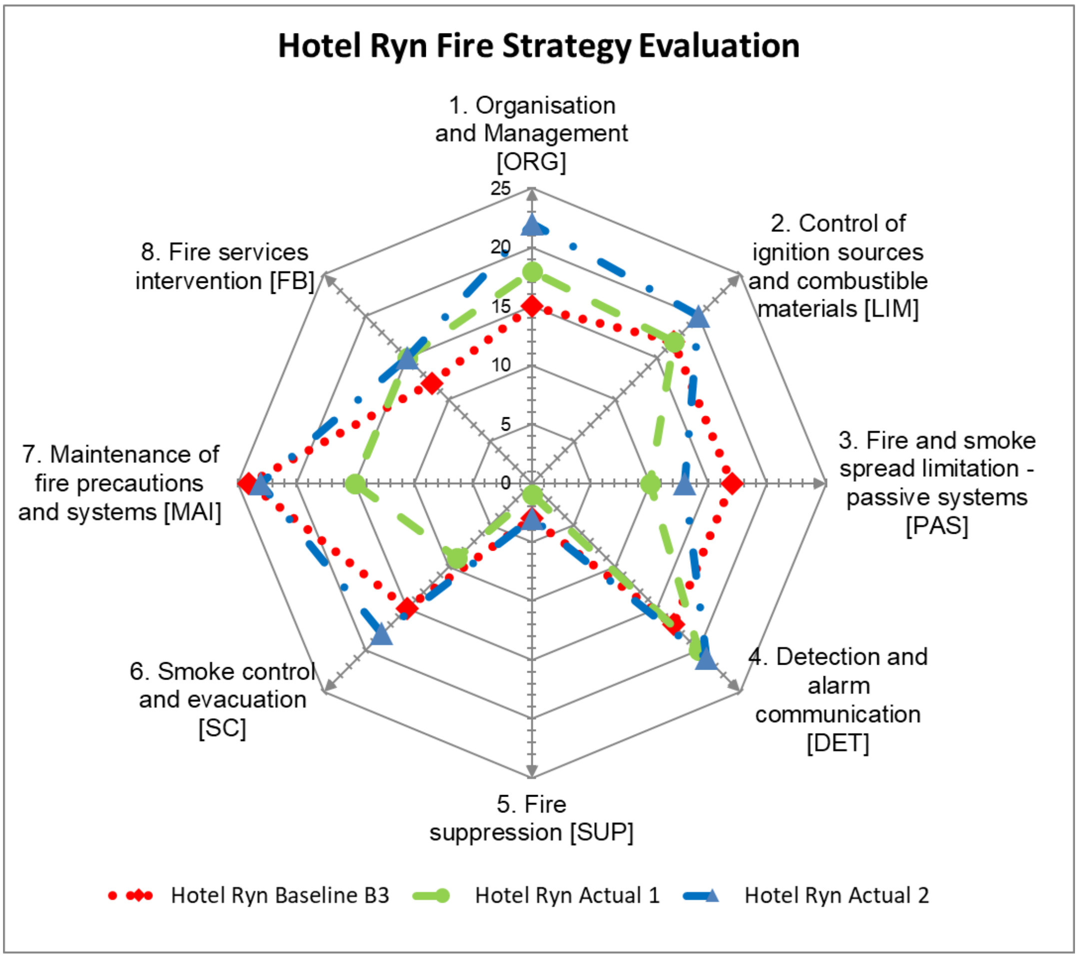


Fig. 45. Ryn Castle Hotel - Fire strategy value grid.

6.2.7. The fire strategy risk index

A summary of the calculated weighting and scoring as based on the equations 5.1-5.5 presented in chapter 5, and is given below. The details of the scoring are provided in the Table Appendix B.

Table 19. Ryn Castle Hotel - PM Calculations.

	Ryn Castle Hotel - PM Calculations						
Fire safety factor (FSF)	***B/L***	***Act 1***	***Act 2***	***W***	***PM (B/L)***	***PM (Act 1)***	***PM (Act 2)***
ORG	15	18	22	3.0	45.0	54.0	66.0
LIM	17	17	20	3.4	57.8	57.8	68.0
PAS	17	10	13	3.4	57.8	34.0	44.2
DET	17	20	21	3.4	57.8	68.0	71.4
SUP	3	1	3	0.6	1.8	0.6	1.8
SC	15	9	18	3.0	45.0	27.0	54.0
MAI	24	15	23	4.8	115.2	72.0	110.4
FB	12	15	15	2.4	28.8	36.0	36.0
				Totals:	**409.2**	**349.4**	**451.8**

A summary of the calculated weighting and scoring is given below:

Baseline strategy: PM = 409.2

Actual strategy 1: PM = 349.4

Actual strategy 2: PM = 451.8

PH (in all cases) = 409.2 / 100 = 4.092

Actual strategy 1: FHI = PH/PM × 100 = (4.092/349.4) × 100 = 1.17

Actual strategy 2: FHI = PH/PM × 100 = (4.092/451.8) × 100 = 0.91

(Note that for the baseline strategy: FHI = 1)

The value of Fi for hotels is given as Fi of $8.0 \cdot 10^{-2}$ as given by PD 7974-7 (Table 10), what for the actual area A = 700 m^2, gives Fi = **5.60×10^{-2}.**

Therefore, the Fire Strategy Risk Index (FSRI) for each strategy is:

Baseline strategy: FSRI = FHI·Fi =1 × 5.60×10^{-1} = 5.60×10^{-1}

Actual strategy 1: FSRI = FHI·Fi = 1.17 × 5.60×10^{-1} = 6.56×10^{-1}

Actual strategy 2: FSRI = FHI·Fi = 0.91 × 5.60×10^{-1} = 5.07×10^{-1}

The results of the assessment of the actual fire strategy for the building, in comparison with the baseline strategy, showed that the value of the actual strategy 1 fire strategy risk index exceeds the value of that index for the expected baseline strategy, which means that improvements to some elements of the strategy will be required. The additional safeguard measures proposed in the study (actual strategy 2) made it possible to reduce the fire risk index in the building below the index value for the baseline strategy, which means that, according to the method adopted here, the level of fire protection of the building will be considered satisfactory after the introduction of these additional control measures. The main improvement proposed is in the re-allocation of the usable areas of the Hall in terms of location of combustible materials and identification of escape routes. Supply air improvements via the main door are also proposed. This can be best represented in *Fig. 46*.

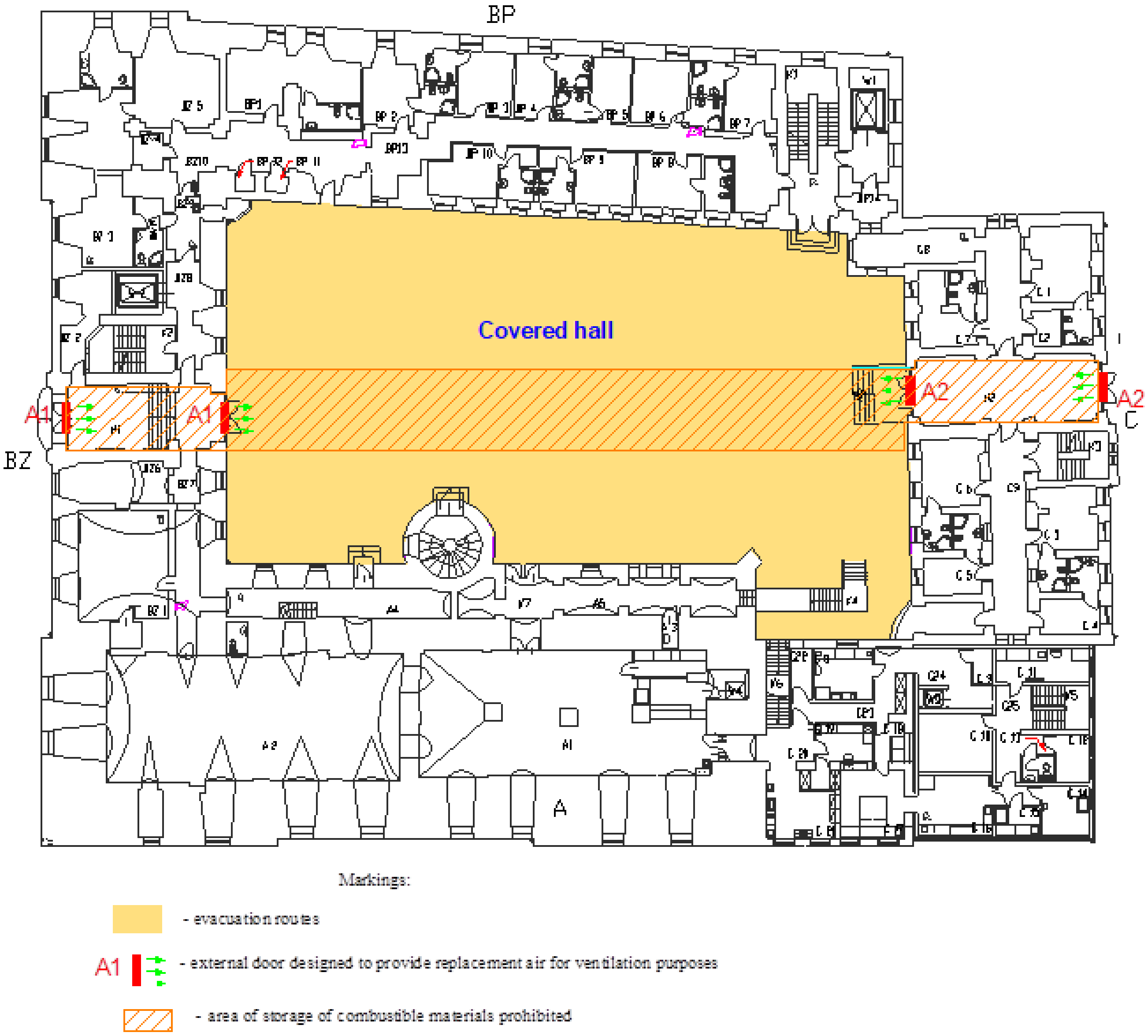


Fig. 46. Ryn Castle Hotel - revised control measure arrangements to aid tenability of escape.

6.3. A Hospital located in Chelsea, London, UK

Chelsea and Westminster Hospital's Main Building was constructed in 1992 and has been occupied since 1993. Its maximum occupiable floor is less than 30 metres above ground floor level.

6.3.1. Description of the building

The Hospital Building is of steel frame construction with brick and glazed exterior. It is made up of the following floors:

- Basement Level, which is used predominantly as a car park, together with plant rooms;
- Lower Ground floor combines office spaces with some clinical facilities and further plant areas. There are 2 lecture theatres (incl. Cinema) and a small number of seminar rooms. A canteen and coffee shop are also located at this level;
- Ground floor level. The main entrance for the Hospital is at ground level. This leads into a main atrium (described below). The ground floor includes the main reception, security room, a number of small retail units, the pharmacy, and offices. The A&E department occupies a large part of the rear of the building. At the front of the building are a number of self-contained retail units including a coffee shop and post office;
- 1st to 5th floor levels. Hospital wards, laboratories, theatres and research departments;
- Roof: Additional plant.

A key feature of this Hospital is the large single zone atrium (see *Fig. 47*) which acts as the main form of access for visitors and staff to all levels of the building. This encompasses a series of lifts, escalators, open stair cores and glass and steel walkways from lower ground to 5th floor level. The atrium includes four interconnected lightwells.

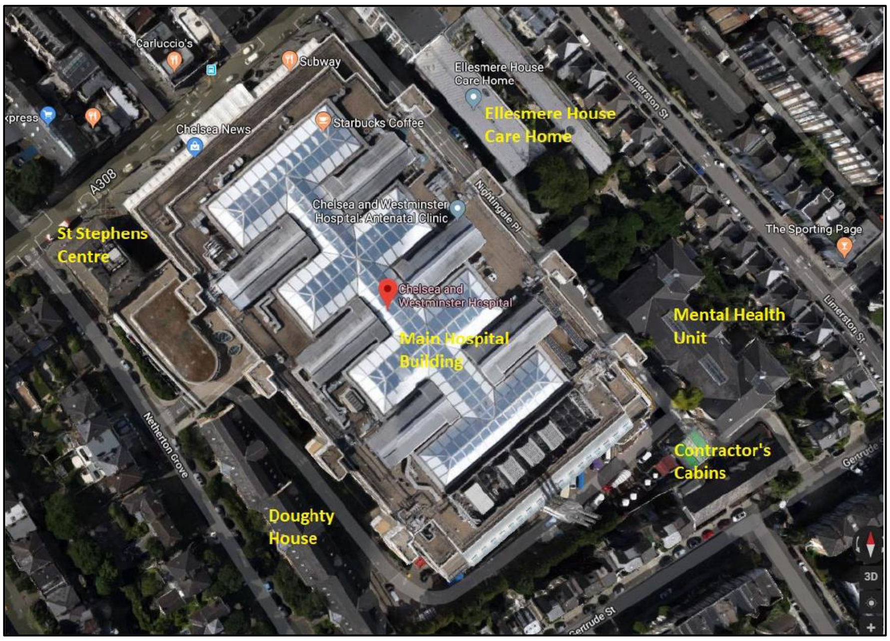


Fig. 47. Hospital - View from above showing large central atrium (169).

Located around the external boundaries of the building are eight stair core cores serving the basement level to the fifth-floor level, with four also serving the roof level. These stair core cores are designed to be used for firefighter access. There are a further two protected stair cores serving the front and rear of the building.

The occupancy profile for healthcare premises typically differs from other types of premises, in that there are grades of occupants based upon their level of mobility. HTM 05 defines three grades of persons:

1. independent: Patients are considered to be independent if their mobility is not impaired in any way and they are able to physically leave the premises without staff assistance;
2. dependent: This applies to all patients except those classified as "independent" or "very high dependency";
3. very high dependency: Those whose clinical treatment and/or condition creates a high dependency on staff. This will include those in intensive care areas, operating theatres, coronary care etc and those for whom evacuation would prove potentially life-threatening.

A key feature of this Hospital is the large single zone atrium which acts as the main form of access for visitors and staff to all levels of the building. This encompasses a series of lifts, escalators, open stair cores and glass and steel walkways from lower ground to 5th floor level. The atrium includes four interconnected lightwells as shown in Fig. 47. It is via the atrium that allows normal access to all the wards.

One feature of this Hospital that is rare in the United Kingdom is that all areas other than the central atrium are protected by an automatic sprinkler system. Note that, the key control measures adopted in the Hospital are:

- highly responsive security team to react to any alarm within 5 minutes;
- fire detection throughout the Hospital. A high-level aspirating smoke detection system is installed to monitor the atrium;
- sprinkler protection in all areas other than the atrium;
- separation of wards and designated areas by fire resisting compartmentation of 60 minutes;
- smoke venting control in the atrium;
- air handling unit control for all areas.

The risk profile for Hospitals can be difficult to ascertain, bearing in mind the range of occupancy profiles and processes. However, it is suggested that (167) medical day centres and clinics are considered as a form of awake and unfamiliar. This would equate to the B class risk profile of BS 9999. Hospitals, care or nursing homes and homes for the elderly are considered as a form of sleeping and unfamiliar. This would relate mostly to the C class risk profile of BS 9999. Where staff are well-trained, and in suitable numbers to directly assist all patients, then it is possible that the A class risk profile of BS 9999 could be applied. In common parts of the building a B risk profile would be appropriate with the potential fire growth varying for enclosed areas with a B2 classification and the atrium a B3 classification. In addition to this British Standard are a healthcare specific set of standards referred to as Healthcare Technical Memorandums (HTMs). The standards applicable to this Hospital are

HTM 05-01: Managing healthcare fire safety and HTM 05-02: Fire safety in the design of healthcare premises. These will be used to score baseline conditions for the fire strategy.

6.3.2. Fire scenario risk analysis

Based upon the above description and judgement of the varying risks, the following fire scenarios are deemed as most likely in terms of fire risk:

- fire in the central atrium;
- a hospital ward fire;
- a fire in the accident and emergency ward;
- a basement car park fire.

The following equation will be used as developed in the chapter 4 (Equation 4.8):

$$SFR = P_g C_g \frac{(P_{ie} + P_{ip})}{10}$$

In terms of a consequence C_g, the rating should be regarded as suitably high in all occupied parts of the hospital (e.g. 4) and slightly lower for the car park (a rating of 3).

There are of course many potential fire scenarios in a working Hospital. However, there are some key fire scenarios that are often considered for special examination. These are shown in *Table 20*. It can be deduced that the fire scenario that should be further analysed is that of a fire in the central atrium given the high score. However, the A&E department may also warrant separate analysis although this is not covered in this analysis.

Table 20. Hospital: Suggested scoring system for SFR.

Location	P_{ie}	P_{ip}	P_g	SFR	Commentary
The central atrium	4	4	3	9.6	There are some rules that specify allowances for operations within a central atrium, namely that combustible sources (such as coffee shops, retail outlets, etc.) should be limited to areas with a maximum fire loading of 150 kW and a minimum distance is specified between these areas based upon combustibility classes. Note that, in the case of this Hospital, the atrium is extremely large so contains a combined risk of many megawatts of fire loading. Within the SFR calculation, this would point to a potential sizeable environmental risk of ignition. The processes within the atrium, i.e. visitors, patients, staff are similarly not negligible. In terms of fire spread, if here is a major fire within the atrium it would need to be major. However, the atrium is fire separated from the other parts of the building. Therefore, the potential to spread unhindered is not high but also not negligible.
Ward	3	3	2	4.8	A typical ward similarly contains some environmental risk. One of these risk factors is not typical. Localised oxygen supplies are known by many hospital fire experts to increase the severity of any ignition event. The processes within an operational ward are also not negligible. However, most wards are fire separated from other areas of a building, usually by a fire resistance rating of 60 minutes.

Location	P_{ie}	P_{ip}	P_g	SFR	Commentary
A&E (Accident & Emergency)	3	3	3	7.2	A&E is normally treated as one evacuation zone. A&R are normally located at ground floor level. In terms of risk, the risks found in a typical ward would be repeated here. However, the probability of fire growth is slightly greater due to the nature of the operations and the constant need to access other parts of the Hospital.
Car Park	1	4	2	3	The car park is located in the basement. The environment is highly sterile although the process (cars/car parking) could be regarded as high. The car park is fire separated from all other parts of the building.

6.3.3. The baseline fire strategy

The atrium has been identified as a B3 risk profile in accordance with BS 9999. This is based on the fact that many occupants are not familiar with the building and the fire growth in the atrium is potentially fast. However, the UK Healthcare Technical Memorandum HTM 05 (168) is highly relevant. *Table 21* provides the typical scoring for this risk profile for an optimum baseline fire strategy. Detailed scoring is given in Appendix C.

Table 21. Hospital - Baseline scoring table.

Fire safety factor	B/L	Commentary
ORG	20	Hospital must abide by a specific UK supported standard for healthcare - HTM 05-01. This recognises the importance of a proper fire safety management regime for all healthcare premises. It also provides categories of management based on the profile of the building and its occupancy. For hospitals – the highest level (Level 1) of fire safety management is deemed to be appropriate and applies to all parts of the building function. This recommends a fire strategy document, fully documented procedures, and trained wardens although regular evacuation drills are not a feature.
LIM	14	The HTM suggests that the atrium is considered to have a limited fire load where all the combustible materials are arranged in discrete islands of up to 10 m^2 with a fire load density of up to 115 MJ/m^2. Alternatively, each island is separated from other areas of combustible materials by at least 4 metres or is protected by a sprinkler system. Similarly, Part D of HTM 05-03 includes recommendations for the inclusion of retail areas within the atrium space. HTM 05 – 02 recommends that all linings used in the building construction and furnishings meet with the following criteria: a) Wall and ceiling linings within all circulation spaces, and rooms greater in area than 4 m^2 including communal areas of the residential floor should make use of materials having a Class 0 surface spread of flame. This is the highest level of specification. b) In small rooms with areas of 4 m^2 or less, this requirement is reduced to Class 1 surface spread of flame.
PAS	17	Compartmentation is particularly important where the evacuation strategy of progressive horizontal evacuation as it is in the case of Hospitals. Hospital buildings should make use of primary and secondary (sub-compartment) fire resisting compartmentation. The primary compartmentation is designed for the use of progressive horizontal evacuation and should be typically 60 minutes. The secondary compartmentation provides separation between risk areas and escape corridors and could be 30 minutes. Compartment zones should be within 2,000 m^3 although in some cases this may be exceeded by agreement. All stair core cores designated for fire-fighting use will be fire separated from the rest of the building by a total fire resistance of 120 minutes. Doors and shutters should typically activate automatically after verification.
DET	19	HTM 05 requires that fires are detected at the earliest possible opportunity and that suitable warning is then given to the occupants and the emergency services. Health Technical Memorandum 05-03 Part B – 'Fire detection and alarm systems' provides general principles and technical guidance. Response times are not stated but the type and spacing requirements would suggest an activation time within 300s.
SUP	11	Fire suppression systems are not required although recommendations are made for fire suppression for retail units and storage requirements. Where fitted, the systems would follow BS/EN standards

Fire safety factor	B/L	Commentary
SC	19	Evacuation from any enclosed part of the building does not make use of the atrium, other than for those who are in the atrium at the time of a fire. Part M recommends that an appropriate smoke-exhaust system should be provided within the atrium space that is automatically activated either by the detection and alarm system or by other suitable means. Such smoke-control measures should be designed to maintain a steady buoyant layer of smoke at least 1 m above the uppermost opening in the atrium enclosure. Where balconies or bridges are provided within the atrium (as is the case with this Hospital), the smoke-control measures should ensure that smoke is maintained at least 3 m above the balcony or bridge level; and the temperature of the smoke layer does not exceed 200°C for at least the period of time required to evacuate any occupants of the balcony or bridge. Replacement air should be incorporated into the atrium design to ensure the correct operation of the smoke-exhaust system. Inlets for replacement air should be located at low level within the atrium and sized appropriately such that the velocity of air drawn in through the inlets is no greater than 2 m/s.
MAI	23	Maintenance and management systems are prescribed by the Regulations against HTM 05-01 which requires the highest levels. Note that some testing over and above BS recommendations is included in the HTM.
FB	14	Nominal requirements are made for firefighter access and facilities. The HTM recommends basic requirements such as dry risers and firefighting lifts based upon building heights. A desired arrival time is not stated but 600 seconds is viewed as typical. Adequate levels of internal communications within the building are recommended.

6.3.4. Supportive analysis of actual fire strategy

Before the actual fire strategy evaluation, it is necessary to prepare supportive performance based analysis, which allow to know the effectiveness of the action of protective measures planned for installation in the building.

The analysis of the assumed evacuation time is based upon British Standard Published Document PD 7974 -6: 2004 (66). When determining the evacuation times, the existing fire strategy elements were considered, specifically for the main atrium, including:

- an aspirating fire detection system installed at high level;
- a 5-minute investigation period before initiation of an alarm;
- the use of a sounder alarm system;
- there is an alternative, independent, power source to power fire protection systems;
- emergency lighting and escape illuminated signage throughout.

The following categories and assessments were assumed taking into account the above:

Occupant profile: The profile used is B (awake and unfamiliar). Note that only the atrium space is being analysed because all the other spaces of the hospital are in the separated fire zones and have independent evacuation routes and fire strategies.

Fire detection profile: The category required for Hospitals is L1 in accordance with BS 5839-1. Note that all structures, such as retail areas, within the atrium are fitted with point smoke detectors. The main open areas of the Atrium rely on detection from an aspirating detection system located to monitor the high-level passive air ventilation.

Influence of the building complexity on the evacuation time: At ground floor level the main way out will be via the main entrance and rear exit. Persons at this level will be directly escorted via the security teams and other staff. At higher levels, persons will be located on the many walkways and would be expected to enter into one of many wards and other areas that surround each upper level and are fire separated by 60 minutes from the atrium. The maximum travel distance at these levels is assessed at 40 metres.

Building management: In accordance with HTM 05-01, the highest level of fire safety management can be expected.

Breakdown of RSET Factors

Fire detection time: An aspirating fire detection system located at the apex of the atrium and surrounding the external parameter. Aspirating systems are typically highly sensitive and will respond to the first detection of smoke. Analysis as shown in *Fig. 48* suggest that the response time is 220 seconds from ignition. This figure will be used for further analysis.

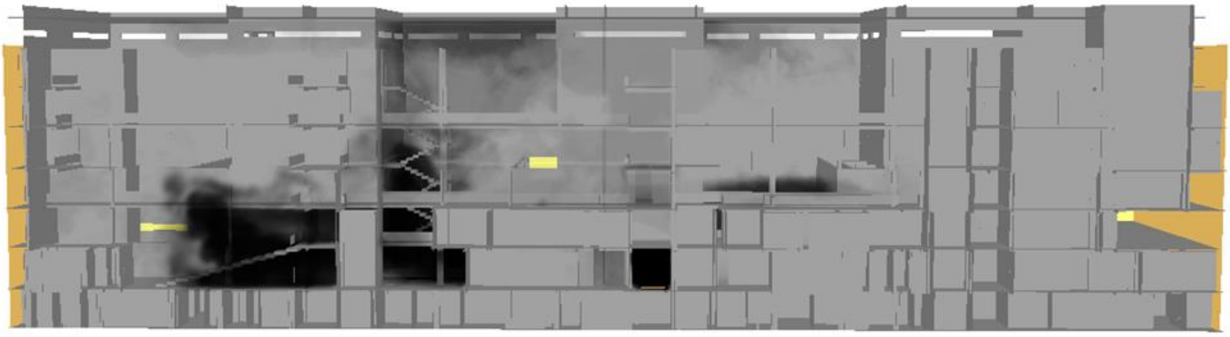


Fig. 48. Hospital - Preliminary analysis of fire model.

Pre-movement time: It will be assumed that persons directly affected by the fire will evacuate immediately within 140 s. The pre-movement time for the first occupants (closest to the fire) shall be Δt_{pre} (1st percentile) = 60 s, and for the last persons another time Δt_{pre} (99th percentile) = 240 s. It is assumed that 30 s is required for wayfinding.

It is assumed, that in case of fire the evacuating occupants shall use the designated evacuation routes to the nearest evacuation exits in directions other than the location of the fire. The walking speed of people moving along the evacuation routes is assumed as 1.2 m/s. Consequently, the worst case, the travel time at upper levels to the nearest evacuation exit is Δt_{trav} (Upper levels) = 40 m x 1.2 m/s = 34 s

At ground floor level, the longest travel distance is about 70 m. The walking speed of people along the evacuation routes is taken as 1.2 m/s. Therefore, for the worst-case condition, the travel time to the nearest evacuation exit is Δt_{trav} = 70 m x 1.2 m/s = 84 s

The building was designed in such a way that an exit width of 0.6 m per every 100 persons was assumed, however each exit width shall not be less than 0.9 m. Taking into account the velocity of people moving through the evacuation door = 1.3 persons per one metre of the active door opening width as well as the fact that the minimum width of any evacuation door is 0.9 m (thus is equal to 150 persons) – the maximum time of exiting for this number of people is 150 persons / (0.9 m x 1.3 persons/sqm) = 128 s.

Accordingly, the Required Safe Escape Time (RSET) can be calculated as follows:

For the first occupants evacuating:

$$\text{RSET (1\%)} = \Delta t_{det} + \Delta t_{a} + \Delta t_{pre,1\%} + \Delta t_{find} + \Delta t_{trav} + \Delta t_{pass} =$$

$$220\ \text{s} + 0\ \text{s} + 60\ \text{s} + 30\ \text{s} + 34\ \text{s} + 128\ \text{s} = 472\ \text{s}$$

For the remaining occupants evacuating:

$$\mathrm{RSET} = \Delta t_{det} + \Delta t_{a} + \Delta t_{pre,1\%} + \Delta t_{find} + \Delta t_{trav} + \Delta t_{pass} =$$

$$220\ \mathrm{s} + 0\ \mathrm{s} + 240\ \mathrm{s} + 30\ \mathrm{s} + 34\ \mathrm{s} = 524\ \mathrm{s}.$$

Based on the above calculations, it is assumed that the time needed to evacuate people from the building is 524 s (8.8 minutes).

Determination of the attendance time of the Fire Brigade

Chelsea and Westminster Hospital is located at a distance of 1.3 km from the nearest fire brigade station (264 King's Rd, Chelsea, London – see *Fig. 49*). The expected time of arrival of rescue crews to the site of the fire, from the moment of receipt of information, is up to 8 min (480 s), based upon the distance assessment and the likelihood of busy roads.

The detection time has previously been assessed as 220 s. The investigation period for an atrium fire has been discounted. The time for preparation to fight a fire in the atrium will be assumed as 2 minutes (120 s). Consequently, the time for Fire Brigade response will be taken as 220 s detection + 480 s FB journey time + 120 s fire location and commencing firefighting operations = 820 s.

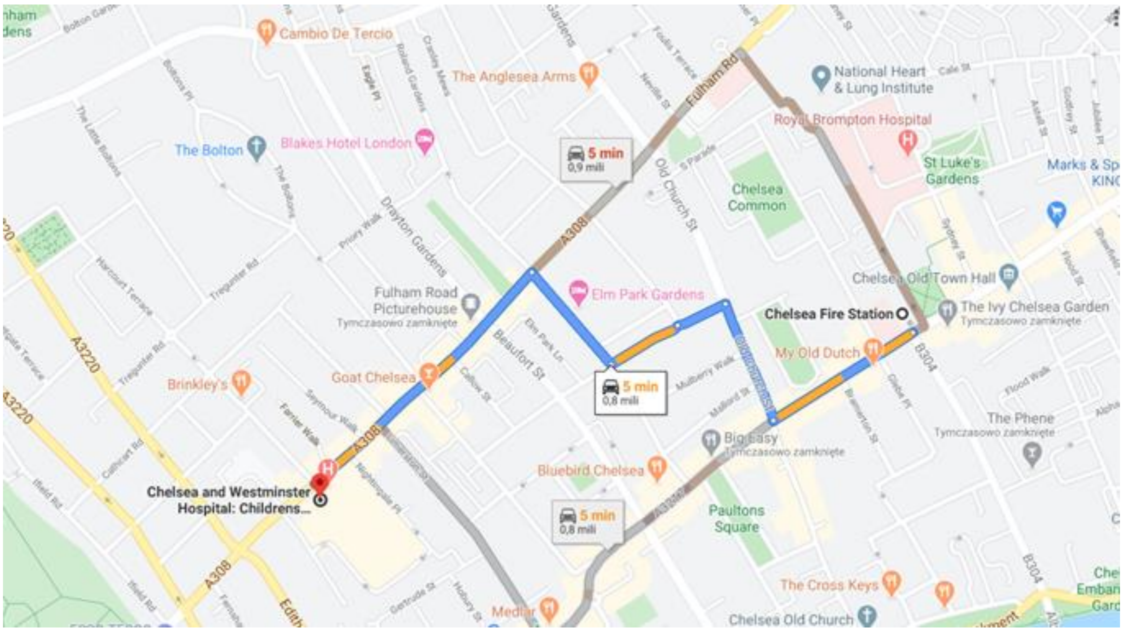


Fig. 49. Hospital – Expected route taken by fire brigade.

Boundary and Initial Conditions

Initial conditions for the external and internal air parameters for the simulation were assumed as: air temperature: 20°C, ambient pressure: 1013 hPa, relative air humidity: 40%. Building partitions assumed concrete as the construction material, with a density of 2,100 kg/m^3, a thermal conductivity of 1.0 W/mK and a specific heat of 0.88 kJ/kgK. A mixture of polystyrene and wood was taken as the combustion material, which could represent combustible materials potentially present in the room for which simulations were carried out. The SOOT_YIELD coefficient, i.e. the mass fraction of the fuel, which is converted into soot, was 0.07 kg/kg, the SOOT_YIELD coefficient, , the heat of combustion: 20,000 kJ/kg. A computational grid with a density of 0.3 m in the X, Y and Z directions in simulation was adopted.

The NFPA 92 (164) standard was used to prepare the analysis using computer simulations, based on the standard fire development curve given in NFPA 204 (165) (Eq. 6.1):

$$Q=\alpha t^2$$

where:

Q – heat release rate [kW],
α – fire growth coefficient of 0.047 [kW/s²] (a fast growth fire),
t – time [s].

In the case of fire scenarios providing for fire in the absence of protection of the firefighting system, it was assumed that due to the limited number of combustible materials, the maximum fire size will not exceed 5000 kW (at a perimeter of 12 m), as shown in *Fig. 50*.

Determination of the required safe escape time (RSET) from the Atrium

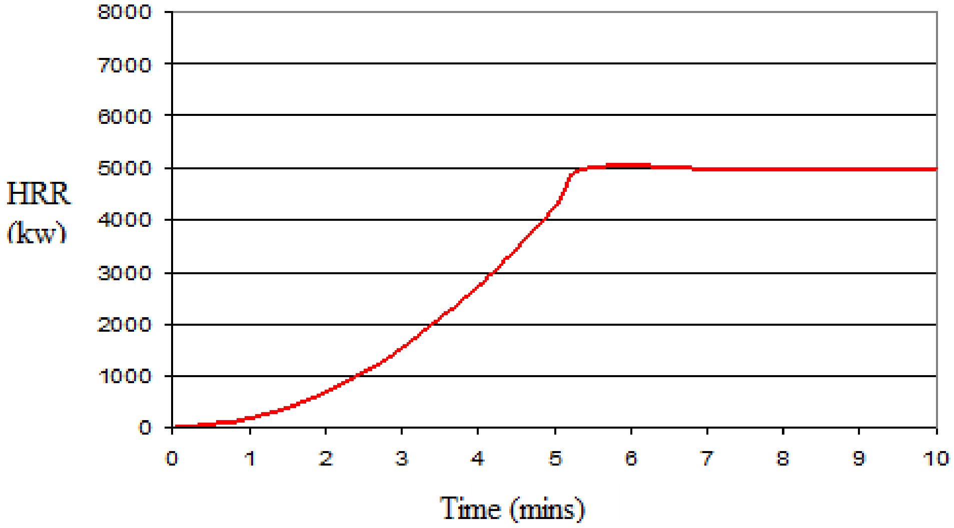


Fig. 50. Hospital - Fire development curve adopted in the fire scenarios.

Fire parameters analysed: Temperature distribution and visibility range at an altitude of up to 1.8 m from the floor were modelled simulation using FDS. According to the literature data, the limits of the values of the individual parameters should be:

- the maximum tenable temperature for escape is 60°C. Note that, to take into account a suitable margin of error for the simulation and the actual temperature means that the tenable temperature should be reduced to 52°C);
- the visibility range is taken as 10 m for non-lit areas elements, and 30 m with illuminated evacuation signs.

CFD simulations results

Two simulations were run using two different positions at ground floor atrium level (see *Fig. 51 and 52*). Position F1 was located directly underneath an upper level walkway on the lower ground. Position F2 was located at ground floor level so that there was an open path to the atrium ceiling above. *Fig. 53 and 54* show the walkways on the upper levels of the Atrium.

The time periods chosen for analysis and based on the prior calculations are:

1. 140 s: this period represents the commencement of the evacuation from the immediate effects of fire. Of relevance in this case is the tenability and visibility of escape routes;
2. 220 s: this represents the time of detection;
3. 472 s: this represents the start of the evacuation of the last occupants from the immediate effects of fire. Similarly, it is the visibility range that is of interest;
4. 524 s: this represents the completion of the evacuation from the immediate effects of fire. The visibility range that is of interest;
5. 820 s: this is the time calculated as when the fire brigade will arrive on site. Note that the visibility range and temperature distribution are of interest at this point;
6. 900 s: this is completion of the simulation period.

Fig. 55 and 56 provide graphical representation of the results over these periods.

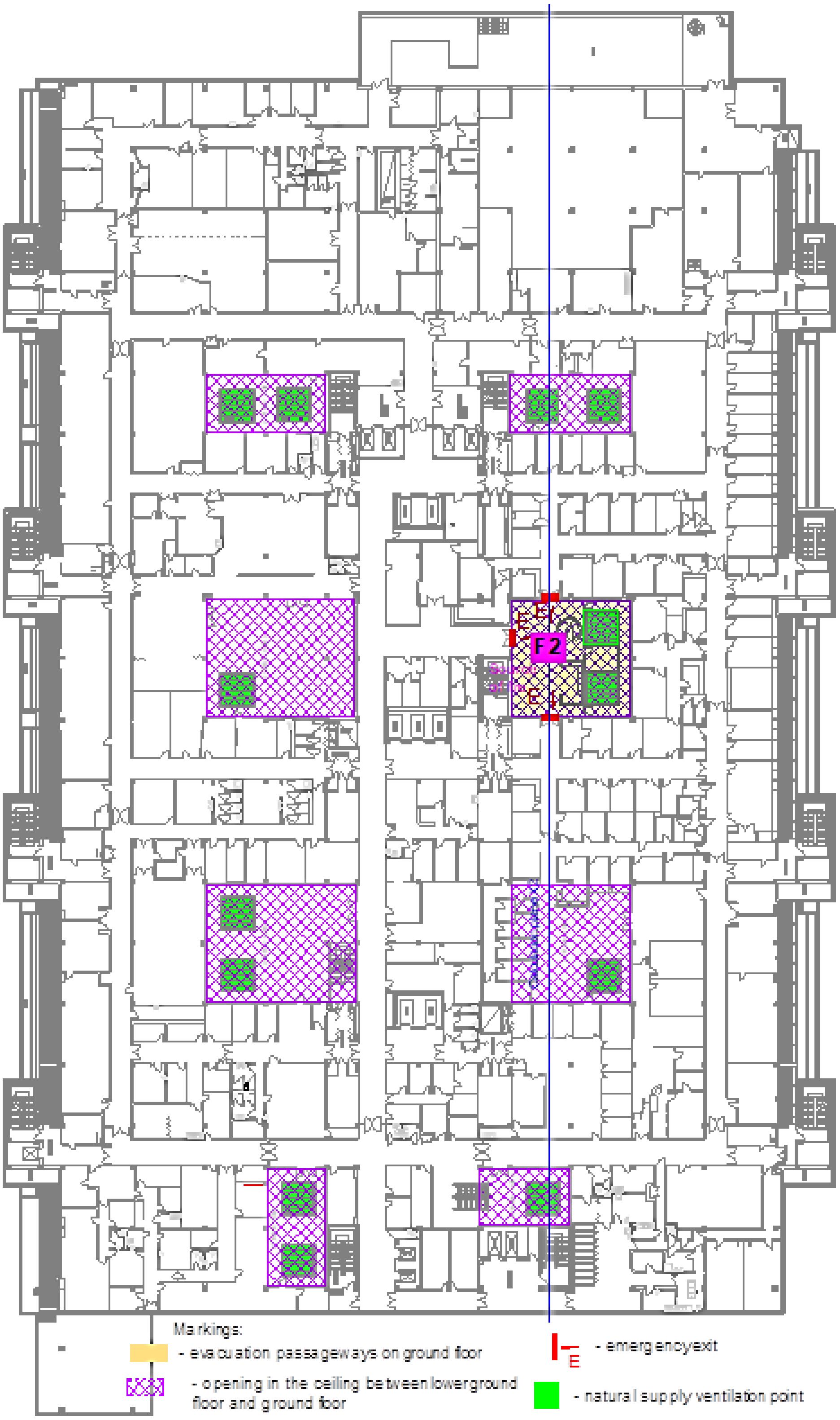


Fig. 51. Hospital – Lover ground floor plan and design fire location F2.

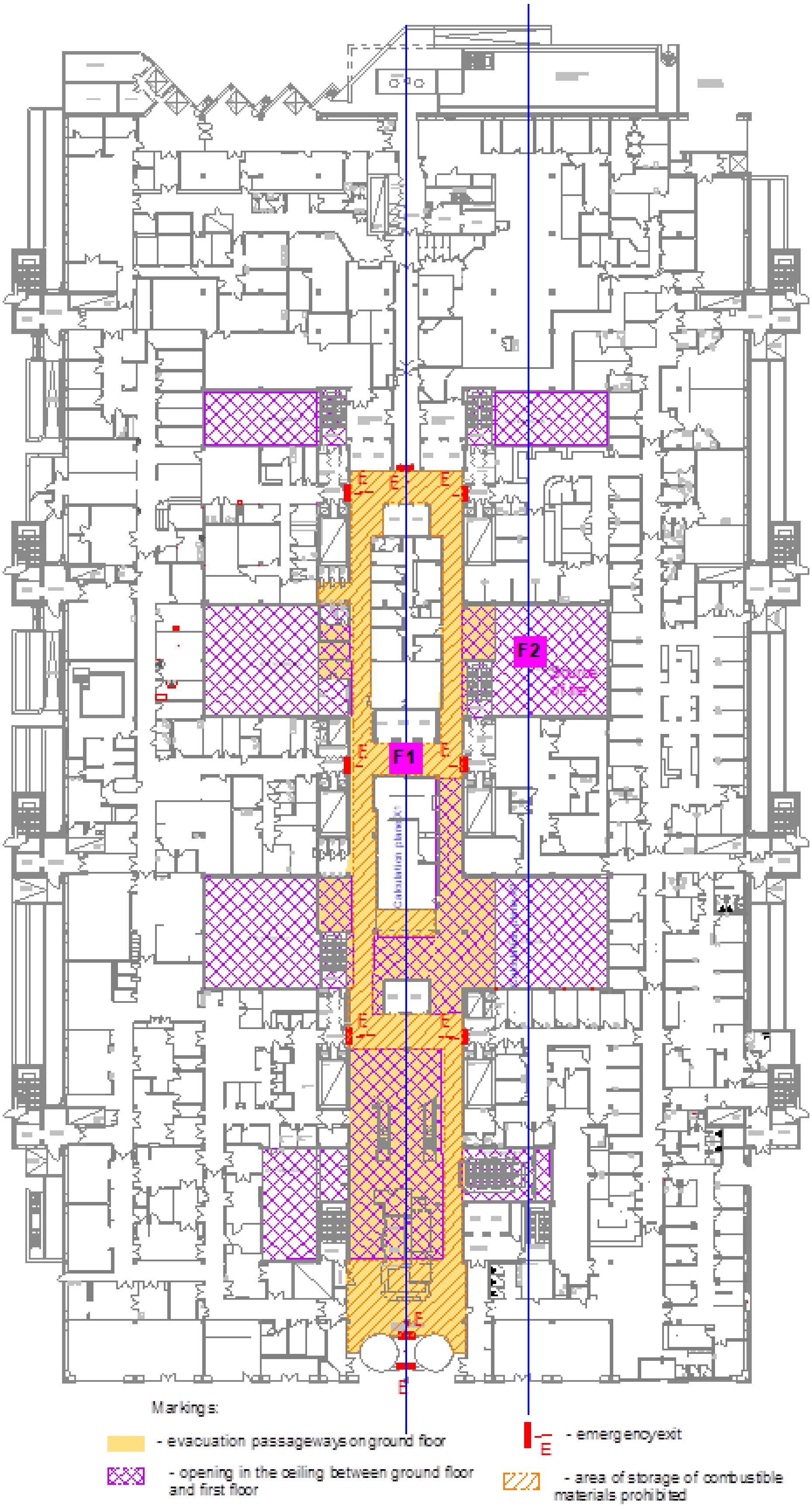


Fig. 52. Hospital – Ground floor plan and design fire locations F1 and F2.

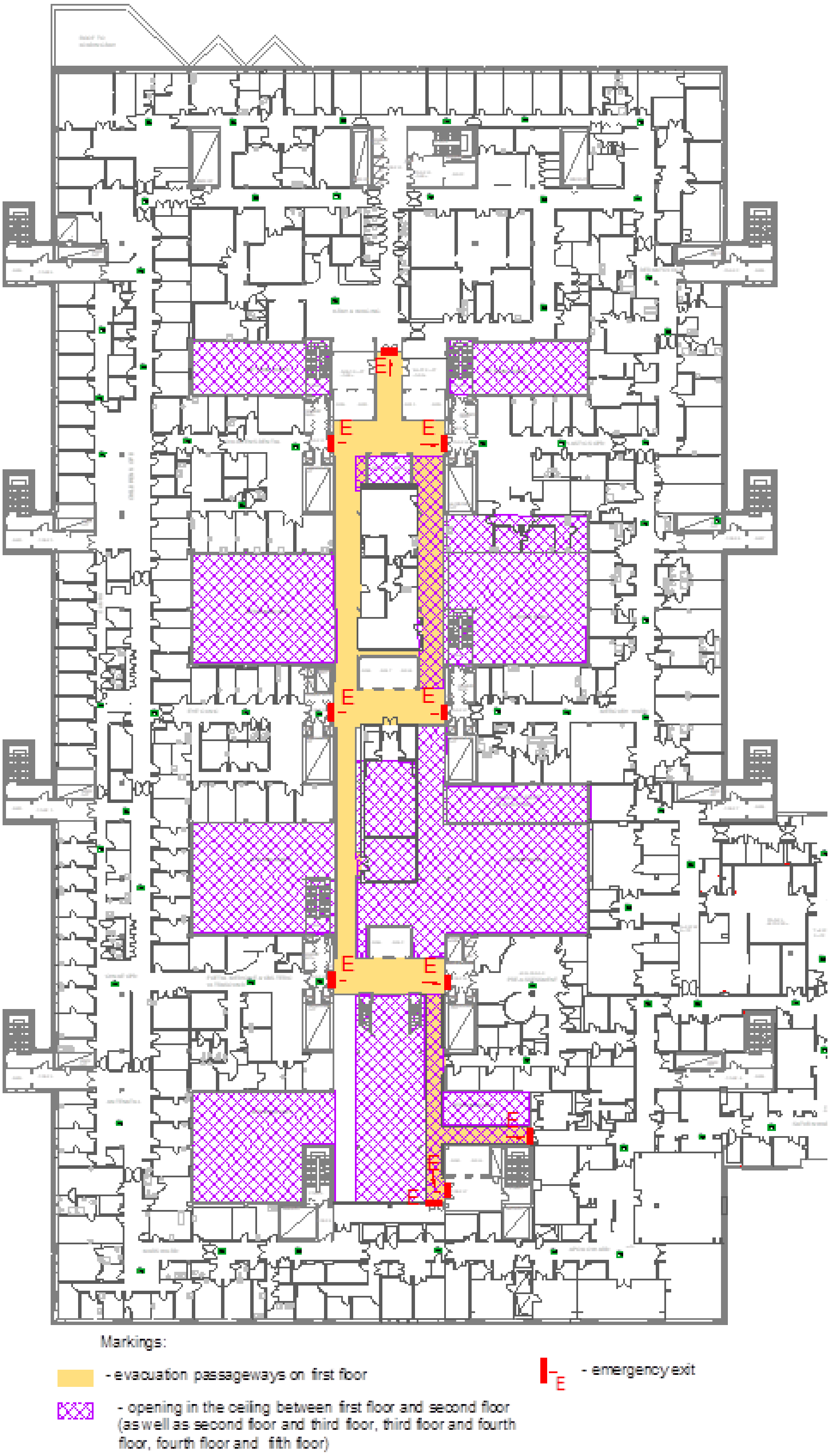


Fig. 53. Hospital - repeatable floor (from first to fourth floor).

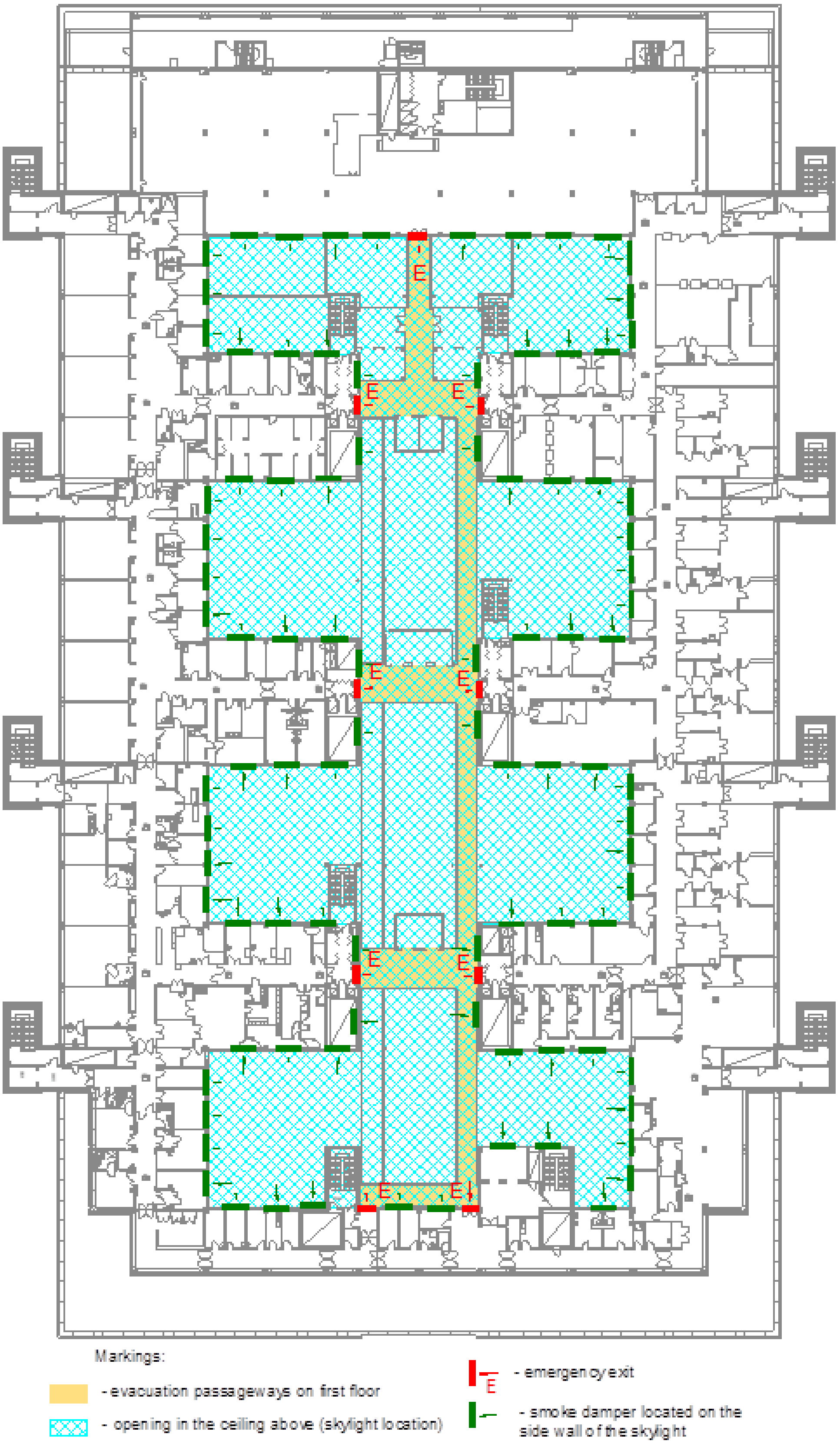


Fig. 54. Hospital – fifth floor.

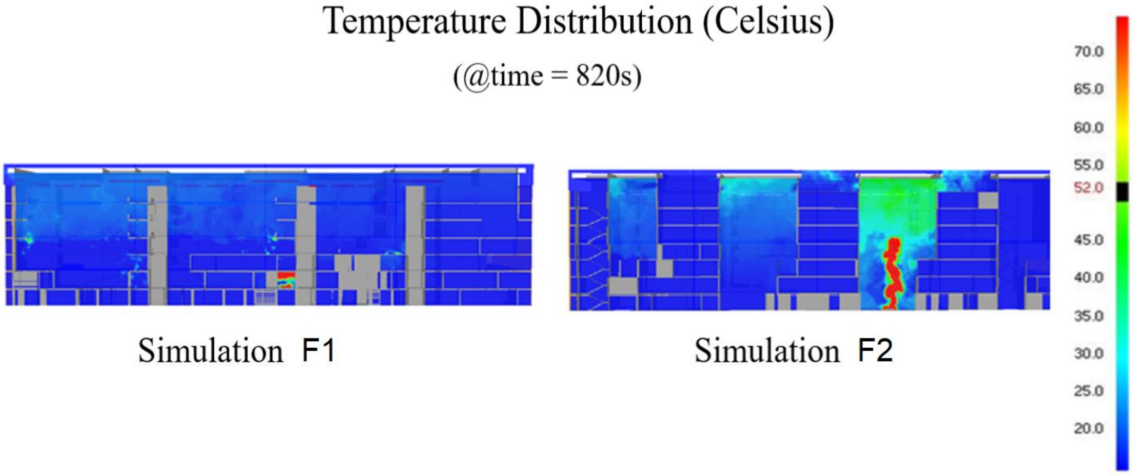


Fig. 55. Hospital - Temperature distribution at time of Fire Brigade arrival.

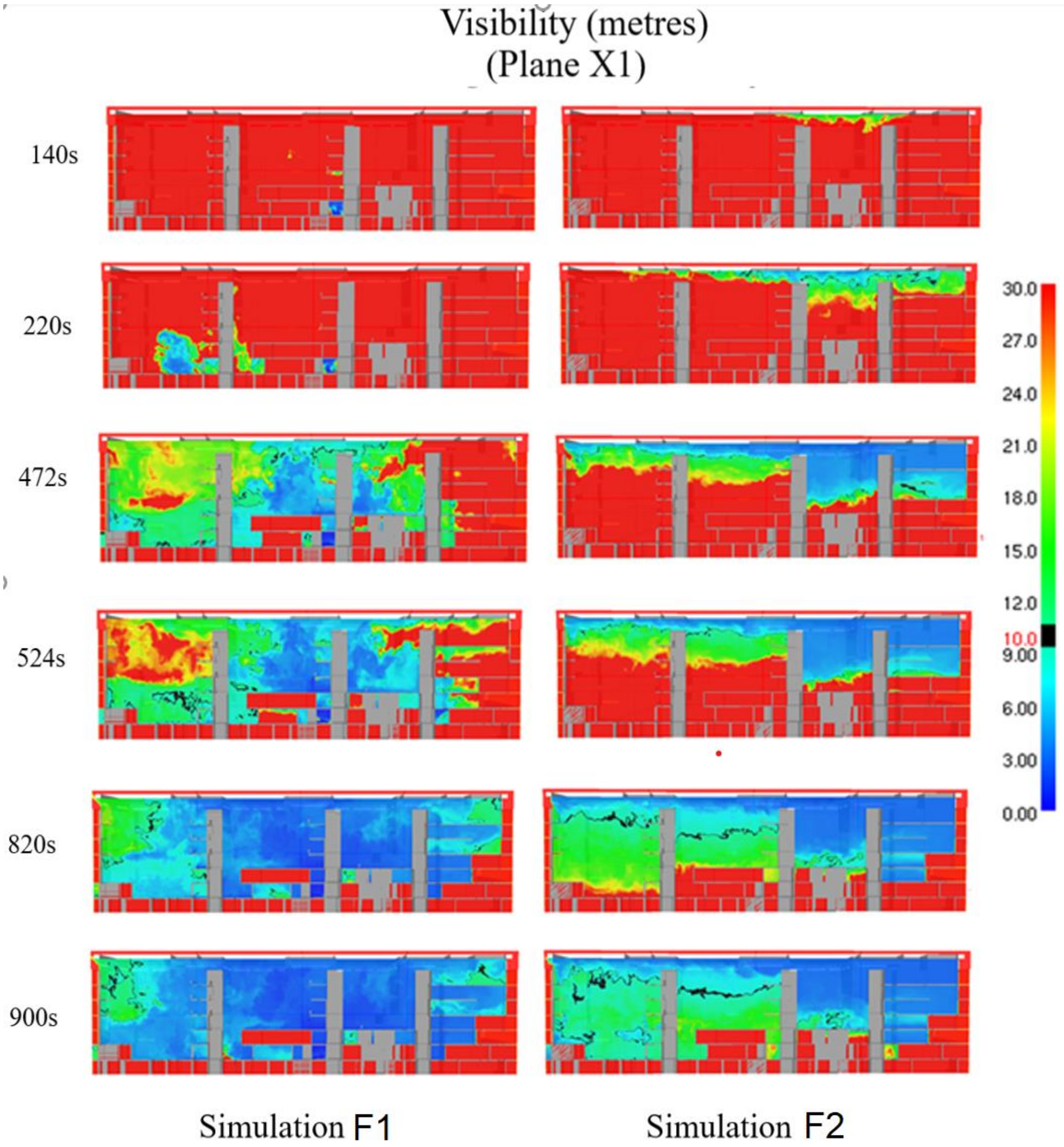


Fig. 56. Hospital - Visibility (m) over several time periods.

Conclusions from the CFD analysis

Analysis of the visibility (evacuation tenability) for the fire scenario F1 (fire directly under a balcony) showed substantial smoke dispersion by the balcony structure on the evacuation passages, assessed at a head height of 1.8 m over several levels. The decrease in visibility range below 10 m was exceeded before 472 s (at 370 s, when viewing the model) which means that the fire ventilation system did not provide adequate tenability conditions at most levels.

In the case of fire scenario F2 (fire at the open space-a no smoke dispersion by the balcony structure), the lack of smoke dilution caused by the balconies means that required 10 m visibility was maintained at most levels at 524 s, when the last occupants of the atrium complete the evacuation.

It can be noted from the temperature distribution at 820 s (when the fire brigade should commence firefighting operations) that the smoke dilution that was a problem for visibility has resulted in cooler smoke temperatures.

It is therefore concluded that the location of fire loading at the atrium plays a part in the tenability of escape routes over many levels of the atrium. This will be assessed by using two actual fire strategy conditions, Fire Strategy Actual 1 will be where the location of retail units and other areas holding combustible materials is not incorporated into the strategy, and the second (Fire Strategy Actual 2) will be where such areas are only located at places where there are no walkways above.

6.3.5. Actual fire strategy evaluation

Table 22 provides a description of the specific issues for each of the eight designated fire safety factors (nodes) as well as the scoring of the actual fire strategies based upon the existing situation (169) (Actual 1) and suggested areas where fire loading could be acceptable (Actual 2). The supportive analysis results and conclusions from previous section were also taken into account here.

Table 22. Hospital - Scoring of actual fire strategies.

Fire safety factor	Building description	Actual score 1	Actual score 2
ORG	A full fire strategy has been developed and documented in 2018 for the building against a specific UK Healthcare standard – HTM 05-02. The central atrium for this hospital is a key feature of the design of this building. It is used as the normal main route of access to all parts of the Hospital. It contains a series of raised walkways, escalators and lifts serving all levels from the Lower Ground to 5th Floor.	**22**	**22**
LIM	Given that this Hospital features an extremely large multi-level atrium area, there is a tendency to make use of the space for a variety of reasons, ranging from the staging of shows, to the use of space for the temporary storage of items such as hospital bedding. Furthermore, there has been increased construction of enclosures within the atrium space over the years. such as the Prayer Room and Medi Cinema. Each of these do in fact increase the fire risk. There are strict controls on ignition sources. An equipment testing scheme is operated. By restricting the location of Units as per Actual 2, then this would improve the score.	**14**	**16**
PAS	Given that the building is protected by a sprinkler system, there are allowances on the level of fire compartmentation. However, the Hospital does maintain primary fire compartments at REI 60, high hazard rooms at REI 30 and firefighter lobbies by a total of REI 120.	**16**	**16**
DET	The Atrium is monitored by an aspirating smoke detection system. This system is configured at high level and positioned in front of the high-level ventilation and around 2 metres below the highest level to avoid the effects of stratification. Point smoke detection is located within the lower ground floor area connected to the atrium. Manual call points are positioned at all exits from the Atrium. An audible alarm system is fitted throughout the Hospital providing a minimum sound level in accordance with British Standards. There is an investigation period of 5 minutes to allow security staff to determine if there is a fire.	**16**	**16**
SUP	The risk areas are fitted with a life-safety, fast response, automatic wet sprinkler system in accordance with BS EN 12845. The sprinkler system is installed in all risk areas including wards, offices, laboratories, stores, internal corridors, the basement car park, etc. It is not fitted in the central atrium or in lobbies between the atrium and risk areas. The main enclosed retail and other units within the atrium are also protected by the sprinkler system although “open” retail areas and the coffee shop are not.	**14**	**14**
SC	The Atrium is fitted with high level ventilation in conjunction with inlet supply air at low level. In the event of fire in the Atrium, this will be detected by the aspirating system and signalled to the central fire detection and alarm system, via the outstations (mounted at high and low level). Note that the high and low-level louvres will open. The main front entrance swing door will open on receipt of a signal by the fire detection system to improve inlet conditions. Note that the failsafe condition will revert to the fire condition arrangement. The system does not utilise forced extract fans. By utilising the arrangement suggested by Actual 2, the current method of smoke ventilation will be improved to allow more tenable conditions for evacuation.	**13**	**19**
MAI	All fire systems installations are subject to a high-level maintenance regime as specified by HTM 05-01.	**23**	**23**
FB	The building is located on a busy London road. However, it is possible that Fire Appliances can park directly outside the main entrance. They will be greeted by the Security staff who are trained to provide them with all relevant information. Each of the outer cores (Cores 1 to 8) are designed for use by firefighters. An atrium fire will be fought from either the front or the rear of the building.	**15**	**15**

6.3.6. The fire strategy value grid

The following fire strategy value grid (*Fig. 57*) can be established from the information of previous steps. It can be seen, once again, all strategies follow a similar pattern. However, for Actual strategy 1, this falls short in the area of smoke control and evacuation. This is rectified by Actual strategy 2.

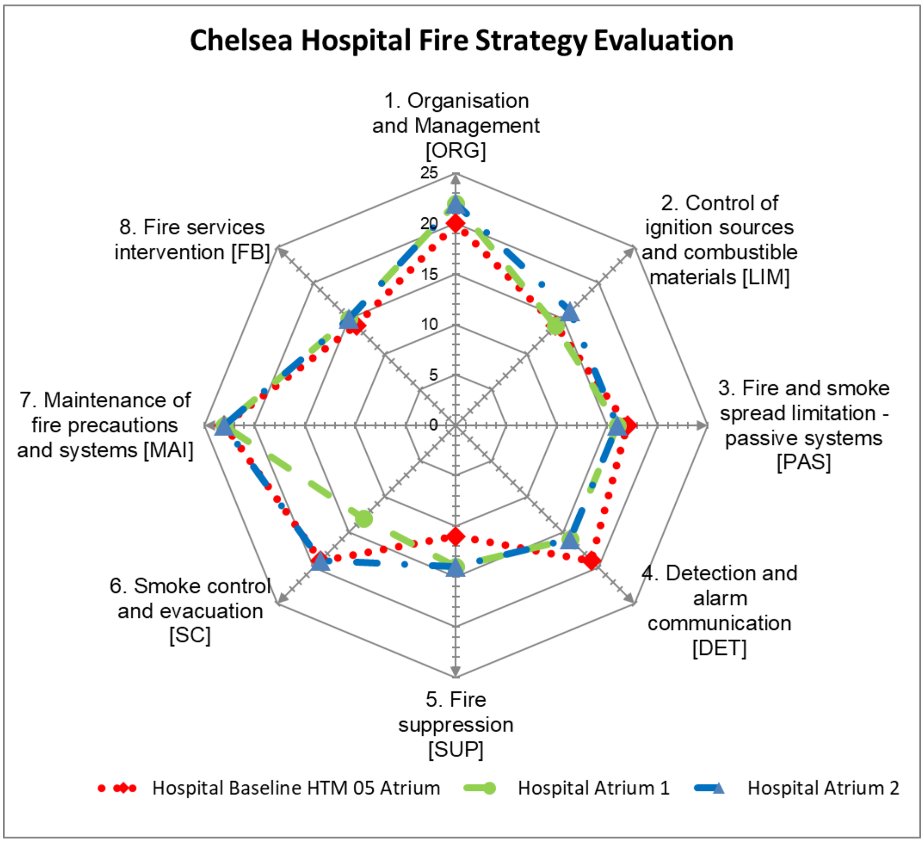


Fig. 57. Hospital - Fire strategy value grid.

6.3.7. The fire strategy risk index

A summary of the calculated weighting and scoring is based on the equations 5.1-5.5 presented in chapter 5 and is given in *Table 23*. The details of the scoring are provided in the Table Appendix C.

Table 23. Hospital - Calculation of PM.

Hospital, London PM Calculation							
Fire safety factor (FSF)	***B/L***	***Act 1***	***Act 2***	***W***	***PM (B/L)***	***PM (Act 1)***	***PM (Act 2)***
ORG	20	22	22	4.0	80.0	88.0	88.0
LIM	14	14	16	2.8	39.2	39.2	44.8
PAS	17	16	16	3.4	57.8	54.4	54.4
DET	19	16	16	3.8	72.2	60.8	60.8
SUP	11	14	14	2.2	24.2	30.8	30.8
SC	19	13	19	3.8	72.2	49.4	72.2
MAI	23	23	23	4.6	105.8	105.8	105.8
FB	14	15	15	2.8	39.2	42.0	42.0
				Totals:	**490.6**	**470.4**	**498.8**

A summary of the calculated weighting and scoring is given below:

Baseline strategy: PM = 490.6

Actual strategy 1: PM = 470.4

Actual strategy 2: PM = 498.8

PH (in all cases) = 345.2 / 100 = 4.906

Actual strategy 1: FHI = PH/PM × 100 = (4.906/470.4) × 100 = 1.04

Actual strategy 2: FHI = PH/PM × 100 = (4.906/498.8) × 100 = 0.98

(Note that for the baseline strategy: FHI = 1)

The value of Fi for public buildings (the atrium in the hospital is assumed to be a public space) is given as Fi of 6.6·10–2 as given by PD 7974-7 (Table 10), what for the actual area A = 2857 m^2, gives Fi = 1.89x10^{-1}.

Therefore, the Fire Strategy Risk Index (FSRI) for each strategy is:

Baseline strategy: FSRI = FHI·Fi =1 × 1.89x10^{-1} = 1.89x10^{-1}

Actual strategy 1: FSRI = FHI·Fi = 1.04× 1.89x10^{-1} = 1.97x10^{-1}

Actual strategy 2: FSRI = FHI·Fi = 0.98 × 1.89x10^{-1} = 1.86 x10^{-1}

In this case, the FSRI for the actual fire strategy as currently provided (actual strategy 1) is slightly higher than that required for baseline conditions which would require some re-assessment of one or more aspects of the strategy. However, the revised actual strategy (actual strategy 2) shows some improvement and scores marginally better. This is largely due to suggested improvements to the smoke control arrangements.

7. Summary and Conclusions

Fire science, and the application of fire science in the form of fire engineering, is a discipline that has matured over many decades. Despite this, there continues to be a lack of consistency in approach when applying the discipline to the design of buildings, both nationally and internationally. This lack of consistency can also create problems for those who are tasked to assess and approve the resulting fire strategy (a document that specifies the range of fire safety and protection measures deemed necessary for a building).

This Thesis proposes to rectify this by applying a semi-quantitative methodology to improve the consistency of approach for the formulation, verification, and approval of fire strategies for public buildings. These methodologies have either been developed specifically for this Thesis or are based upon earlier research and development of ideas by the Author. The term used for this novel methodology is Holistic Fire Strategies, given that it is designed to provide a holistic model, geographically, and in terms of the scope for assessment and in consideration of different building profiles.

The development of the concept of holistic fire strategies was first considered as an improved methodology for fire strategy formulation and evaluation in 2017. However, the roots of the concept date back to the 1990s when strategic tools for fire strategies were developed by the Author, leading to inclusion in a 2007 British Standard Specification covering fire strategies. The overall concept took the ideas behind these strategic evaluation tools and was designed to cater to the following:

- To provide a consistent global approach for both the formulation and evaluation of fire strategies. This idea was conceived as a result of discussions with enforcement agencies that are tasked with approving fire strategy documents in many countries around the world. The variation in styles and content can make this task resource-intensive and will often not give those agencies the confidence that the fire strategy is fit for purpose;
- To extend the considerations of a fire strategy to include a more thorough consideration of fire prevention and protection objectives and threats assessment. These objectives are to consider the wider implications of life safety, property and asset protection, business continuity, and environmental protection. Furthermore, given the current variation in potential threats that could lead to a fire, the opportunity to undertake a proper and thorough threat analysis could help identify possible fire scenarios that may otherwise have been ignored;
- To develop an online portal to allow access to the concept.

This Thesis takes one of the themes – the first point above, to provide for an improvement in the understanding and verification of fire strategies. The focus is to improve the specific needs of third-party enforcement agencies, around the world, by using a singular concept. A novel idea is proposed, making use of a pictorial approach first published in a British Standard and developed by the Author.

The Thesis introduces the subject of fire engineering and the concept of fire strategies. A "state of the art" review focuses on the need for the suggested novel approach. The chapter examines the relationship between fire engineering and other core engineering disciplines, including civil, chemical, mechanical, and systems engineering. The close working relationship between civil and fire engineering is further explored, and the key areas of interaction are detailed. The chapter also discusses how the subject of fire engineering has developed over recent times.

The Author describes the development of fire (safety) regulations over time and uses the UK as an example. The more recent introduction of "performance-based" fire engineering solutions is explained and how the approach has many distinct advantages over the more traditional prescriptive rules, particularly for more complex building arrangements such as those designed for use by the public. This chapter introduces the term "fire strategy", and how the term is understood. A British Standard Specification for fire strategies (PAS 911) in 2007 (a standard written by the Author) is highlighted, and how this provides a strategic approach to fire engineering using both prescriptive and performance-based design solutions.

One of the objectives behind this Thesis is to develop a methodology that is global rather than national. To determine how feasible this is in the short term, the Author introduces an analysis of key fire safety standards and rules for a few countries to find out if there were commonalities. The countries approached were China, India, Iran, New Zealand, Poland, UK, and USA. It was found that, in many aspects, there were some commonalities, such as in the field of fire detection systems whilst in other areas, such as passive fire protection, there was still a divide of opinions reflected in national standards. Although this was a relatively simplistic evaluation, a wider assessment could hopefully point to areas where a global rather than national fire safety philosophy could emerge.

Strengths and weaknesses related to the current formulation and verification of fire strategies are introduced. A holistic approach towards the development of fire strategies is proposed to overcome the described shortfalls. The need for a more formal and extended assessment of fire safety objectives as well as threats that could lead to fire are explained. These concepts will form part of the holistic fire strategy approach but are not specifically explored in this Thesis.

It is also proposed that a novel method is necessary to allow for the evaluation of fire strategies to determine if they are sufficient and fit for purpose. The method should improve not just the formulation of fire strategies but also their evaluation and approval by those tasked to sign off the strategies – the enforcement authorities.

Current issues, such as building sustainability and the advent of building information modelling (BIM) are also considered.

The Author also reviews how fire safety is currently measured via the use of fire risk assessments. The various methods and techniques for assessing fire risk around the world are presented. A novel method of assessing fire scenario risk is introduced by separating the assessment of fire ignition from fire growth. The method then breaks down the assessment of fire ignition in terms of environment and process. The chapter explains the reasons behind this concept, which was originally included in the British Standard Specification PAS 911.

The calculation of a Scenario Risk Factor allows users to determine the most appropriate fire in a building for subsequent evaluation.

Finally, the semi-quantitative methodology for fire strategy analysis is developed. The Fire Strategy Value Grid is akin to a *spider web diagram* formulated by the Author for British Standard Specification PAS 911. This allows a separate assessment of eight key factors relevant to each fire strategy. A modified version of this diagram was further developed in Poland to provide for a specific evaluation technique to allow the actual fire strategy to be assessed against a baseline strategy. The scoring is based upon a detailed questionnaire developed for this purpose. A series of steps are proposed to allow for the calculation of a Fire Strategy Risk Index for both the baseline and actual fire strategies. Furthermore, a software application was developed to allow the automatic evaluation and illustration of the Fire Strategy Value Grid as well as the calculation of the Fire Strategy Risk Index.

The proposed methodology was tested in 2018/19 at a selection of operational buildings in Poland and UK. Chapter 6 details testing of the proposed methodology for three exemplar public buildings: City of Culture EC1 in Lodz, Poland, Hotel Castle Ryn, Poland, and a Hospital in Chelsea, London, UK. Each analysis followed a designated process. This included choosing the most appropriate fire scenario analysis, the undertaking of fire modelling to analyse smoke and heat movement over a number of time periods, and the production of the fire strategy value grid together with the calculation of the FSRI (Fire Strategy Risk Index) for baseline and actual conditions.

In conclusion, this Thesis includes the following novel ideas and developments in the understanding and application of fire engineering:

- A review of fire standards and regulations in seven countries confirms the possibility of creating a global methodology for fire strategy formulation and evaluation. However, it is also recommended that a more detailed investigation of all elements of a fire strategy, and taken from a much larger sample of countries, would provide greater levels in confidence in the conclusions reached. This may form the scope for a separate area of research.
- The development of a new *Scenario Fire Risk* analysis technique, which allows for the determination of adverse fire scenarios for use in subsequent fire safety assessment.
- The development of a semi-quantitative method that allows for greater consistency in both the preparation of holistic fire strategies and in their evaluation. This includes the production of a Fire Strategy Value Grid and calculation of a Fire Strategy Risk Index. A beta version software application had been developed to assist in this calculus and presentation of results. The current version uses the Polish language but future versions will be other language versions.

It is believed that the above conclusions verify the objectives and research behind the formulation of this Thesis.

Further Research

The contents and conclusions of this Thesis are simply the first stages in developing a globally accepted methodology designed to greatly improve the formulation and verification of fire strategies. To be successful, the idea will require further development to become attractive to the various stakeholders involved in the whole process of fire standards setting through to application to buildings. Some areas for suggested additional research are given below.

A thorough review of the use of fire safety codes and regulations around the world: Despite many countries embracing the benefits of non-standardised fire safety engineering, national codes tend to still be based upon prescription. This Thesis evaluated some fundamental facets of fire safety and protection and how seven countries applied their requirements. This review was a simplistic sample study. Ideally, a more thorough review of several countries, considering the many factors behind a detailed fire strategy, will provide a more conclusive result. The aim here is to reduce the national differences and to allow for a consistent international approach. Many organisations, as highlighted in the chapter, are seeking this, although much headway is still required.

Improving the fire strategy "analysis" questionnaire: The introduced questionnaire used to help formulate the eight-node diagram for baseline and actual conditions for a fire strategy, was specifically prepared to be used to cover the specifics of Polish Regulations. It is suggested that a more "objectives-based" set of questions would help in gaining global acceptance. An alternative approach would be to prepare a set of questions based upon the building's risk profile or regional requirements.

Incorporating the concept within building information modelling: The use of algorithms to develop the fire strategy diagrams and calculate the fire strategy risk index has already been developed, albeit the results are very much a first pass. However, this illustrates that the development and evaluation of fire strategies can be automated. Given the move towards the adoption of building information modelling (BIM), it is quite feasible that an automated scheme for fire strategies can be tied into the BIM process itself. The algorithms would take the decisions made by the analysis prescribed in this Thesis and apply them into working modifications to the BIM designed building. The BIM management system would then provide an audit trail of how the fire strategy is modified following the evaluation of the fire strategy risk index.

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Curriculum vitae

Paul Bryant was born 23.12.1958 in London England. He commenced his career in the Fire Industry in 1981 after completing a Bachelor of Honours degree in Electrical and Electronic Engineering. His first role was as Technical Officer for the now defunct organization called Fire Offices' Committee - FOC, based in the City of London. From 1868, this organisation was the leading authority in determining the rates of fire insurance for UK insurance companies. To support this, the FOC had a technical wing employing engineers with a series of specialities covering all aspects of active and passive fire protection. In this role he set up schemes to approve fire detection and alarm systems and write standards for the UK Fire Insurance Industry. He was also involved in working on European insurance standards in conjunction with experts from other parts of Europe as the official representative for the British fire insurers. This organization promoted European insurance companies and, among many other tasks, was responsible for developing European technical standards. In the 90's he was the chief fire engineer of the London Underground. He participated in the development of British Standards BS 5839 (2002 edition), especially in the scope of Part 1 which concerned fire detection systems. The work of the FOC was passed over to the Loss Prevention Council (LPC) in 1985 and he moved with them where he continued his role. During this time he was involved in the creation of many British Standards as a member and Chairman of a number of Technical Committees. He left the LPC in 1993 and became Head of Fire Engineering for London Underground. In 1995, he formed his own fire consulting and specialist fire engineering company, Kingfell plc, and in 2015 and formed another company - Fire Cubed LLP in that year. Over his career he has become influential on a global basis, particularly in the subject of fire strategies. He has been involved in fire standards making for much of his career. Some British Standards he oversaw and assisted with were the BS 7273 series (covering activation of fire protection systems), BS 6266 (fire protection of for electronic installations), BS5839-1 (fire detection and alarm). He also wrote one of a series of British Standards covering the principles of applying fire safety engineering - BS 7974. He wrote PD 7974-4: 2003 covering detection and alarm systems and BS PAS 911:2007Fire Strategies standard.

Qualifications and affiliations

2004 - **Freeman of the City of London & LIveried Member,** COMPANY OF FIRE FIGHTERS
2003 - **Chartered engineer and member,** INSTITUTION OF FIRE ENGINEERS
1993 - **Master of business administration (MBA),** CITY UNIVERSITY BUSINESS SCHOOL, UK.
1992 - **Chartered engineer and member,** INSTITUTION OF ENGINEERS AND TECHNICIANS
1981 - **BSc (HONS) 2 II,** NORTH EAST LONDON UNIVERSITY, UK.

Work History

2015 to date **- Partner,** FIRE CUBED LLP
2015 to date - **Director,** KINGFELL (PUBLICATIONS) LTD
1995 to 2015 - **Owner / Director,** KINGFELL PLC AND KINGFELL LTD
1993 to 1995 - **Head of fire engineering,** LONDON UNDERGROUND LTD UK.
1985 to 1993 - **Technical Officer,** LOSS PREVENTION COUNCIL
1981 to 1985 - **Assistant Technical Officer,** FIRE OFFICES COMMITTEE (FOC)

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Appendix A: EC1 Łódź - City of Culture, Poland: Scoring Table

Fire safety factor (FSF)	Nr	Fire safety element	Max	EC1 Baseline B3	EC1 Actual 1
ORG	1	Fire strategy: not developed (0) / has been developed for selected aspects (1) / has been developed and documented in all aspects necessary for the pre-defined strategy objectives (4)	4	**4**	**4**
	2	Documented fire safety procedures for the building (1) + implementation of the procedures (1) + regularly controlled updates (1) + documented evacuation plans for all floors (1)	4	**3**	**4**
	3	Central building security personnel for the building (1) + trained fire wardens on all floors/in zones (3) + regular evacuation drills with specific staff participation (2) / regular evacuation drills involving all building occupants (3)	7	**3**	**4**
	4	Fire safety training: only key staff (2) / all staff (4)	4	**2**	**4**
	5	Independent certification and audit system for fire safety management: only mandatory checks (1) + full regular fire safety audits, undertaken by specialist bodies (1)	2	**0**	**1**
	6	Management commitment to fire safety including fire safety management review meetings and training of personnel in the key aspects of the management, operation and maintenance of fire protection systems, and the principles of fire strategy, evacuation strategy awareness, etc. (0 to 4)	4	**0**	**2**
		Total	**25**	**12**	**19**
LIM	1	Fire load density [MJ/m2] (>4000) (0) / (>2000, ≤4000) (1) / (>1000, ≤2000) (2) / (>500, ≤1000) (4) / (≤ 500) (5) + High hazard ignition sources Y (0) / N (2)	7	**3**	**7**
	2	Expected fire growth: ultrafast (0), fast (1), medium (4), slow (5)	5	**1**	**4**
	3	High risk areas of the building are separated from other parts of the building by suitable fire resisting construction Y (2) / N (0) + high levels of combustible materials stored in the building - Y (0) / N (2)	4	**4**	**4**
	4	Smoke production from construction products and fixed equipment (the worst case): s3 and products of reaction to fire class ≤E (0) / s2 (1) / s1 and products of reaction to fire class A1 (2)	2	**1**	**2**
	5	Reaction to fire class of construction products (claddings/coverings) (the worst case) ≤E (0) / D i C (1) / B (2) ≥A2 (3)	3	**2**	**3**
	6	Reaction to fire class of the building insulation products (external walls, roof) (the worst case): ≤E (0) / D i C (1) / B (2) ≥A2 (4)	4	**2**	**4**
		Total	**25**	**13**	**24**
PAS	1	Fire resistance of structural elements: <15 min (0), 15 min (1), 30 min (2), 60 min (3), 90 min (4), ≥120 min (6),	6	**4**	**6**
	2	Maximum fire resistance of internal subdivisions: 30 min (1), 60 min (2), 120 min (3), 240 min (4)	4	**3**	**2**
	3	Fire resistance of doors and shutters: No resistance rating (0) / 30 min (1), 60 min (2), 120 min (3), 240 min (4)	4	**3**	**2**
	4	Distance from neighbouring buildings: Not in accordance with regulations (0) / in accordance with regulations (2) / fire wall used as separation (2) / the heat flux density on adjacent object walls < 12,5 kW/m² (2)	2	**2**	**2**
	5	Compartmentation - fire zones [m2] (>20000) (0) / (>10000, ≤20000) (1) / (>5000, ≤10000) (2) / (>2000, ≤5000) (3) / (>1000, ≤2000) (4) / (≤1000) (5)	5	**3**	**3**
	6	Activation of fire shutters, doors, dampers etc. with fusible links (1), manual activation via control panel (2) / automatic after verification (3) / automatic (4)	4	**3**	**3**
		Total	**25**	**18**	**18**
DET	1	Full monitoring, i.e. detection in all risk areas (5) / partial monitoring (1) + detection in evacuation routes (1) / manual system (1) / no detection (0)	5	**3**	**5**
	2	Expected detection response time (>420 s) (0) / (>300 s, ≤ 420 s) (2) / (>180 s, ≤ 300 s) (3) / (≤180 s) (5)?	5	**3**	**3**
	3	All detection devices are appropriate for the risk (0 to 4)	4	**3**	**4**
	4	Sufficient and suitable control and indicating equipment in the building, including power supplies and cables (2) + certified systems (1)	3	**2**	**3**
	5	False alarms controlling procedures: No (0) / Yes (4)	4	**2**	**4**
	6	Alarm warning systems: sounders (1) / voice alarm (2) / Voice alarm with public address (3) + active visual support signage (1)	4	**3**	**4**
		Total	**25**	**16**	**23**
SUP	1	Fire suppression systems covering all risk areas (3) / partial coverage only (2) / no suppression systems (0) + fast response sprinklers (1)	4	**3**	**2**
	2	Fire suppression response time index (RTI): standard B (>200, ≤ 300) (1)/ standard A (>80, ≤ 200) (2)/ special (>50, ≤ 80) (3) / fast (≤ 50) (4)?	4	**2**	**2**
	3	Expected activation time: (s): >300 (0)/ (>200, ≤ 300) (1) / (>150, ≤ 200) (2)/ (>120, ≤ 150) (3) / (≤ 120) (4)?	4	**3**	**2**
	4	Fire suppression systems appropriate to: the height of storage (2) + type of combustible material (2) + storage method (2)	6	**6**	**4**
	5	Reliability of suppression installation: system monitoring (1), independent power supply and water suppression systems (1) operation + dual water supply (1) + double source water supply (1)	4	**1**	**3**
	6	Hose reels covering all parts of the building Y (1) / N (0) + portable fire extinguishers (pfe) with rated extinguishing efficiency provided sited to standard accepted densities (1) or enhanced densities (2).	3	**3**	**3**
		Total	**25**	**18**	**16**
SC	1	Stair core smoke control: Non-existent (0) / in place but effectiveness not specified (1) / assured protection of means of escape (2) + assured support for firefighting operations (1) + monitored for all system failures (1)	4	**2**	**2**
	2	Horizontal evacuation routes smoke control system: Non-existent (0) / in place but effectiveness not specified (1) / assured protection of means of escape (2) + assured support for firefighting operations (1) + monitored for all system failures (1)	4	**2**	**2**
	3	Smoke enclosure control system: Non-existent (0) / in place but effectiveness not specified (1) / assured protection of means of escape (2) + assured support for firefighting operations (1) + monitored for all system failures (1)	4	**2**	**2**
	4	Aspects of the construction of the means of escape could potentially lead to uncontrolled smoke production (0) / Suitable control of combustible materials on horizontal evacuation routes (1) + vertical evacuation routes (2)	3	**3**	**3**
	5	Dimensions of stair cores and horizontal evacuation routes relevant to the amount and profile of occupants (0 to 2) + at least two stair cores (2) + at least two directions of travel from each area (2).	6	**2**	**4**
	6	Evacuation signage: Passive signage correctly selected and arranged (1) / illuminated signage systems (2) / dynamic illuminated signage systems to control movement of occupants (4)	4	**1**	**2**
		Total	**25**	**12**	**15**
MAI	1	Has the design, installation and commissioning of fire-fighting and fire protection systems been carried out in accordance with the manufacturer's instructions and standards? Y (2) / N (0) + by certified contractors Y (2) / partly (1) / N (0)	4	**2**	**4**
	2	Is there a suitable inventory of fire-fighting and fire protection systems (1) + operation and maintenance information (2)?	3	**0**	**3**
	3	Maintenance procedures and inspections in accordance with minimum national regulations (1) + manufacturer's instructions (2) + national standards (2)?	5	**2**	**5**
	4	Functional testing (over and above minimum requirements) of fire-fighting and fire protection systems to ensure maximum levels of availability and reliability: Y (6) / partly (3) / N (0)?	6	**6**	**6**
	5	Systems used to monitor in real time the availability and reliability of fire-fighting and fire protection systems: Y (3) / partly (1) / N (0)?	3	**1**	**3**
	6	Modifications to fire fighting and protection system recorded (1) + monitored (1) + audited (2)	4	**2**	**4**
		Total	**25**	**13**	**25**
FB	1	Method of communication with fire-fighters: Manual means by building user (e.g. no automatic fire detection) (0) / manual means by building user in the case of fire detection operation (1) / automatic, via alarm receiving centre with alarm confirmed by external staff (2) / automatic, via alarm receiving centre with alarm confirmed by staff on site (4).	4	**2**	**4**
	2	Availability of on-site fire safety personnel to assist (2) / nominal or part time availability (1) / no availability (0)	2	**1**	**2**
	3	Fire brigade arrival time[s] (>900) (0) / (>600, ≤900) (2) / (>300, ≤600) (4) / (≤300) (6)	6	**4**	**4**
	4	Access to the building: No direct access (0) / limited access to the building (1) / direct access to at least 50% or two sides of building (2) / direct access to all parts of building perimeter (3)	3	**2**	**2**
	5	Internal communication for fire-fighting purposes within the building: difficult (0) / easy (1) + easy access to the fire control panel (1) + graphic display showing fire locations (1) + lighting of evacuation routes suitable for firefighting effort (1) + at least 2 staircases (1) + fire-fighters lifts with lobbies (1)	6	**3**	**5**
	6	Maintenance procedures and inspections in accordance with minimum national regulations (1) + manufacturer's instructions (2) + national standards (2)?	4	**2**	**4**
		Total	**25**	**14**	**21**

Appendix B: A Castle converted to a hotel, Ryn, Poland: Scoring Table

Fire safety factor (FSF)	Nr	Fire safety element	Max	Hotel Ryn Baseline	Hotel Ryn Actual 1	Hotel Ryn Actual 2
ORG	1	Fire strategy: not developed (0) / has been developed for selected aspects (1) / has been developed and documented in all aspects necessary for the pre-defined strategy objectives (4)	4	0	4	4
	2	Documented fire safety procedures for the building (1) + implementation of the procedures (1) + regularly controlled updates (1) + documented evacuation plans for all floors (1)	4	3	4	4
	3	Central building security personnel for the building (1) + trained fire wardens on all floors/in zones (3) + regular evacuation drills with specific staff participation (2) / regular evacuation drills involving all building occupants (3)	7	3	3	4
	4	Fire safety training: only key staff (2) / all staff (4)	4	4	4	4
	5	Independent certification and audit system for fire safety management: only mandatory checks (1) + full regular fire safety audits, undertaken by specialist bodies (1)	2	1	1	2
	6	Management commitment to fire safety including fire safety management review meetings and training of personnel in the key aspects of the management, operation and maintenance of fire protection systems, and the principles of fire strategy, evacuation strategy awareness, etc. (0 to 4)	4	4	2	4
		Total	25	15	18	22
LIM	1	Fire load density [MJ/m2] (>4000) (0) / (>2000, ≤4000) (1) / (>1000, ≤2000) (2) / (>500, ≤1000) (4) / (≤ 500) (5) + High hazard ignition sources Y (0) / N (2)	7	0	6	6
	2	Expected fire growth: ultrafast (0), fast (1), medium (4), slow (5)	5	5	1	4
	3	High risk areas of the building are separated from other parts of the building by suitable fire resisting construction Y (2) / N (0) + high levels of combustible materials stored in the building - Y (0) / N (2)	4	4	2	2
	4	Smoke production from construction products and fixed equipment (the worst case): s3 and products of reaction to fire class ≤E (0) / s2 (1) / s1 and products of reaction to fire class A1 (2)	2	2	2	2
	5	Reaction to fire class of construction products (claddings/coverings) (the worst case) ≤E (0) / D i C (1) / B (2) ≥A2 (3)	3	2	2	2
	6	Reaction to fire class of the building insulation products (external walls, roof) (the worst case): ≤E (0) / D i C (1) / B (2) ≥A2 (4)	4	4	4	4
		Total	25	17	17	20
PAS	1	Fire resistance of structural elements: <15 min (0), 15 min (1), 30 min (2), 60 min (3), 90 min (4), ≥120 min (6),	6	3	3	3
	2	Maximum fire resistance of internal subdivisions: 30 min (1), 60 min (2), 120 min (3), 240 min (4)	4	3	3	3
	3	Fire resistance of doors and shutters: No resistance rating (0) / 30 min (1), 60 min (2), 120 min (3), 240 min (4)	4	3	0	2
	4	Distance from neighbouring buildings: Not in accordance with regulations (0) / in accordance with regulations (2) / fire wall used as separation (2) / the heat flux density on adjacent object walls < 12,5 kW/m² (2)	2	2	2	2
	5	Compartmentation - fire zones [m2] (>20000) (0) / (>10000, ≤20000) (1) / (>5000, ≤10000) (2) / (>2000, ≤5000) (3) / (>1000, ≤2000) (4) / (≤1000) (5)	5	3	2	2
	6	Activation of fire shutters, doors, dampers etc. with fusible links (1), manual activation via control panel (2) / automatic after verification (3) / automatic (4)	4	3	0	1
		Total	25	17	10	13
DET	1	Full monitoring, i.e. detection in all risk areas (5) / partial monitoring (1) + detection in evacuation routes (1) / manual system (1) / no detection (0)	5	3	5	5
	2	Expected detection response time (>420 s) (0) / (>300 s, ≤ 420 s) (2) / (>180 s, ≤ 300 s) (3) / (≤180 s) (5)?	5	3	5	5
	3	All detection devices are appropriate for the risk (0 to 4)	4	3	4	4
	4	Sufficient and suitable control and indicating equipment in the building, including power supplies and cables (2) + certified systems (1)	3	2	2	2
	5	False alarms controlling procedures: No (0) / Yes (4)	4	3	2	3
	6	Alarm warning systems: sounders (1) / voice alarm (2) / Voice alarm with public address (3) + active visual support signage (1)	4	3	2	2
		Total	25	17	20	21
SUP	1	Fire suppression systems covering all risk areas (3) / partial coverage only (2) / no suppression systems (0) + fast response sprinklers (1)	4	0	0	0
	2	Fire suppression response time index (RTI): standard B (>200, ≤ 300) (1)/ standard A (>80, ≤ 200) (2)/ special (>50, ≤ 80) (3) / fast (≤ 50) (4)?	4	0	0	0
	3	Expected activation time: (s): >300 (0)/ (>200, ≤ 300) (1) / (>150, ≤ 200) (2)/ (>120, ≤ 150) (3) / (≤ 120) (4)?	4	0	0	0
	4	Fire suppression systems appropriate to: the height of storage (2) + type of combustible material (2) + storage method (2)	6	0	0	0
	5	Reliability of suppression installation: system monitoring (1), independent power supply and water suppression systems (1) operation + dual water supply (1) + double source water supply (1)	4	0	0	0
	6	Hose reels covering all parts of the building Y (1) / N (0) + portable fire extinguishers (pfe) with rated extinguishing efficiency provided sited to standard accepted densities (1) or enhanced densities (2).	3	3	1	3
		Total	25	3	1	3
SC	1	Stair core smoke control: Non-existent (0) / in place but effectiveness not specified (1) / assured protection of means of escape (2) + assured support for firefighting operations (1) + monitored for all system failures (1)	4	2	1	4
	2	Horizontal evacuation routes smoke control system: Non-existent (0) / in place but effectiveness not specified (1) / assured protection of means of escape (2) + assured support for firefighting operations (1) + monitored for all system failures (1)	4	0	0	0
	3	Smoke enclosure control system: Non-existent (0) / in place but effectiveness not specified (1) / assured protection of means of escape (2) + assured support for firefighting operations (1) + monitored for all system failures (1)	4	3	3	4
	4	Aspects of the construction of the means of escape could potentially lead to uncontrolled smoke production (0) / Suitable control of combustible materials on horizontal evacuation routes (1) + vertical evacuation routes (2)	3	3	0	3
	5	Dimensions of stair cores and horizontal evacuation routes relevant to the amount and profile of occupants (0 to 2) + at least two stair cores (2) + at least two directions of travel from each area (2).	6	4	2	4
	6	Evacuation signage: Passive signage correctly selected and arranged (1) / illuminated signage systems (2) / dynamic illuminated signage systems to control movement of occupants (4)	4	3	3	3
		Total	25	15	9	18
MAI	1	Has the design, installation and commissioning of fire-fighting and fire protection systems been carried out in accordance with the manufacturer's instructions and standards? Y (2) / N (0) + by certified contractors Y (2) / partly (1) / N (0)	4	4	2	4
	2	Is there a suitable inventory of fire-fighting and fire protection systems (1) + operation and maintenance information (2)?	3	3	3	3
	3	Maintenance procedures and inspections in accordance with minimum national regulations (1) + manufacturer's instructions (2) + national standards (2)?	5	5	4	4
	4	Functional testing (over and above minimum requirements) of fire-fighting and fire protection systems to ensure maximum levels of availability and reliability: Y (6) / partly (3) / N (0)?	6	6	3	6
	5	Systems used to monitor in real time the availability and reliability of fire-fighting and fire protection systems: Y (3) / partly (1) / N (0)?	3	3	1	3
	6	Modifications to fire fighting and protection system recorded (1) + monitored (1) + audited (2)	4	3	2	3
		Total	25	24	15	23
FB	1	Method of communication with fire-fighters: Manual means by building user (e.g. no automatic fire detection) (0) / manual means by building user in the case of fire detection operation (1) / automatic, via alarm receiving centre with alarm confirmed by external staff (2) / automatic, via alarm receiving centre with alarm confirmed by staff on site (4).	4	4	4	4
	2	Availability of on-site fire safety personnel to assist (2) / nominal or part time availability (1) / no availability (0)	2	1	2	2
	3	Fire brigade arrival time[s] (>900) (0) / (>600, ≤900) (2) / (>300, ≤600) (4) / (≤300) (6)	6	0	2	2
	4	Access to the building: No direct access (0) / limited access to the building (1) / direct access to at least 50% or two sides of building (2) / direct access to all parts of building perimeter (3)	3	2	2	2
	5	Internal communication for fire-fighting purposes within the building: difficult (0) / easy (1) + easy access to the fire control panel (1) + graphic display showing fire locations (1) + lighting of evacuation routes suitable for firefighting effort (1) + at least 2 staircases (1) + fire-fighters lifts with lobbies (1)	6	3	3	3
	6	Maintenance procedures and inspections in accordance with minimum national regulations (1) + manufacturer's instructions (2) + national standards (2)?	4	2	2	2
		Total	25	12	15	15

Appendix C: A Hospital located in Chelsea, London, UK: Scoring Table

Fire safety factor (FSF)	Nr	Fire safety element	Max	Hospital Baseline HTM 05 Atrium	Hospital Actual Atrium 1	Hospital Actual Atrium 2
ORG	1	Fire strategy: not developed (0) / has been developed for selected aspects (1) / has been developed and documented in all aspects necessary for the pre-defined strategy objectives (4)	4	2	4	4
	2	Documented fire safety procedures for the building (1) + implementation of the procedures (1) + regularly controlled updates (1) + documented evacuation plans for all floors (1)	4	4	4	4
	3	Central building security personnel for the building (1) + trained fire wardens on all floors/in zones (3) + regular evacuation drills with specific staff participation (2) / regular evacuation drills involving all building occupants (3)	7	4	4	4
	4	Fire safety training: only key staff (2) / all staff (4)	4	4	4	4
	5	Independent certification and audit system for fire safety management: only mandatory checks (1) + full regular fire safety audits, undertaken by specialist bodies (1)	2	2	2	2
	6	Management commitment to fire safety including fire safety management review meetings and training of personnel in the key aspects of the management, operation and maintenance of fire protection systems, and the principles of fire strategy, evacuation strategy awareness, etc. (0 to 4)	4	4	4	4
		Total	**25**	**20**	**22**	**22**
LIM	1	Fire load density [MJ/m2] (>4000) (0) / (>2000, ≤4000) (1) / (>1000, ≤2000) (2) / (>500, ≤1000) (4) / (≤ 500) (5) + High hazard ignition sources Y (0) / N (2)	7	3	3	5
	2	Expected fire growth: ultrafast (0), fast (1), medium (4), slow (5)	5	1	1	1
	3	High risk areas of the building are separated from other parts of the building by suitable fire resisting construction Y (2) / N (0) + high levels of combustible materials stored in the building - Y (0) / N (2)	4	2	2	2
	4	Smoke production from construction products and fixed equipment (the worst case): s3 and products of reaction to fire class ≤E (0) / s2 (1) / s1 and products of reaction to fire class A1 (2)	2	2	2	2
	5	Reaction to fire class of construction products (claddings/coverings) (the worst case) ≤E (0) / D i C (1) / B (2) ≥A2 (3)	3	3	3	3
	6	Reaction to fire class of the building insulation products (external walls, roof) (the worst case): ≤E (0) / D i C (1) / B (2) ≥A2 (4)	4	3	3	3
		Total	**25**	**14**	**14**	**16**
PAS	1	Fire resistance of structural elements: <15 min (0), 15 min (1), 30 min (2), 60 min (3), 90 min (4), ≥120 min (6),	6	4	4	4
	2	Maximum fire resistance of internal subdivisions: 30 min (1), 60 min (2), 120 min (3), 240 min (4)	4	3	3	3
	3	Fire resistance of doors and shutters: No resistance rating (0) / 30 min (1), 60 min (2), 120 min (3), 240 min (4)	4	2	2	2
	4	Distance from neighbouring buildings: Not in accordance with regulations (0) / in accordance with regulations (2) / fire wall used as separation (2) / the heat flux density on adjacent object walls < 12,5 kW/m² (2)	2	2	2	2
	5	Compartmentation - fire zones [m2] (>20000) (0) / (>10000, ≤20000) (1) / (>5000, ≤10000) (2) / (>2000, ≤5000) (3) / (>1000, ≤2000) (4) / (≤1000) (5)	5	3	2	2
	6	Activation of fire shutters, doors, dampers etc. with fusible links (1), manual activation via control panel (2) / automatic after verification (3) / automatic (4)	4	3	3	3
		Total	**25**	**17**	**16**	**16**
DET	1	Full monitoring, i.e. detection in all risk areas (5) / partial monitoring (1) + detection in evacuation routes (1) / manual system (1) / no detection (0)	5	5	5	5
	2	Expected detection response time (>420 s) (0) / (>300 s, ≤ 420 s) (2) / (>180 s, ≤ 300 s) (3) / (≤180 s) (5)?	5	3	1	1
	3	All detection devices are appropriate for the risk (0 to 4)	4	3	2	2
	4	Sufficient and suitable control and indicating equipment in the building, including power supplies and cables (2) + certified systems (1)	3	3	3	3
	5	False alarms controlling procedures: No (0) / Yes (4)	4	4	4	4
	6	Alarm warning systems: sounders (1) / voice alarm (2) / Voice alarm with public address (3) + active visual support signage (1)	4	1	1	1
		Total	**25**	**19**	**16**	**16**
SUP	1	Fire suppression systems covering all risk areas (3) / partial coverage only (2) / no suppression systems (0) + fast response sprinklers (1)	4	2	4	4
	2	Fire suppression response time index (RTI): standard B (>200, ≤ 300) (1)/ standard A (>80, ≤ 200) (2)/ special (>50, ≤ 80) (3) / fast (≤ 50) (4)?	4	2	2	2
	3	Expected activation time: (s): >300 (0)/ (>200, ≤ 300) (1) / (>150, ≤ 200) (2)/ (>120, ≤ 150) (3) / (≤ 120) (4)?	4	2	1	1
	4	Fire suppression systems appropriate to: the height of storage (2) + type of combustible material (2) + storage method (2)	6	2	4	4
	5	Reliability of suppression installation: system monitoring (1), independent power supply and water suppression systems (1) operation + dual water supply (1) + double source water supply (1)	4	2	2	2
	6	Hose reels covering all parts of the building Y (1) / N (0) + portable fire extinguishers (pfe) with rated extinguishing efficiency provided sited to standard accepted densities (1) or enhanced densities (2).	3	1	1	1
		Total	**25**	**11**	**14**	**14**
SC	1	Stair core smoke control: Non-existent (0) / in place but effectiveness not specified (1) / assured protection of means of escape (2) + assured support for firefighting operations (1) + monitored for all system failures (1)	4	4	4	4
	2	Horizontal evacuation routes smoke control system: Non-existent (0) / in place but effectiveness not specified (1) / assured protection of means of escape (2) + assured support for firefighting operations (1) + monitored for all system failures (1)	4	2	0	2
	3	Smoke enclosure control system: Non-existent (0) / in place but effectiveness not specified (1) / assured protection of means of escape (2) + assured support for firefighting operations (1) + monitored for all system failures (1)	4	2	0	2
	4	Aspects of the construction of the means of escape could potentially lead to uncontrolled smoke production (0) / Suitable control of combustible materials on horizontal evacuation routes (1) + vertical evacuation routes (2)	3	3	1	3
	5	Dimensions of stair cores and horizontal evacuation routes relevant to the amount and profile of occupants (0 to 2) + at least two stair cores (2) + at least two directions of travel from each area (2).	6	6	6	6
	6	Evacuation signage: Passive signage correctly selected and arranged (1) / illuminated signage systems (2) / dynamic illuminated signage systems to control movement of occupants (4)	4	2	2	2
		Total	**25**	**19**	**13**	**19**
MAI	1	Has the design, installation and commissioning of fire-fighting and fire protection systems been carried out in accordance with the manufacturer's instructions and standards? Y (2) / N (0) + by certified contractors Y (2) / partly (1) / N (0)	4	4	4	4
	2	Is there a suitable inventory of fire-fighting and fire protection systems (1) + operation and maintenance information (2)?	3	3	3	3
	3	Maintenance procedures and inspections in accordance with minimum national regulations (1) + manufacturer's instructions (2) + national standards (2)?	5	5	5	5
	4	Functional testing (over and above minimum requirements) of fire-fighting and fire protection systems to ensure maximum levels of availability and reliability: Y (6) / partly (3) / N (0)?	6	4	4	4
	5	Systems used to monitor in real time the availability and reliability of fire-fighting and fire protection systems: Y (3) / partly (1) / N (0)?	3	3	3	3
	6	Modifications to fire fighting and protection system recorded (1) + monitored (1) + audited (2)	4	4	4	4
		Total	**25**	**23**	**23**	**23**
FB	1	Method of communication with fire-fighters: Manual means by building user (e.g. no automatic fire detection) (0) / manual means by building user in the case of fire detection operation (1) / automatic, via alarm receiving centre with alarm confirmed by external staff (2) / automatic, via alarm receiving centre with alarm confirmed by staff on site (4).	4	2	2	2
	2	Availability of on-site fire safety personnel to assist (2) / nominal or part time availability (1) / no availability (0)	2	1	1	1
	3	Fire brigade arrival time[s] (>900) (0) / (>600, ≤900) (2) / (>300, ≤600) (4) / (≤300) (6)	6	4	4	4
	4	Access to the building: No direct access (0) / limited access to the building (1) / direct access to at least 50% or two sides of building (2) / direct access to all parts of building perimeter (3)	3	2	3	3
	5	Internal communication for fire-fighting purposes within the building: difficult (0) / easy (1) + easy access to the fire control panel (1) + graphic display showing fire locations (1) + lighting of evacuation routes suitable for firefighting effort (1) + at least 2 staircases (1) + fire-fighters lifts with lobbies (1)	6	2	2	2
	6	Fire service facilities: No firefighting facilities (0) / suitable fire-fighting hose reels or dry /wet risers on each level (2) + smoke ventilation controls available (1) + fire pump provisions on site (1)	4	4	3	3
		Total	**25**	**14**	**15**	**15**

Appendix D: Baseline Fire Strategies for all risk profiles: Scoring Table

Fire safety factor (FSF)	Fire safety element	Max	Risk Profile											
			A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
1. Organisation and Management [ORG]	Fire strategy: not developed (0) / has been developed for selected aspects (1) / has been developed and documented in all aspects necessary for the pre-defined strategy objectives (4)	4	0	0	4	4	0	0	4	4	0	0	4	4
	Documented fire safety procedures for the building (1) + implementation of the procedures (1) + regularly controlled updates (1) + documented evacuation plans for all floors (1)	4	3	3	3	3	3	3	3	3	3	3	3	3
	Central building security personnel for the building (1) + trained fire wardens on all floors/in zones (3) + regular evacuation drills with specific staff participation (2) / regular evacuation drills involving all building occupants (3)	7	0	0	1	7	1	3	3	6	1	0	0	7
	Fire safety training: only key staff (2) / all staff (4)	4	0	0	2	4	2	2	2	4	0	0	2	2
	Independent certification and audit system for fire safety management: only mandatory checks (1) + full regular fire safety audits, undertaken by specialist bodies (1)	2	0	0	0	0	0	0	0	0	0	0	0	0
	Management commitment to fire safety including fire safety management review meetings and training of personnel in the key aspects of the management, operation and maintenance of fire protection systems, and the principles of fire strategy, evacuation strategy awareness, etc. (0 to 4)	4	0	0	0	2	0	0	0	0	0	0	0	0
	Total	25	3	3	10	20	6	8	12	17	4	3	9	16
2. Control of ignition sources and combustible materials [LIM]	Fire load density [MJ/m2] (>4000) (0) / (>2000, ≤4000) (1) / (>1000, ≤2000) (2) / (>500, ≤1000) (4) / (≤ 500) (5) + High hazard ignition sources Y (0) / N (2)	7	7	6	3	0	7	6	3	0	7	6	3	0
	Expected fire growth: ultrafast (0), fast (1), medium (4), slow (5)	5	5	4	1	0	5	4	1	0	5	4	1	0
	High risk areas of the building are separated from other parts of the building by suitable fire resisting construction Y (2) / N (0) + high levels of combustible materials stored in the building - Y (0)	4	4	4	4	4	4	4	4	4	4	4	4	4
	Smoke production from construction products and fixed equipment (the worst case): s3 and products of reaction to fire class ≤E (0) / s2 (1) / s1 and products of reaction to fire class A1 (2)	2	1	1	1	1	1	1	1	1	1	1	1	1
	Reaction to fire class of construction products (claddings/coverings) (the worst case) ≤E (0) / D i C (1) / B (2) ≥A2 (3)	3	2	2	2	2	2	2	2	2	2	2	2	2
	Reaction to fire class of the building insulation products (external walls, roof) (the worst case): ≤E (0) / D i C (1) / B (2) ≥A2 (4)	4	2	2	2	2	2	2	2	2	2	2	2	2
	Total	25	21	19	13	9	21	19	13	9	21	19	13	9
3. Fire and smoke spread limitation - passive systems [PAS]	Fire resistance of structural elements: <15 min (0), 15 min (1), 30 min (2), 60 min (3), 90 min (4), ≥120 min (6),	6	2	2	4	4	2	2	4	6	2	2	4	6
	Maximum fire resistance of internal subdivisions: 30 min (1), 60 min (2), 120 min (3), 240 min (4)	4	1	1	3	3	1	1	3	4	1	1	3	4
	Fire resistance of doors and shutters: No resistance rating (0) / 30 min (1), 60 min (2), 120 min (3), 240 min (4)	4	1	1	3	3	1	1	3	4	1	1	3	4
	Distance from neighbouring buildings: Not in accordance with regulations (0) / in accordance with regulations (2) / fire wall used as separation (2) / the heat flux density on adjacent object walls < 12,5 kW/m² (2)	2	2	2	2	2	2	2	2	2	2	2	2	2
	Compartmentation - fire zones [m2] (>20000) (0) / (>10000, ≤20000) (1) / (>5000, ≤10000) (2) / (>2000, ≤5000) (3) / (>1000, ≤2000) (4) / (≤1000) (5)	5	0	1	2	3	1	2	3	4	1	2	3	4
	Activation of fire shutters, doors, dampers etc. with fusible links (1), manual activation via control panel (2) / automatic after verification (3) / automatic (4)	4	2	2	3	4	2	3	3	4	3	4	4	4
	Total	25	8	9	17	19	9	11	18	24	10	12	19	24
4. Detection and alarm communication [DET]	Full monitoring, i.e. detection in all risk areas (5) / partial monitoring (1) + detection in evacuation routes (1) / manual system (1) / no detection (0)	5	1	1	2	5	1	2	3	5	2	2	3	5
	Expected detection response time (>420 s) (0) / (>300 s, ≤ 420 s) (2) / (>180 s, ≤ 300 s) (3) / (≤180 s) (5)?	5	0	2	3	5	0	2	3	5	2	3	5	5
	All detection devices are appropriate for the risk (0 to 4)	4	0	1	2	3	0	1	3	4	0	2	3	4
	Sufficient and suitable control and indicating equipment in the building, including power supplies and cables (2) + certified systems (1)	3	0	0	1	2	0	1	2	3	0	1	2	3
	False alarms controlling procedures: No (0) / Yes (4)	4	0	0	2	4	0	0	2	4	0	0	2	4
	Alarm warning systems: sounders (1) / voice alarm (2) / Voice alarm with public address (3) + active visual support signage (1)	4	0	1	3	4	0	1	3	4	1	2	3	4
	Total	25	1	5	13	23	1	7	16	25	5	10	18	25
5. Fire suppression [SUP]	Fire suppression systems covering all risk areas (3) / partial coverage only (2) / no suppression systems (0) + fast response sprinklers (1)	4	0	0	2	4	0	0	3	4	0	0	3	4
	Fire suppression response time index (RTI): standard B (>200, ≤ 300) (1)/ standard A (>80, ≤ 200) (2)/ special (>50, ≤ 80) (3) / fast (≤ 50) (4)?	4	0	0	2	3	0	0	2	4	0	0	2	4
	Expected activation time: (s): >300 (0)/ (>200, ≤ 300) (1) / (>150, ≤ 200) (2)/ (>120, ≤ 150) (3) / (≤ 120) (4)?	4	0	0	1	4	0	0	3	4	0	0	3	4
	Fire suppression systems appropriate to: the height of storage (2) + type of combustible material (2) + storage method (2)	6	0	0	6	6	0	0	6	6	0	0	6	6
	Reliability of suppression installation: system monitoring (1), independent power supply and water suppression systems (1) operation + dual water supply (1) + double source water supply (1)	4	0	0	0	1	0	0	1	2	0	0	2	4
	Hose reels covering all parts of the building Y (1) / N (0) + portable fire extinguishers (pfe) with rated extinguishing efficiency provided sited to standard accepted densities (1) or enhanced densities (2)	3	1	1	3	3	1	3	3	3	3	3	3	3
	Total	25	1	1	14	21	1	3	18	23	3	3	19	25
6. Smoke control and evacuation [SC]	Stair core smoke control: Non-existent (0) / in place but effectiveness not specified (1) / assured protection of means of escape (2) + assured support for firefighting operations (1) + monitored for all system failures (1)	4	0	0	2	2	0	1	2	2	1	1	2	2
	Horizontal evacuation routes smoke control system: Non-existent (0) / in place but effectiveness not specified (1) / assured protection of means of escape (2) + assured support for firefighting operations (1) + monitored for all system failures (1)	4	0	0	2	2	0	1	2	2	1	1	2	2
	Smoke enclosure control system: Non-existent (0) / in place but effectiveness not specified (1) / assured protection of means of escape (2) + assured support for firefighting operations (1) + monitored for all system failures (1)	4	0	0	0	2	0	1	2	2	1	1	2	2
	Aspects of the construction of the means of escape could potentially lead to uncontrolled smoke production (0) / Suitable control of combustible materials on horizontal evacuation routes (1) + vertical evacuation routes (2)	3	0	0	1	3	0	2	3	3	2	2	3	3
	Dimensions of stair cores and horizontal evacuation routes relevant to the amount and profile of occupants (0 to 2) + at least two stair cores (2) + at least two directions of travel from each area (2)	6	2	2	4	6	2	2	2	6	6	6	6	6
	Evacuation signage: Passive signage correctly selected and arranged (1) / illuminated signage systems (2) / dynamic illuminated signage systems to control movement of occupants (4)	4	0	0	1	4	0	1	1	4	3	3	3	4
	Total	25	2	2	10	19	2	8	12	19	14	14	18	19
7. Maintenance of fire precautions and systems [MAI]	Has the design, installation and commissioning of fire-fighting and fire protection systems been carried out in accordance with the manufacturer's instructions and standards? Y (2) / N (0) + by certified contractors Y (2) / partly (1) / N (0)	4	0	2	2	2	0	2	2	2	2	2	2	2
	Is there a suitable inventory of fire-fighting and fire protection systems (1) + operation and maintenance information (2)?	3	0	0	0	0	0	0	0	0	0	0	0	0
	Maintenance procedures and inspections in accordance with minimum national regulations (1) + manufacturer's instructions (2) + national standards (2)?	5	1	1	2	5	1	1	2	5	1	1	2	5
	Functional testing (over and above minimum requirements) of fire-fighting and fire protection systems to ensure maximum levels of availability and reliability: Y (6) / partly (3) / N (0)?	6	0	3	6	6	0	3	6	6	0	3	6	6
	Systems used to monitor in real time the availability and reliability of fire-fighting and fire protection systems: Y (3) / partly (1) / N (0)?	3	0	0	1	3	0	0	1	3	0	0	1	3
	Modifications to fire fighting and protection system recorded (1) + monitored (1) + audited (2)	4	0	1	2	3	0	1	2	3	0	1	2	3
	Total	25	1	7	13	19	1	7	13	19	3	7	13	19
8. Fire services intervention [FB]	Method of communication with fire-fighters: Manual means by building user (e.g. no automatic fire detection) (0) / manual means by building user in the case of fire detection operation (1) / automatic, via alarm receiving centre with alarm confirmed by external staff (2) / automatic, via alarm receiving centre with alarm confirmed by staff on site (4).	4	0	1	2	4	0	1	2	4	1	1	2	4
	Availability of on-site fire safety personnel to assist (2) / nominal or part time availability (1) / no availability (0)	2	0	0	1	1	0	0	1	1	0	1	1	1
	Fire brigade arrival time[s] (>900) (0) / (>600, ≤900) (2) / (>300, ≤600) (4) / (≤300) (6)	6	0	0	4	6	0	2	4	6	2	2	4	6
	Access to the building: No direct access (0) / limited access to the building (1) / direct access to at least 50% or two sides of building (2) / direct access to all parts of building perimeter (3)	3	1	1	2	3	1	2	2	3	1	2	2	3
	Internal communication for fire-fighting purposes within the building: difficult (0) / easy (1) + easy access to the fire control panel (1) + graphic display showing fire locations (1) + lighting of evacuation routes suitable for firefighting effort (1) + at least 2 staircases (1) + fire-fighters lifts with lobbies (1)	6	0	1	3	5	0	1	3	5	0	1	3	5
	Fire service facilities: No firefighting facilities (0) / suitable fire-fighting hose reels or dry /wet risers on each level (2) + smoke ventilation controls available (1) + fire pump provisions on site (1)	4	0	0	2	4	0	0	2	4	0	0	2	4
	Total	25	1	3	14	23	1	6	14	23	4	7	14	23

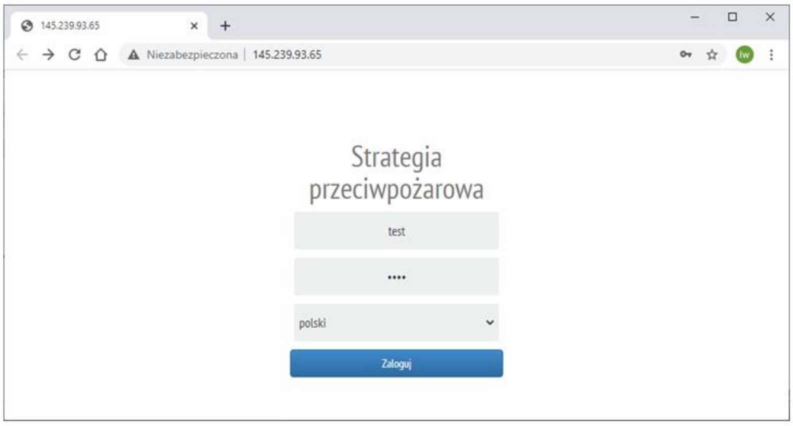
Appendix E: Computer software for fire strategies evaluation

As highlighted in chapter 7, computer software was developed by the Author to allow fast, user-friendly and reliable application of the simple calculation models given in Chapters 3, 4, and 5. The software is available under the link: http://145.239.93.65 and has already been used in projects for the Polish market. The English version is under preparation, and other languages versions are also planned. However, it is also likely that the software's algorithms will be improved as part of future developments. The process incorporated in the software application is given below.

E.1. Building description and baseline strategy

The initial step is to provide a description of the building being analysed and determining the appropriate baseline strategy parameters.

Login: The User must initially login (*Fig. E1*).



Strategia przeciwpożarowa

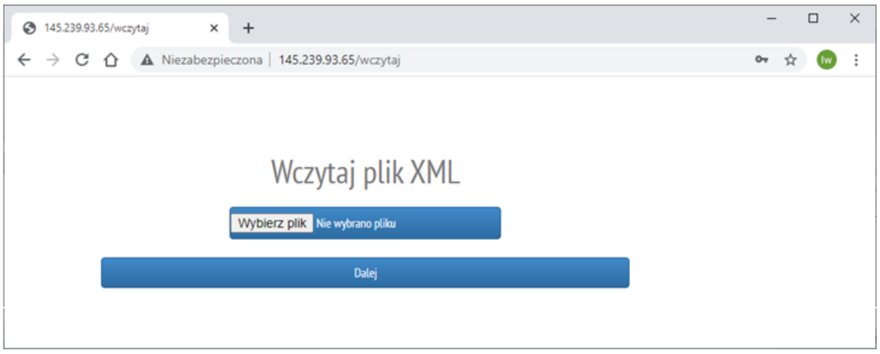
test

••••

polski

Fig. E1. The Software login page.

Data loading: Once the User is logged in, they can upload an existing data file for the project, or skip this option should they want to create a new one (*Fig. E2*).

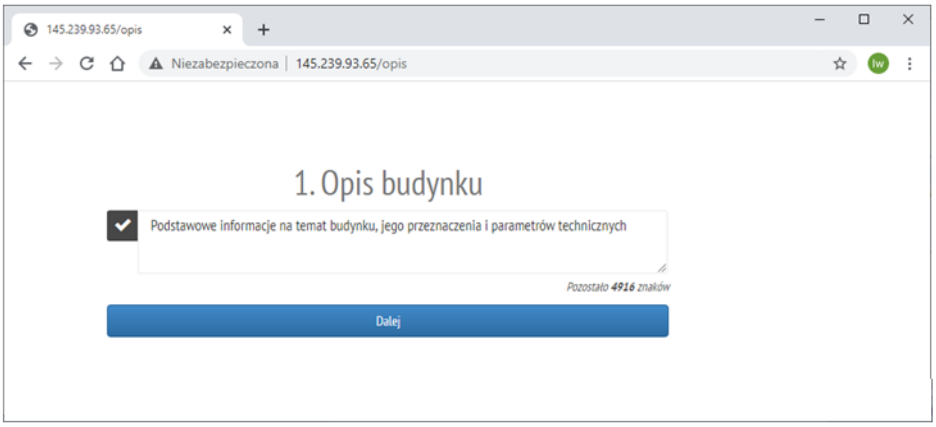


Wczytaj plik XML

Nie wybrano pliku

Fig. E2. Data file loading.

Building Characteristics: The first step of creating the project is to provide a detailed description of the building. The User has 5,000 characters available and should give here all the information necessary for defining the most important building parameters relative to the prepared fire strategy (*Fig. E3*).



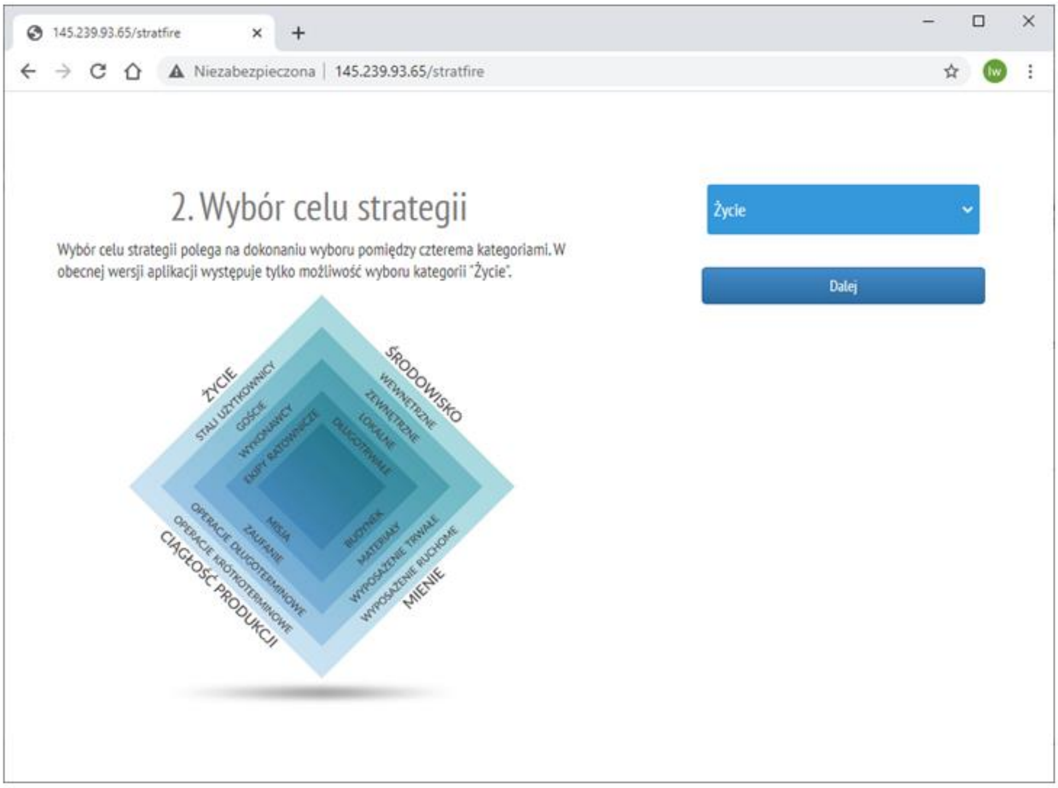
1. Opis budynku

☑ Podstawowe informacje na temat budynku, jego przeznaczenia i parametrów technicznych

*Pozostało **4916** znaków*

Fig. E3. Building characteristic.

Enhanced Objectives Setting: The next step is to decide what are the main objectives of the strategy (*see Chapter 3.3*). At this stage, the software covers only life safety objectives, but all other options are under preparation (*Fig. E4*).



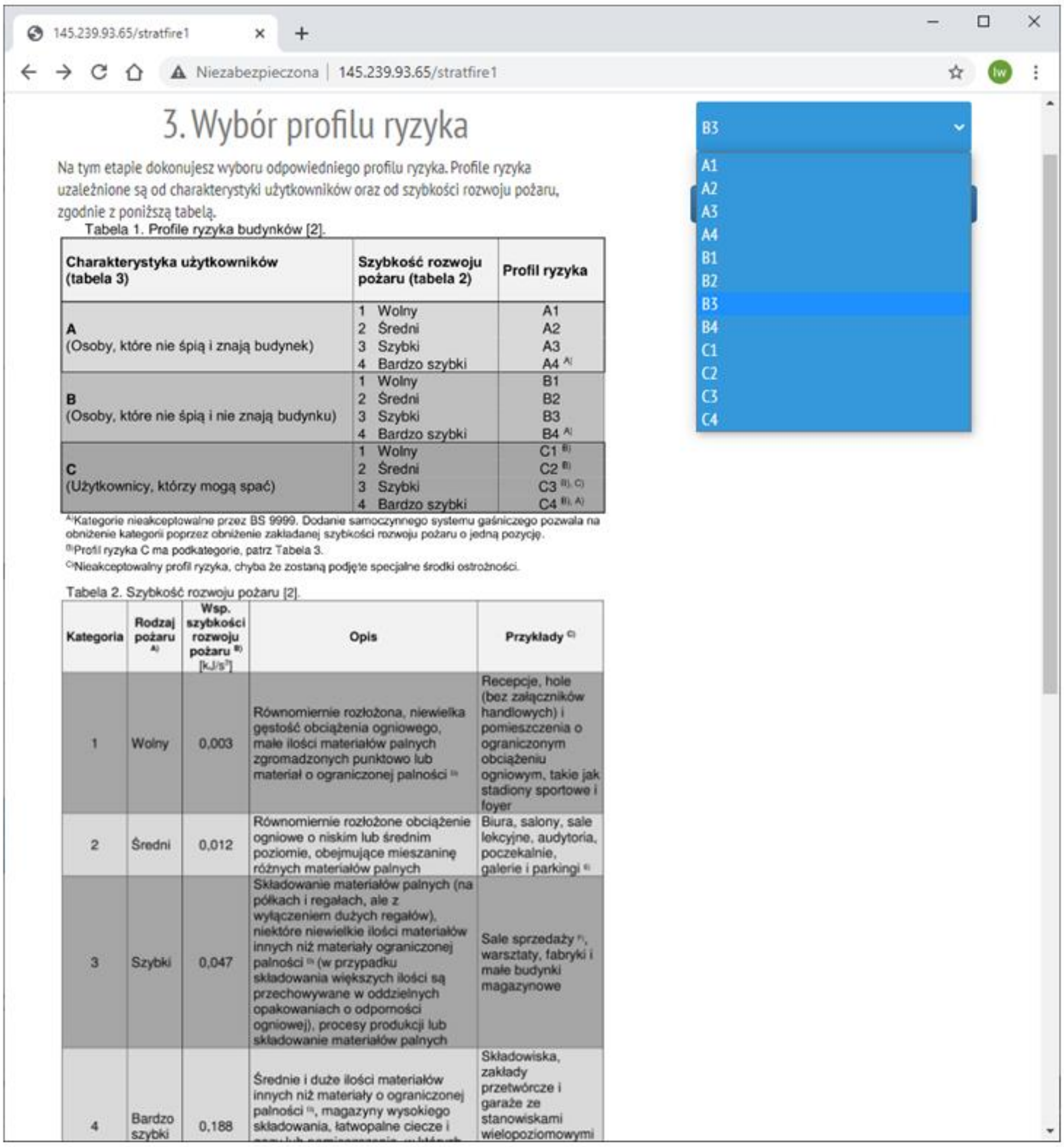
2. Wybór celu strategii

Wybór celu strategii polega na dokonaniu wyboru pomiędzy czterema kategoriami. W obecnej wersji aplikacji występuje tylko możliwość wyboru kategorii "Życie".

Życie

Fig. E4. Fire Strategy Objectives.

Risk Profile: The building Risk Profile can be chosen for the rolled list (*see Chapter 5.3.4*). The User can find here also a detailed description of the available risk profiles, to make his decision easier (*Fig. E5*).



3. Wybór profilu ryzyka

Na tym etapie dokonujesz wyboru odpowiedniego profilu ryzyka. Profile ryzyka uzależnione są od charakterystyki użytkowników oraz od szybkości rozwoju pożaru, zgodnie z poniższą tabelą.

Tabela 1. Profile ryzyka budynków [2].

Charakterystyka użytkowników (tabela 3)	Szybkość rozwoju pożaru (tabela 2)	Profil ryzyka
A (Osoby, które nie śpią i znają budynek)	1 Wolny 2 Średni 3 Szybki 4 Bardzo szybki	A1 A2 A3 A4 [A)]
B (Osoby, które nie śpią i nie znają budynku)	1 Wolny 2 Średni 3 Szybki 4 Bardzo szybki	B1 B2 B3 B4 [A)]
C (Użytkownicy, którzy mogą spać)	1 Wolny 2 Średni 3 Szybki 4 Bardzo szybki	C1 [B)] C2 [B)] C3 [B), C)] C4 [B), A)]

A) Kategorie nieakceptowalne przez BS 9999. Dodanie samoczynnego systemu gaśniczego pozwala na obniżenie kategorii poprzez obniżenie zakładanej szybkości rozwoju pożaru o jedną pozycję.

B) Profil ryzyka C ma podkategorie, patrz Tabela 3.

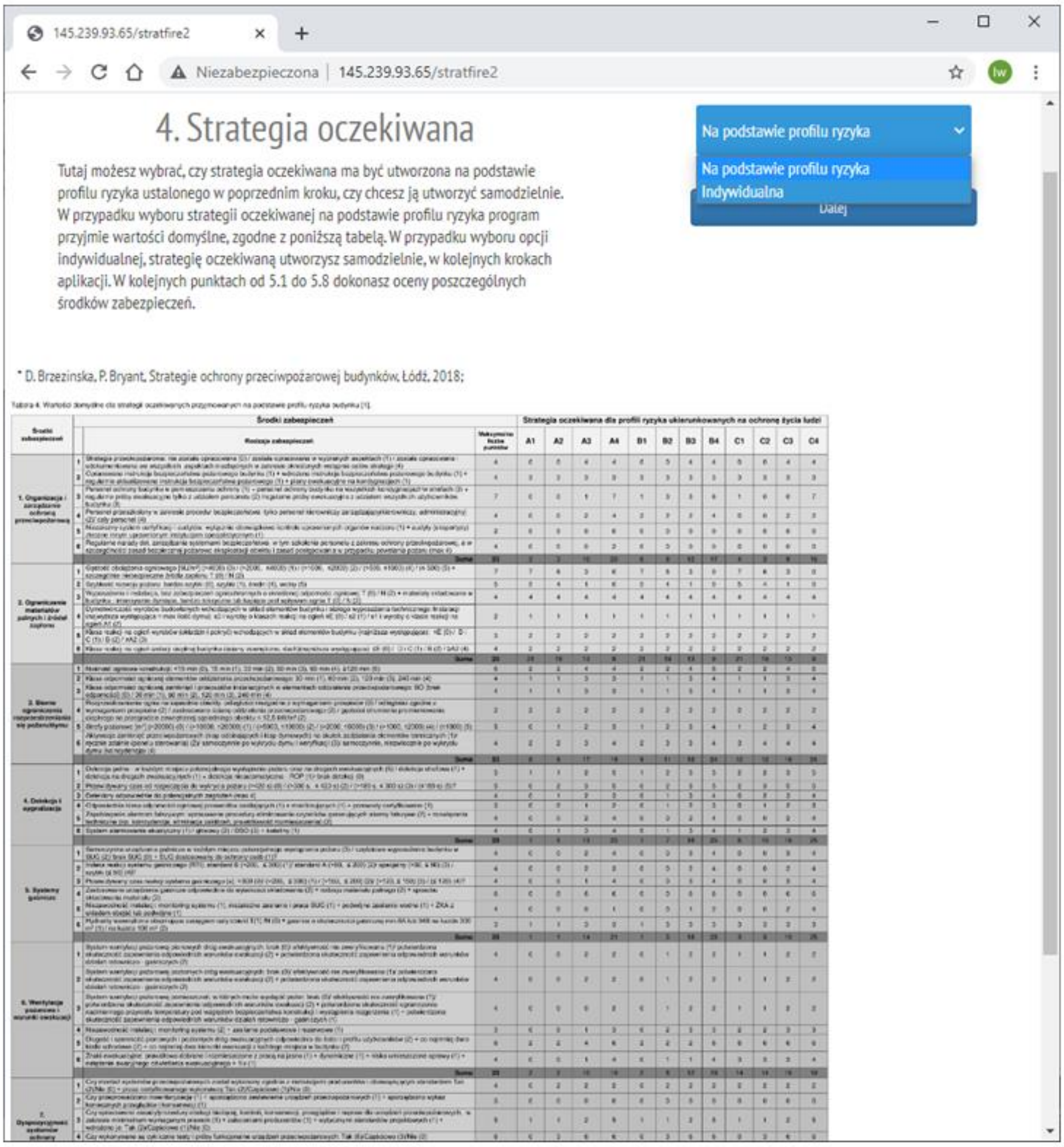
C) Nieakceptowalny profil ryzyka, chyba że zostaną podjęte specjalne środki ostrożności.

Tabela 2. Szybkość rozwoju pożaru [2].

Kategoria	Rodzaj pożaru [A)]	Wsp. szybkości rozwoju pożaru [B)] [kJ/s³]	Opis	Przykłady [C)]
1	Wolny	0,003	Równomiernie rozłożona, niewielka gęstość obciążenia ogniowego, małe ilości materiałów palnych zgromadzonych punktowo lub materiał o ograniczonej palności [D)]	Recepcje, hole (bez załączników handlowych) i pomieszczenia o ograniczonym obciążeniu ogniowym, takie jak stadiony sportowe i foyer
2	Średni	0,012	Równomiernie rozłożone obciążenie ogniowe o niskim lub średnim poziomie, obejmujące mieszaninę różnych materiałów palnych	Biura, salony, sale lekcyjne, audytoria, poczekalnie, galerie i parkingi [E)]
3	Szybki	0,047	Składowanie materiałów palnych (na półkach i regałach, ale z wyłączeniem dużych regałów), niektóre niewielkie ilości materiałów innych niż materiały ograniczonej palności [D)] (w przypadku składowania większych ilości są przechowywane w oddzielnych opakowaniach o odporności ogniowej), procesy produkcji lub składowanie materiałów palnych	Sale sprzedaży [F)], warsztaty, fabryki i małe budynki magazynowe
4	Bardzo szybki	0,188	Średnie i duże ilości materiałów innych niż materiały o ograniczonej palności [D)], magazyny wysokiego składowania, łatwopalne ciecze i	Składowiska, zakłady przetwórcze i garaże ze stanowiskami wielopoziomowymi

Fig. E5. Building Risk Profile.

Baseline Fire Strategy: At this page the User can decide how to score the Baseline Fire Strategy. It could be based on the default values proposed by the Software Authors (*full scoring table is presented in Fig. E6, see also Appendix D of the Thesis*) or can be prepared individually (*see Chapter 5.3.4*).



4. Strategia oczekiwana

Tutaj możesz wybrać, czy strategia oczekiwana ma być utworzona na podstawie profilu ryzyka ustalonego w poprzednim kroku, czy chcesz ją utworzyć samodzielnie. W przypadku wyboru strategii oczekiwanej na podstawie profilu ryzyka program przyjmie wartości domyślne, zgodne z poniższą tabelą. W przypadku wyboru opcji indywidualnej, strategię oczekiwaną utworzysz samodzielnie, w kolejnych krokach aplikacji. W kolejnych punktach od 5.1 do 5.8 dokonasz oceny poszczególnych środków zabezpieczeń.

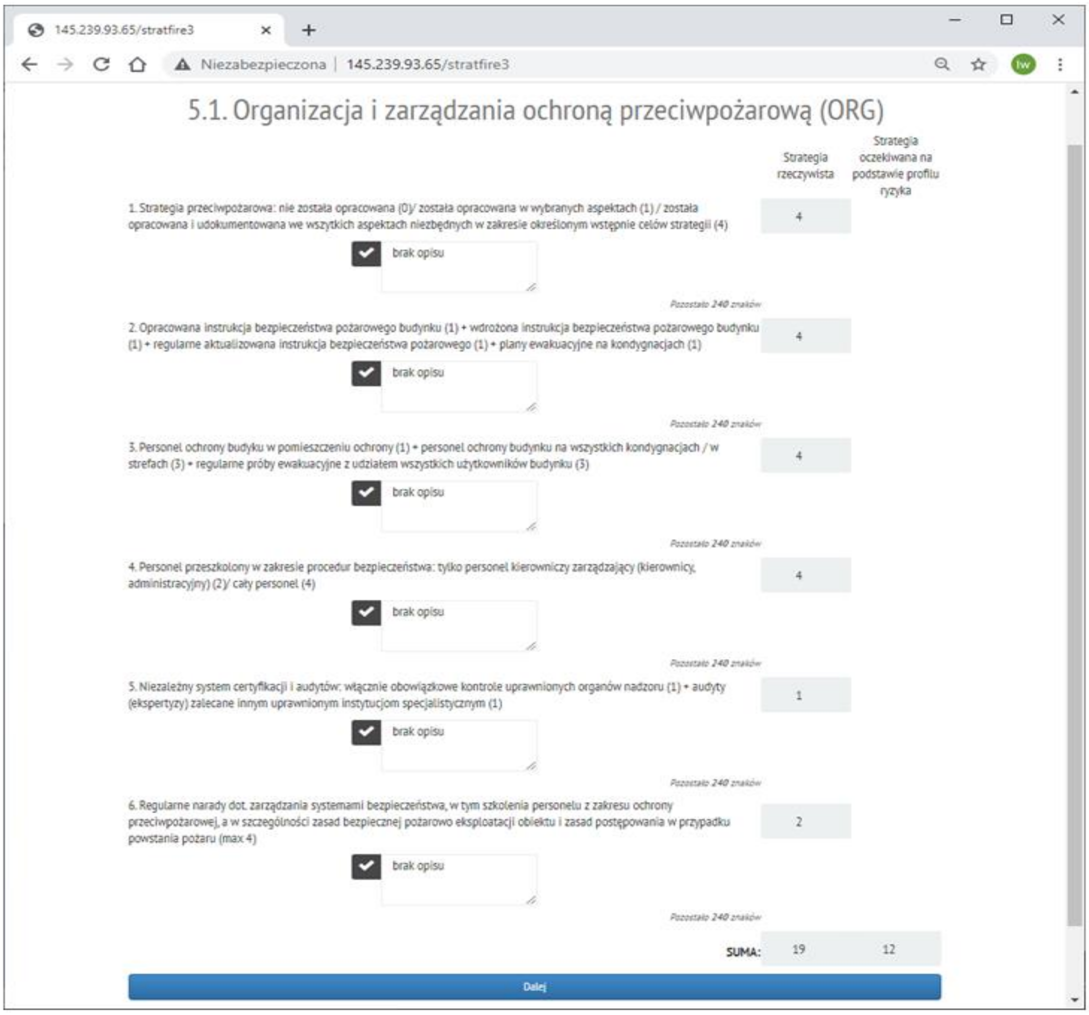
* D. Brzezinska, P. Bryant, Strategie ochrony przeciwpożarowej budynków, Łódź, 2018;

Fig. E6. Baseline Fire Strategy.

E.2. Actual Fire Strategy Evaluation

When the Baseline Fire Strategy is prepared, the User can commence in the evaluation of the Actual Fire Strategy for the building. This stage is about scoring the strategy based upon detailed questions for the Fire Strategy Risk Index, presented in Chapter 5.3.3., relative to several Fire safety factors (*Figs. E7-E14*).

Organisation and Management [ORG]

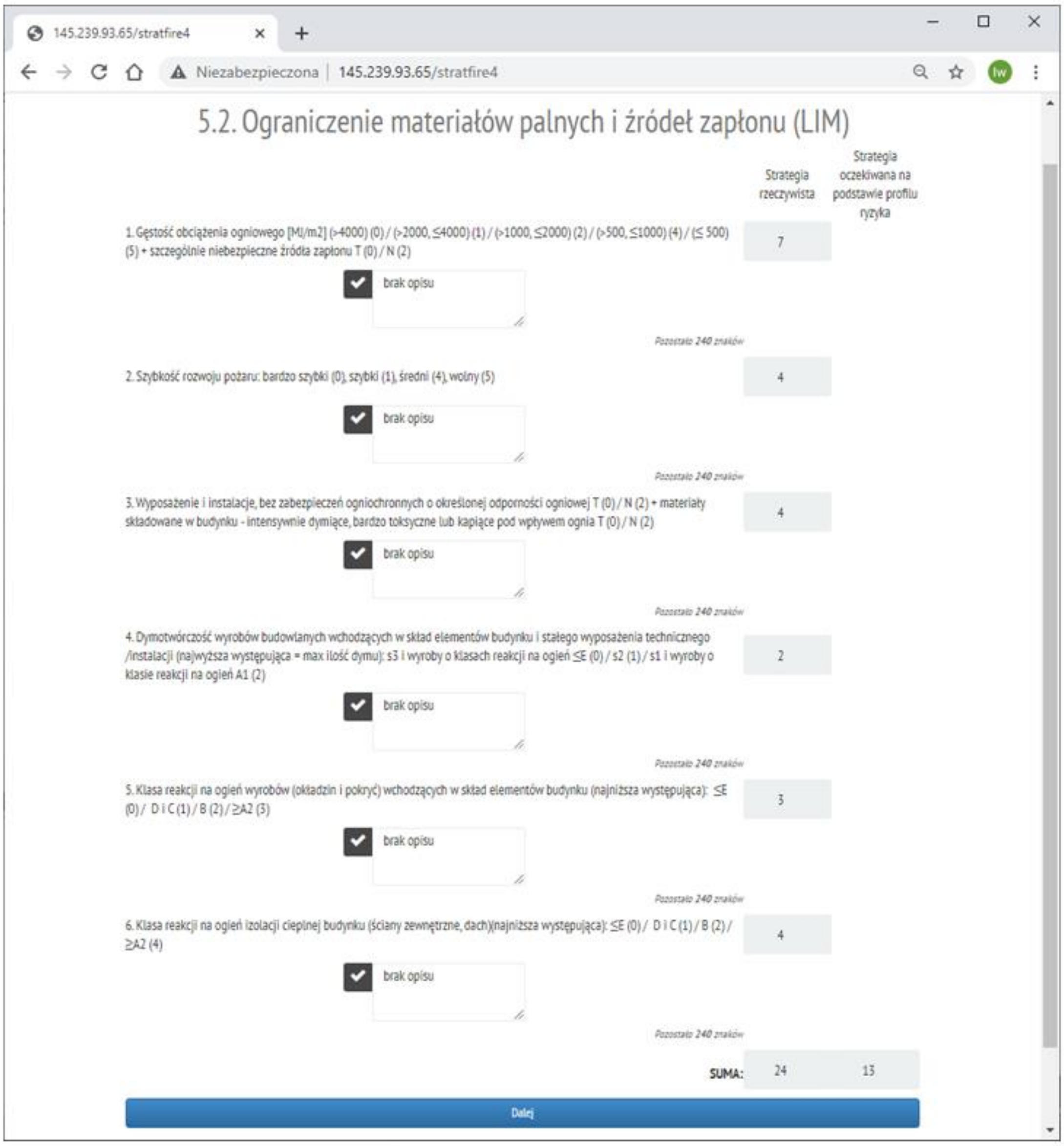


5.1. Organizacja i zarządzania ochroną przeciwpożarową (ORG)

	Strategia rzeczywista	Strategia oczekiwana na podstawie profilu ryzyka
1. Strategia przeciwpożarowa: nie została opracowana (0)/ została opracowana w wybranych aspektach (1) / została opracowana i udokumentowana we wszytkich aspektach niezbędnych w zakresie określonym wstępnie celów strategii (4) ☑ brak opisu Pozostało 240 znaków	4	
2. Opracowana instrukcja bezpieczeństwa pożarowego budynku (1) + wdrożona instrukcja bezpieczeństwa pożarowego budynku (1) + regularne aktualizowana instrukcja bezpieczeństwa pożarowego (1) + plany ewakuacyjne na kondygnacjach (1) ☑ brak opisu Pozostało 240 znaków	4	
3. Personel ochrony budyku w pomieszczeniu ochrony (1) + personel ochrony budynku na wszystkich kondygnacjach / w strefach (3) + regularne próby ewakuacyjne z udziałem wszystkich użytkowników budynku (3) ☑ brak opisu Pozostało 240 znaków	4	
4. Personel przeszkolony w zakresie procedur bezpieczeństwa: tylko personel kierowniczy zarządzający (kierownicy, administracyjny) (2)/ cały personel (4) ☑ brak opisu Pozostało 240 znaków	4	
5. Niezależny system certyfikacji i audytów: włącznie obowiązkowe kontrole uprawnionych organów nadzoru (1) + audyty (ekspertyzy) zalecane innym uprawnionym instytucjom specjalistycznym (1) ☑ brak opisu Pozostało 240 znaków	1	
6. Regularne narady dot. zarządzania systemami bezpieczeństwa, w tym szkolenia personelu z zakresu ochrony przeciwpożarowej, a w szczególności zasad bezpiecznej pożarowo eksploatacji obiektu i zasad postępowania w przypadku powstania pożaru (max 4) ☑ brak opisu Pozostało 240 znaków	2	
SUMA:	19	12

Fig. E7. Organisation and Management.

Fire and smoke spread limitation - passive systems [LIM]

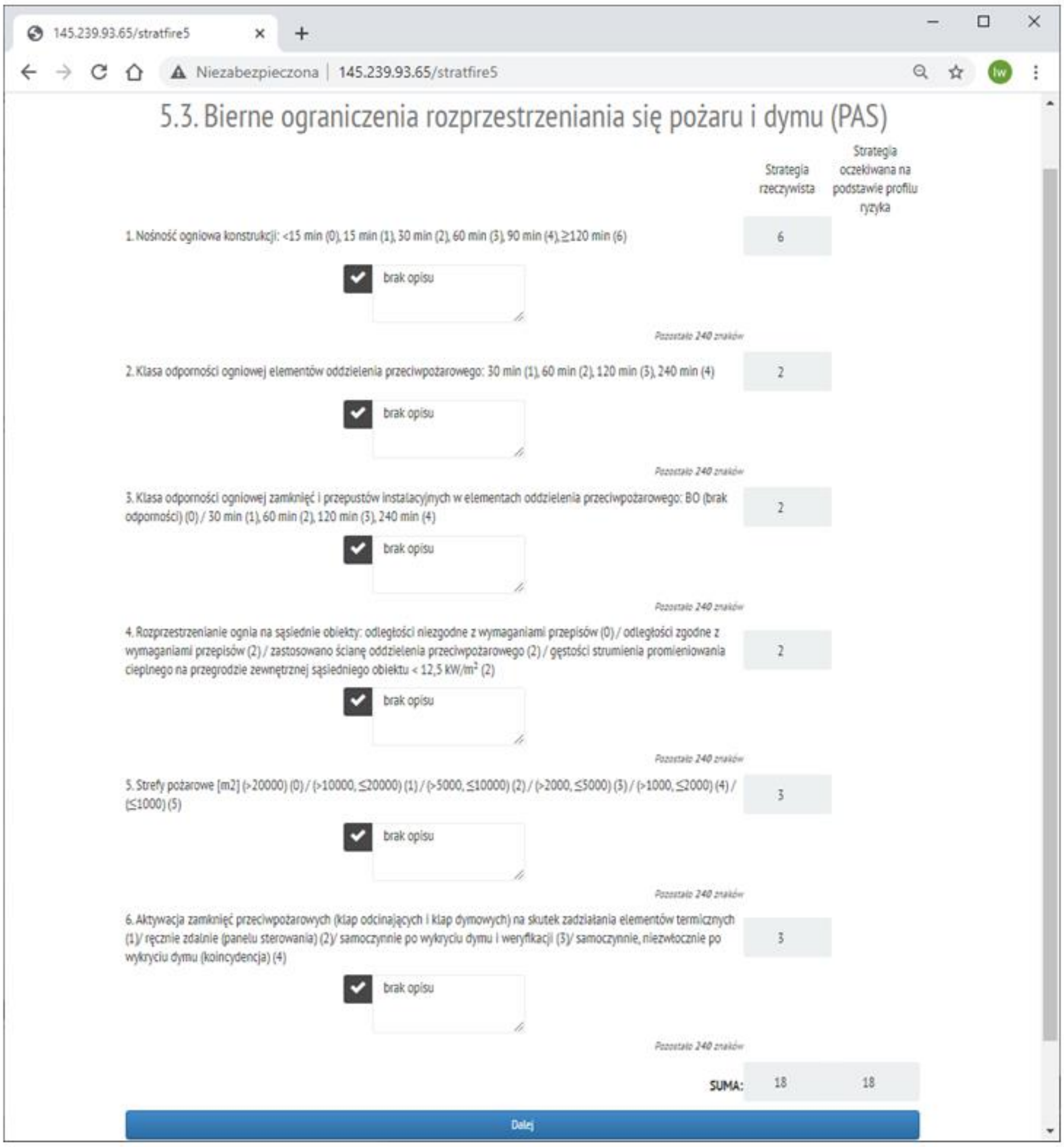


5.2. Ograniczenie materiałów palnych i źródeł zapłonu (LIM)

	Strategia rzeczywista	Strategia oczekiwana na podstawie profilu ryzyka
1. Gęstość obciążenia ogniowego [MJ/m2] (>4000) (0) / (>2000, ≤4000) (1) / (>1000, ≤2000) (2) / (>500, ≤1000) (4) / (≤ 500) (5) + szczególnie niebezpieczne źródła zapłonu T (0) / N (2)	7	
☑ brak opisu		
Pozostało 240 znaków		
2. Szybkość rozwoju pożaru: bardzo szybki (0), szybki (1), średni (4), wolny (5)	4	
☑ brak opisu		
Pozostało 240 znaków		
3. Wyposażenie i instalacje, bez zabezpieczeń ogniochronnych o określonej odporności ogniowej T (0) / N (2) + materiały składowane w budynku - intensywnie dymiące, bardzo toksyczne lub kapiące pod wpływem ognia T (0) / N (2)	4	
☑ brak opisu		
Pozostało 240 znaków		
4. Dymotwórczość wyrobów budowlanych wchodzących w skład elementów budynku i stałego wyposażenia technicznego /instalacji (najwyższa występująca = max ilość dymu): s3 i wyroby o klasach reakcji na ogień ≤E (0) / s2 (1) / s1 i wyroby o klasie reakcji na ogień A1 (2)	2	
☑ brak opisu		
Pozostało 240 znaków		
5. Klasa reakcji na ogień wyrobów (okładzin i pokryć) wchodzących w skład elementów budynku (najniższa występująca): ≤E (0) / D i C (1) / B (2) / ≥A2 (3)	3	
☑ brak opisu		
Pozostało 240 znaków		
6. Klasa reakcji na ogień izolacji cieplnej budynku (ściany zewnętrzne, dach)(najniższa występująca): ≤E (0) / D i C (1) / B (2) / ≥A2 (4)	4	
☑ brak opisu		
Pozostało 240 znaków		
SUMA:	24	13

Fig. E8. Fire and smoke spread limitation - passive systems.

Fire and smoke spread limitation - passive systems [PAS]



5.3. Bierne ograniczenia rozprzestrzeniania się pożaru i dymu (PAS)

Strategia rzeczywista | Strategia oczekiwana na podstawie profilu ryzyka

1. Nośność ogniowa konstrukcji: <15 min (0), 15 min (1), 30 min (2), 60 min (3), 90 min (4), ≥120 min (6) — 6

☑ brak opisu

Pozostało 240 znaków

2. Klasa odporności ogniowej elementów oddzielenia przeciwpożarowego: 30 min (1), 60 min (2), 120 min (3), 240 min (4) — 2

☑ brak opisu

Pozostało 240 znaków

3. Klasa odporności ogniowej zamknięć i przepustów instalacyjnych w elementach oddzielenia przeciwpożarowego: BO (brak odporności) (0) / 30 min (1), 60 min (2), 120 min (3), 240 min (4) — 2

☑ brak opisu

Pozostało 240 znaków

4. Rozprzestrzenianie ognia na sąsiednie obiekty: odległości niezgodne z wymaganiami przepisów (0) / odległości zgodne z wymaganiami przepisów (2) / zastosowano ścianę oddzielenia przeciwpożarowego (2) / gęstości strumienia promieniowania cieplnego na przegrodzie zewnętrznej sąsiedniego obiektu < 12,5 kW/m^2 (2) — 2

☑ brak opisu

Pozostało 240 znaków

5. Strefy pożarowe [m2] (>20000) (0) / (>10000, ≤20000) (1) / (>5000, ≤10000) (2) / (>2000, ≤5000) (3) / (>1000, ≤2000) (4) / (≤1000) (5) — 3

☑ brak opisu

Pozostało 240 znaków

6. Aktywacja zamknięć przeciwpożarowych (klap odcinających i klap dymowych) na skutek zadziałania elementów termicznych (1)/ ręcznie zdalnie (panelu sterowania) (2)/ samoczynnie po wykryciu dymu i weryfikacji (3)/ samoczynnie, niezwłocznie po wykryciu dymu (koincydencja) (4) — 3

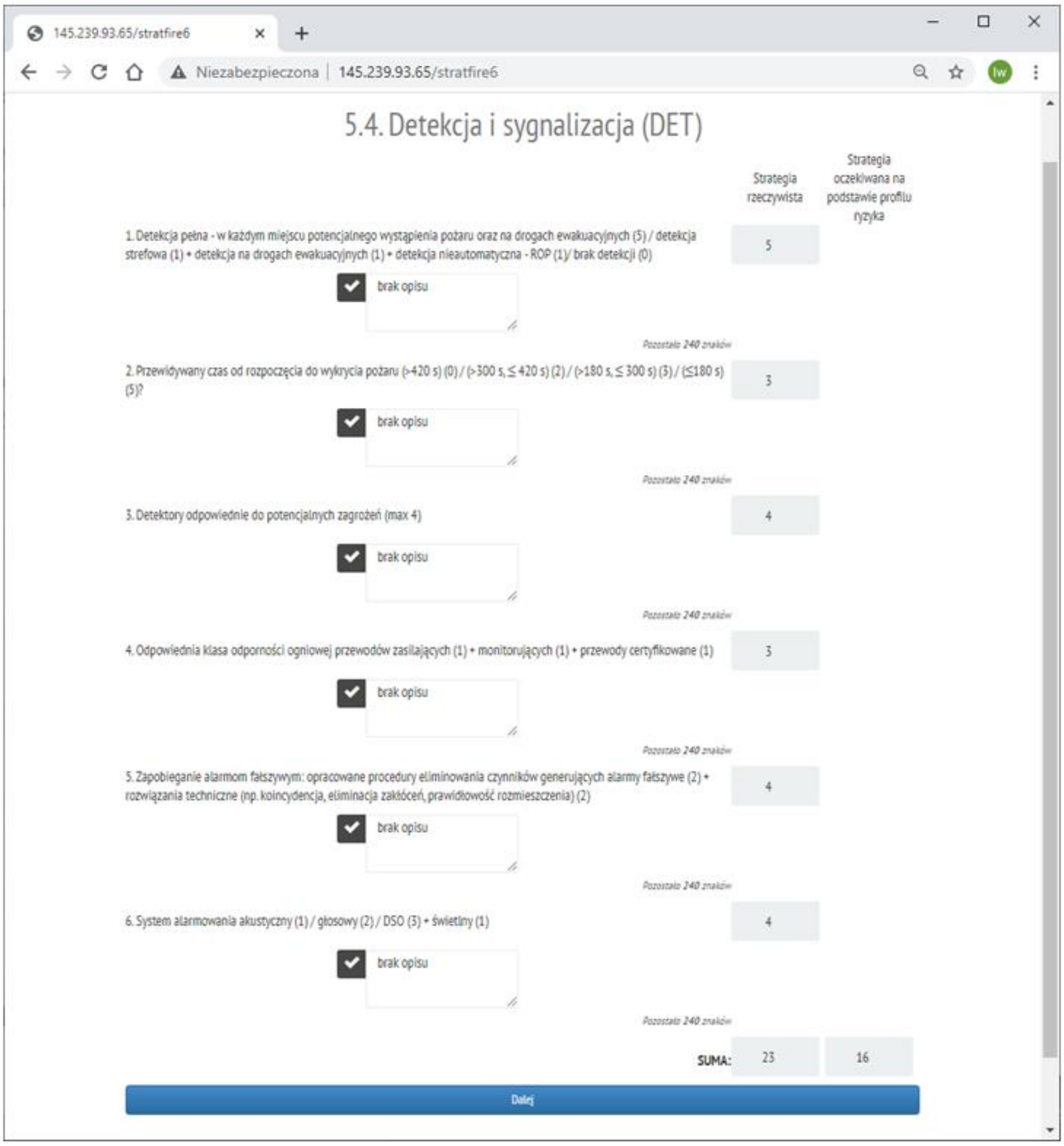
☑ brak opisu

Pozostało 240 znaków

SUMA: 18 18

Fig. E9. Fire and smoke spread limitation - passive systems.

Detection and alarm communication [DET]

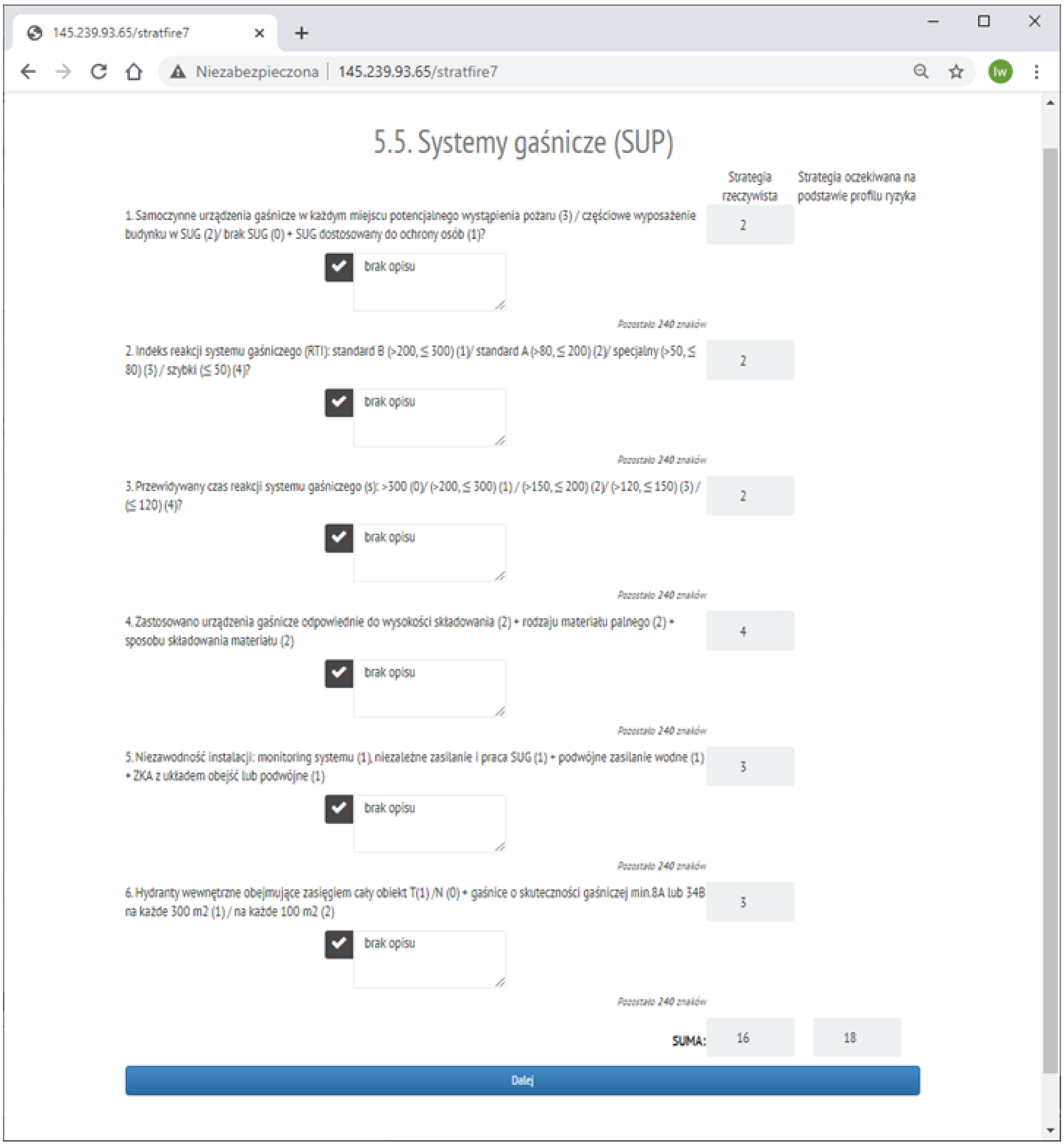


5.4. Detekcja i sygnalizacja (DET)

	Strategia rzeczywista	Strategia oczekiwana na podstawie profilu ryzyka
1. Detekcja pełna - w każdym miejscu potencjalnego wystąpienia pożaru oraz na drogach ewakuacyjnych (5) / detekcja strefowa (1) + detekcja na drogach ewakuacyjnych (1) + detekcja nieautomatyczna - ROP (1)/ brak detekcji (0)	5	
☑ brak opisu Pozostało 240 znaków		
2. Przewidywany czas od rozpoczęcia do wykrycia pożaru (>420 s) (0) / (>300 s, ≤ 420 s) (2) / (>180 s, ≤ 300 s) (3) / (≤180 s) (5)?	3	
☑ brak opisu Pozostało 240 znaków		
3. Detektory odpowiednie do potencjalnych zagrożeń (max 4)	4	
☑ brak opisu Pozostało 240 znaków		
4. Odpowiednia klasa odporności ogniowej przewodów zasilających (1) + monitorujących (1) + przewody certyfikowane (1)	3	
☑ brak opisu Pozostało 240 znaków		
5. Zapobieganie alarmom fałszywym: opracowane procedury eliminowania czynników generujących alarmy fałszywe (2) + rozwiązania techniczne (np. koincydencja, eliminacja zakłóceń, prawidłowość rozmieszczenia) (2)	4	
☑ brak opisu Pozostało 240 znaków		
6. System alarmowania akustyczny (1) / głosowy (2) / DSO (3) + świetliny (1)	4	
☑ brak opisu Pozostało 240 znaków		
SUMA:	23	16

Fig. E10. Detection and alarm communication.

Fire suppression [SUP]

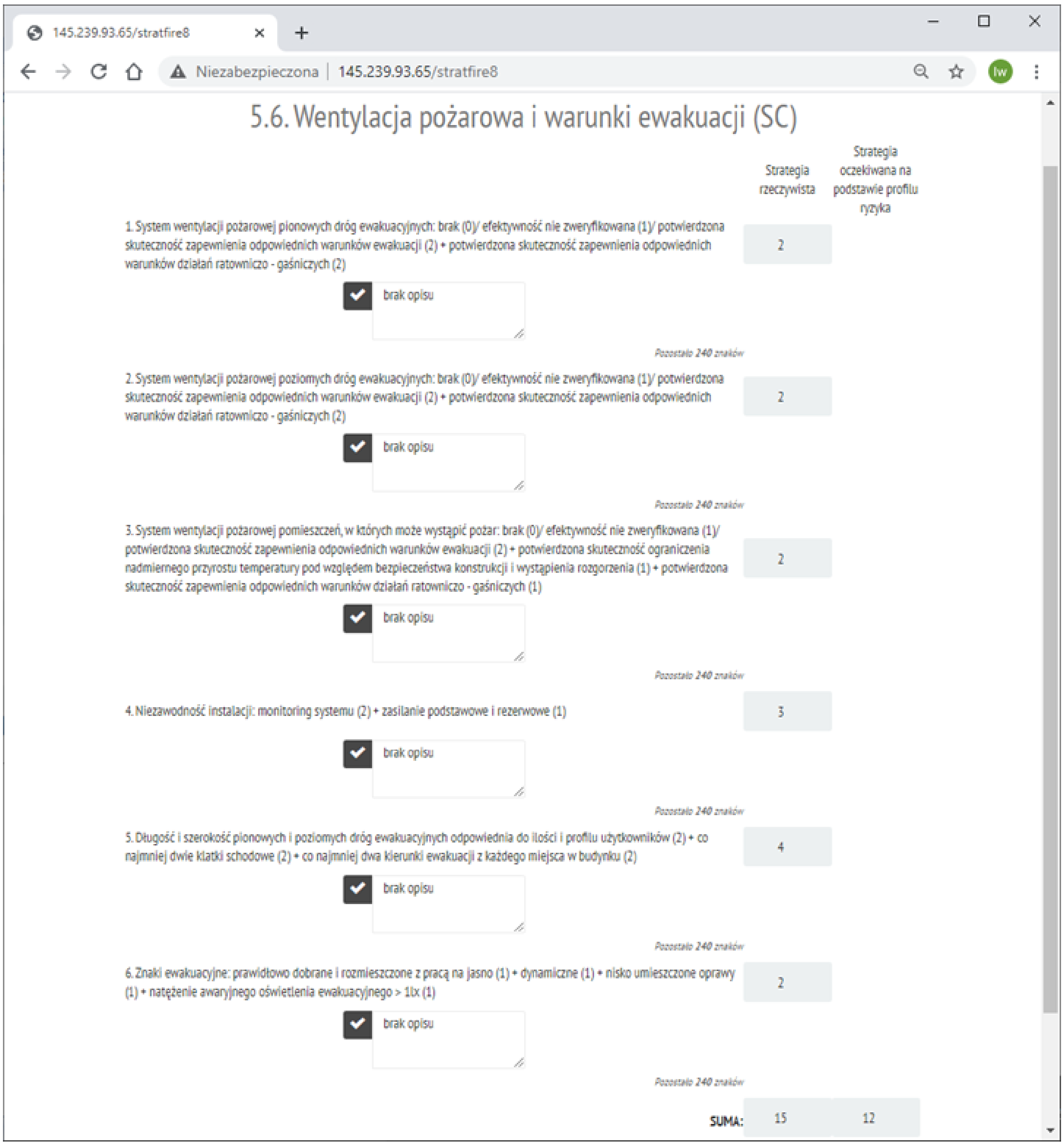


5.5. Systemy gaśnicze (SUP)

	Strategia rzeczywista	Strategia oczekiwana na podstawie profilu ryzyka
1. Samoczynne urządzenia gaśnicze w każdym miejscu potencjalnego wystąpienia pożaru (3) / częściowe wyposażenie budynku w SUG (2)/ brak SUG (0) + SUG dostosowany do ochrony osób (1)?	2	
☑ brak opisu Pozostało 240 znaków		
2. Indeks reakcji systemu gaśniczego (RTI): standard B (>200, ≤ 300) (1)/ standard A (>80, ≤ 200) (2)/ specjalny (>50, ≤ 80) (3) / szybki (≤ 50) (4)?	2	
☑ brak opisu Pozostało 240 znaków		
3. Przewidywany czas reakcji systemu gaśniczego (s): >300 (0)/ (>200, ≤ 300) (1) / (>150, ≤ 200) (2)/ (>120, ≤ 150) (3) / (≤ 120) (4)?	2	
☑ brak opisu Pozostało 240 znaków		
4. Zastosowano urządzenia gaśnicze odpowiednie do wysokości składowania (2) + rodzaju materiału palnego (2) + sposobu składowania materiału (2)	4	
☑ brak opisu Pozostało 240 znaków		
5. Niezawodność instalacji: monitoring systemu (1), niezależne zasilanie i praca SUG (1) + podwójne zasilanie wodne (1) + ZKA z układem obejść lub podwójne (1)	3	
☑ brak opisu Pozostało 240 znaków		
6. Hydranty wewnętrzne obejmujące zasięgiem cały obiekt T(1) /N (0) + gaśnice o skuteczności gaśniczej min.8A lub 34B na każde 300 m2 (1) / na każde 100 m2 (2)	3	
☑ brak opisu Pozostało 240 znaków		
SUMA:	16	18

Fig. E11. Fire suppression.

Smoke control and evacuation [SC]

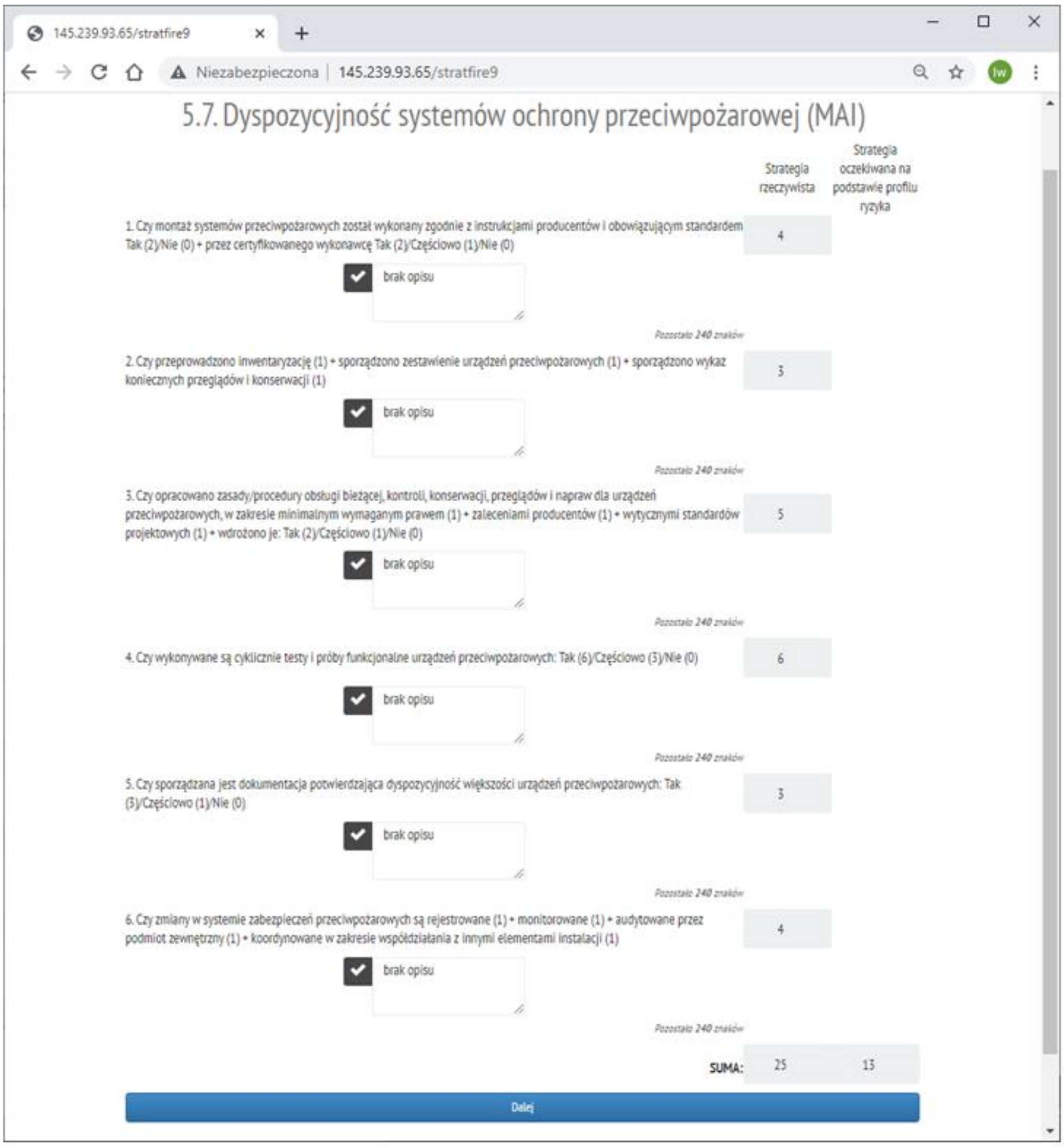


5.6. Wentylacja pożarowa i warunki ewakuacji (SC)

	Strategia rzeczywista	Strategia oczekiwana na podstawie profilu ryzyka
1. System wentylacji pożarowej pionowych dróg ewakuacyjnych: brak (0)/ efektywność nie zweryfikowana (1)/ potwierdzona skuteczność zapewnienia odpowiednich warunków ewakuacji (2) + potwierdzona skuteczność zapewnienia odpowiednich warunków działań ratowniczo - gaśniczych (2) ☑ brak opisu *Pozostało 240 znaków*	2	
2. System wentylacji pożarowej poziomych dróg ewakuacyjnych: brak (0)/ efektywność nie zweryfikowana (1)/ potwierdzona skuteczność zapewnienia odpowiednich warunków ewakuacji (2) + potwierdzona skuteczność zapewnienia odpowiednich warunków działań ratowniczo - gaśniczych (2) ☑ brak opisu *Pozostało 240 znaków*	2	
3. System wentylacji pożarowej pomieszczeń, w których może wystąpić pożar: brak (0)/ efektywność nie zweryfikowana (1)/ potwierdzona skuteczność zapewnienia odpowiednich warunków ewakuacji (2) + potwierdzona skuteczność ograniczenia nadmiernego przyrostu temperatury pod względem bezpieczeństwa konstrukcji i wystąpienia rozgorzenia (1) + potwierdzona skuteczność zapewnienia odpowiednich warunków działań ratowniczo - gaśniczych (1) ☑ brak opisu *Pozostało 240 znaków*	2	
4. Niezawodność instalacji: monitoring systemu (2) + zasilanie podstawowe i rezerwowe (1) ☑ brak opisu *Pozostało 240 znaków*	3	
5. Długość i szerokość pionowych i poziomych dróg ewakuacyjnych odpowiednia do ilości i profilu użytkowników (2) + co najmniej dwie klatki schodowe (2) + co najmniej dwa kierunki ewakuacji z każdego miejsca w budynku (2) ☑ brak opisu *Pozostało 240 znaków*	4	
6. Znaki ewakuacyjne: prawidłowo dobrane i rozmieszczone z pracą na jasno (1) + dynamiczne (1) + nisko umieszczone oprawy (1) + natężenie awaryjnego oświetlenia ewakuacyjnego > 1lx (1) ☑ brak opisu *Pozostało 240 znaków*	2	
SUMA:	15	12

Fig. E12. Smoke control and evacuation.

Maintenance of fire precautions and systems [MAI]

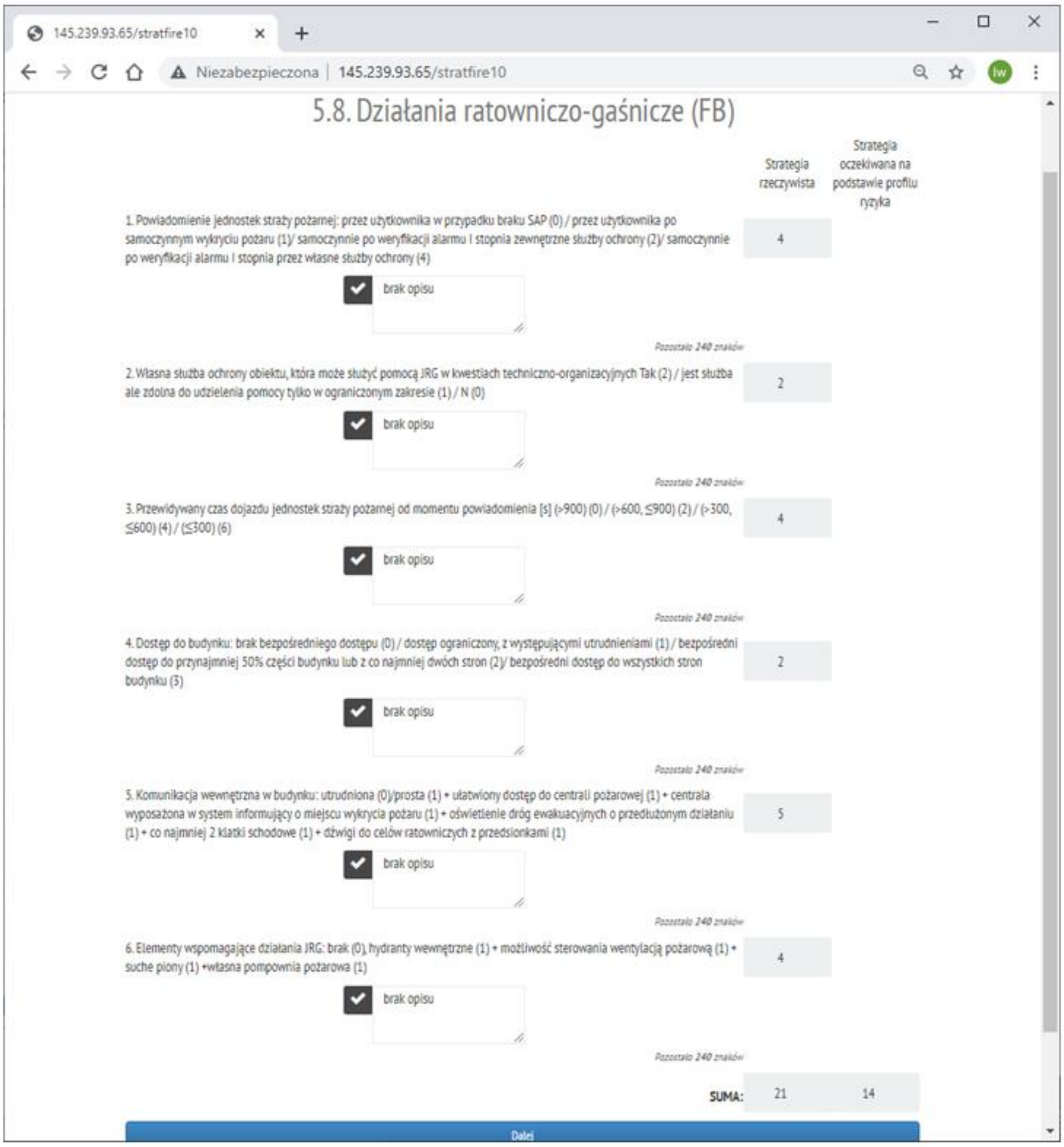


5.7. Dyspozycyjność systemów ochrony przeciwpożarowej (MAI)

	Strategia rzeczywista	Strategia oczekiwana na podstawie profilu ryzyka
1. Czy montaż systemów przeciwpożarowych został wykonany zgodnie z instrukcjami producentów i obowiązującym standardem Tak (2)/Nie (0) + przez certyfikowanego wykonawcę Tak (2)/Częściowo (1)/Nie (0) ☑ brak opisu *Pozostało 240 znaków*	4	
2. Czy przeprowadzono inwentaryzację (1) + sporządzono zestawienie urządzeń przeciwpożarowych (1) + sporządzono wykaz koniecznych przeglądów i konserwacji (1) ☑ brak opisu *Pozostało 240 znaków*	3	
3. Czy opracowano zasady/procedury obsługi bieżącej, kontroli, konserwacji, przeglądów i napraw dla urządzeń przeciwpożarowych, w zakresie minimalnym wymaganym prawem (1) + zaleceniami producentów (1) + wytycznymi standardów projektowych (1) + wdrożono je: Tak (2)/Częściowo (1)/Nie (0) ☑ brak opisu *Pozostało 240 znaków*	5	
4. Czy wykonywane są cyklicznie testy i próby funkcjonalne urządzeń przeciwpożarowych: Tak (6)/Częściowo (3)/Nie (0) ☑ brak opisu *Pozostało 240 znaków*	6	
5. Czy sporządzana jest dokumentacja potwierdzająca dyspozycyjność większości urządzeń przeciwpożarowych: Tak (3)/Częściowo (1)/Nie (0) ☑ brak opisu *Pozostało 240 znaków*	3	
6. Czy zmiany w systemie zabezpieczeń przeciwpożarowych są rejestrowane (1) + monitorowane (1) + audytowane przez podmiot zewnętrzny (1) + koordynowane w zakresie współdziałania z innymi elementami instalacji (1) ☑ brak opisu *Pozostało 240 znaków*	4	
SUMA:	25	13

Fig. E13. Maintenance of fire precautions and systems.

Fire services intervention [FB]



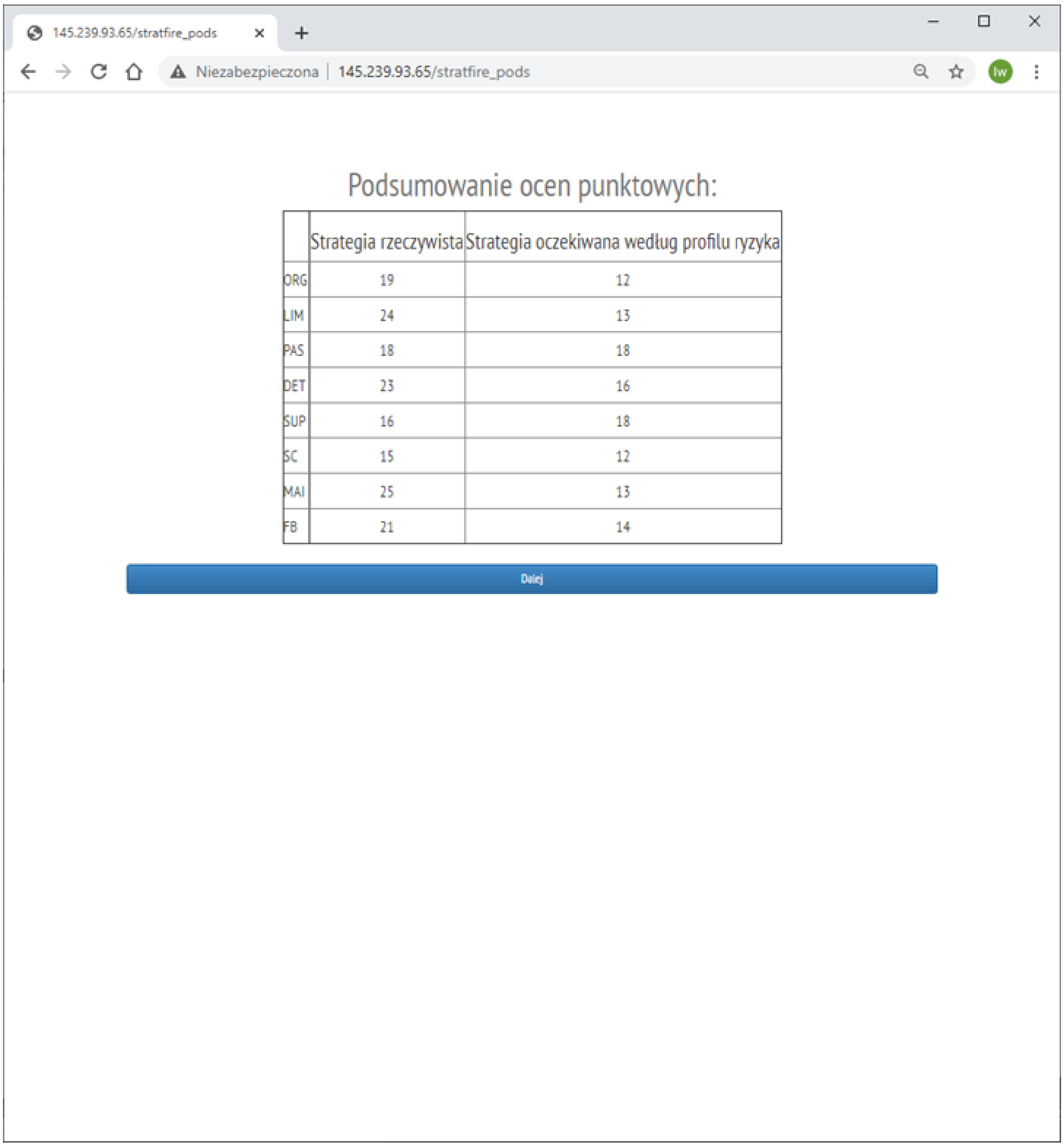
5.8. Działania ratowniczo-gaśnicze (FB)

	Strategia rzeczywista	Strategia oczekiwana na podstawie profilu ryzyka
1. Powiadomienie jednostek straży pożarnej: przez użytkownika w przypadku braku SAP (0) / przez użytkownika po samoczynnym wykryciu pożaru (1)/ samoczynnie po weryfikacji alarmu I stopnia zewnętrzne służby ochrony (2)/ samoczynnie po weryfikacji alarmu I stopnia przez własne służby ochrony (4)	4	
☑ brak opisu Pozostało 240 znaków		
2. Własna służba ochrony obiektu, która może służyć pomocą JRG w kwestiach techniczno-organizacyjnych Tak (2) / jest służba ale zdolna do udzielenia pomocy tylko w ograniczonym zakresie (1) / N (0)	2	
☑ brak opisu Pozostało 240 znaków		
3. Przewidywany czas dojazdu jednostek straży pożarnej od momentu powiadomienia [s] (>900) (0) / (>600, ≤900) (2) / (>300, ≤600) (4) / (≤300) (6)	4	
☑ brak opisu Pozostało 240 znaków		
4. Dostęp do budynku: brak bezpośredniego dostępu (0) / dostęp ograniczony, z występującymi utrudnieniami (1) / bezpośredni dostęp do przynajmniej 50% części budynku lub z co najmniej dwóch stron (2)/ bezpośredni dostęp do wszystkich stron budynku (3)	2	
☑ brak opisu Pozostało 240 znaków		
5. Komunikacja wewnętrzna w budynku: utrudniona (0)/prosta (1) + ułatwiony dostęp do centrali pożarowej (1) + centrala wyposażona w system informujący o miejscu wykrycia pożaru (1) + oświetlenie dróg ewakuacyjnych o przedłużonym działaniu (1) + co najmniej 2 klatki schodowe (1) + dźwigi do celów ratowniczych z przedsionkami (1)	5	
☑ brak opisu Pozostało 240 znaków		
6. Elementy wspomagające działania JRG: brak (0), hydranty wewnętrzne (1) + możliwość sterowania wentylacją pożarową (1) + suche piony (1) +własna pompownia pożarowa (1)	4	
☑ brak opisu Pozostało 240 znaków		
SUMA:	21	14

Fig. E14. Fire services intervention.

E.3. Sum of fire strategies evaluation

Once the Actual Fire Strategy is fully scored, the final scoring results for both Actual and Baseline Strategies are presented in the table below (*Fig. E15*).



Podsumowanie ocen punktowych:

	Strategia rzeczywista	Strategia oczekiwana według profilu ryzyka
ORG	19	12
LIM	24	13
PAS	18	18
DET	23	16
SUP	16	18
SC	15	12
MAI	25	13
FB	21	14

Fig. E15. Sum of fire strategies evaluation.

E.4. Fire strategy value grid

Based on the sums presented in the table Fig. E15 the Software automatically creates the fire strategy value grid based upon a semi-quantitative methodology (*Fig. E16*).

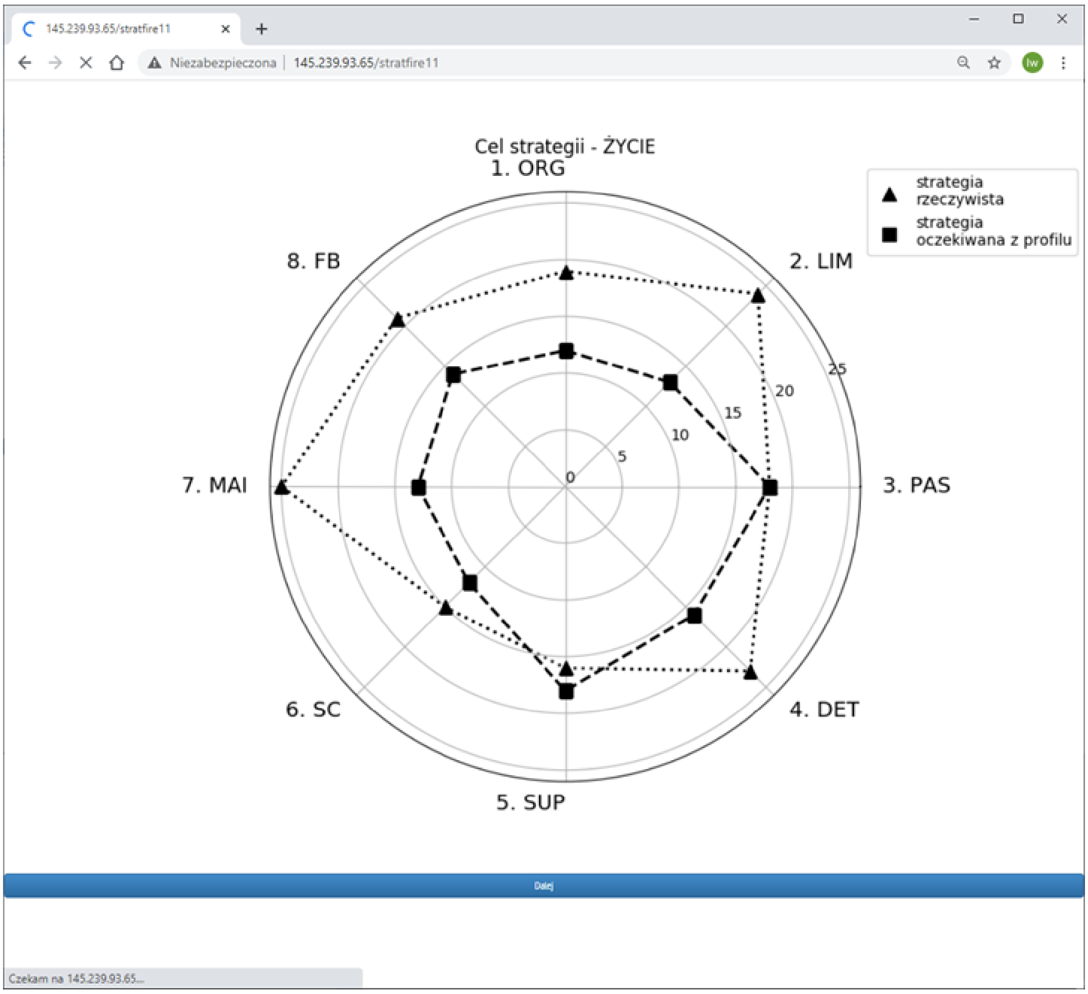
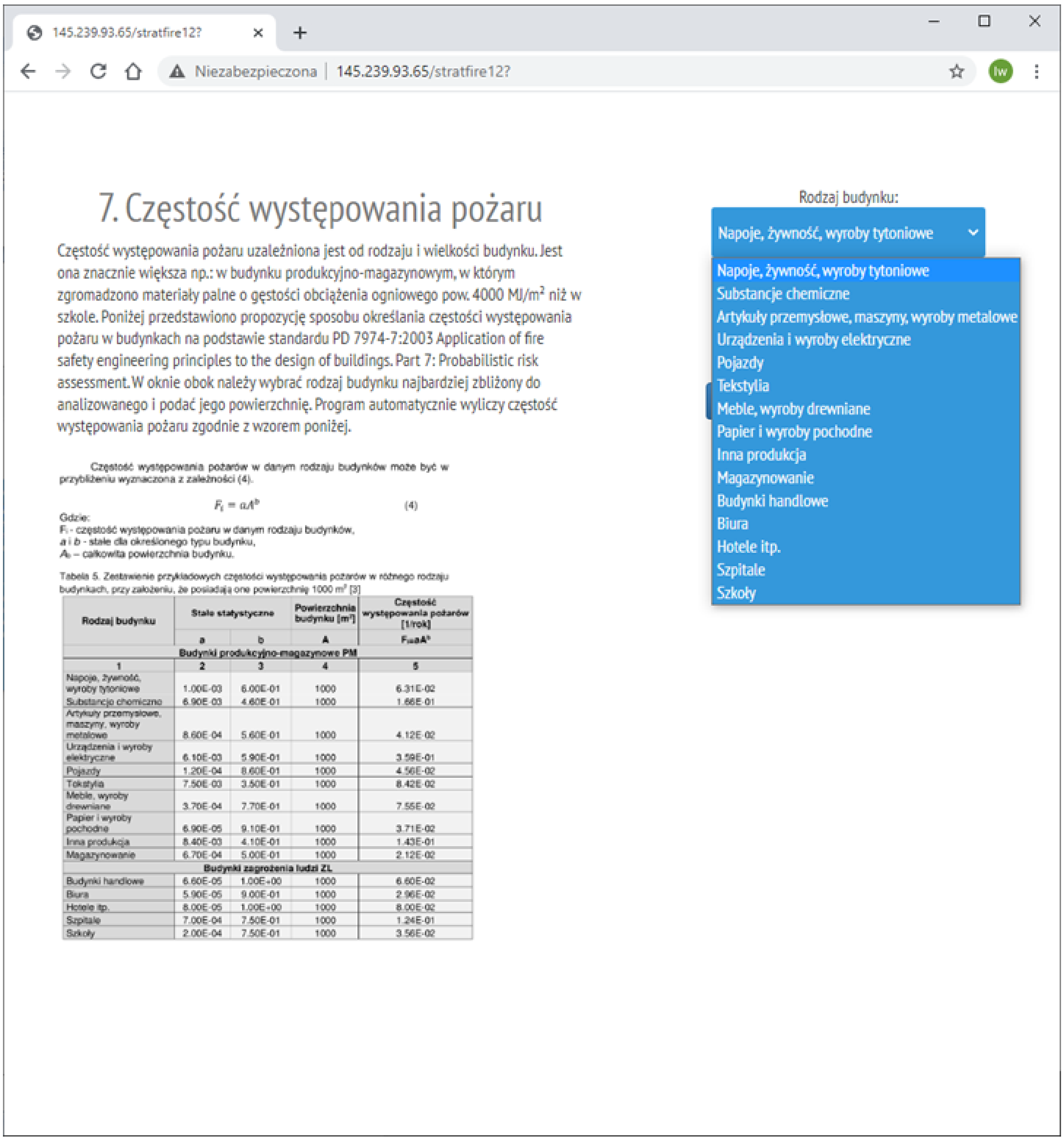


Fig. E16. Fire strategy value grid.

E.5. Frequency of ignition

The Software uses *Frequency of Ignition* data taken from the British Standard PD 7974-7 (*see Chapter 5.3.4*), where the frequency coefficients can be chosen on the base of the building type. Once the actual building profile is defined, the Frequency of Ignition value is calculated automatically (*Fig. E17*).



7. Częstość występowania pożaru

Częstość występowania pożaru uzależniona jest od rodzaju i wielkości budynku. Jest ona znacznie większa np.: w budynku produkcyjno-magazynowym, w którym zgromadzono materiały palne o gęstości obciążenia ogniowego pow. 4000 MJ/m² niż w szkole. Poniżej przedstawiono propozycję sposobu określania częstości występowania pożaru w budynkach na podstawie standardu PD 7974-7:2003 Application of fire safety engineering principles to the design of buildings. Part 7: Probabilistic risk assessment. W oknie obok należy wybrać rodzaj budynku najbardziej zbliżony do analizowanego i podać jego powierzchnię. Program automatycznie wyliczy częstość występowania pożaru zgodnie z wzorem poniżej.

Rodzaj budynku: Napoje, żywność, wyroby tytoniowe

Częstość występowania pożarów w danym rodzaju budynków może być w przybliżeniu wyznaczona z zależności (4).

$$F_i = aA^b \qquad (4)$$

Gdzie:
F_i - częstość występowania pożaru w danym rodzaju budynków,
a i b - stałe dla określonego typu budynku,
A_b – całkowita powierzchnia budynku.

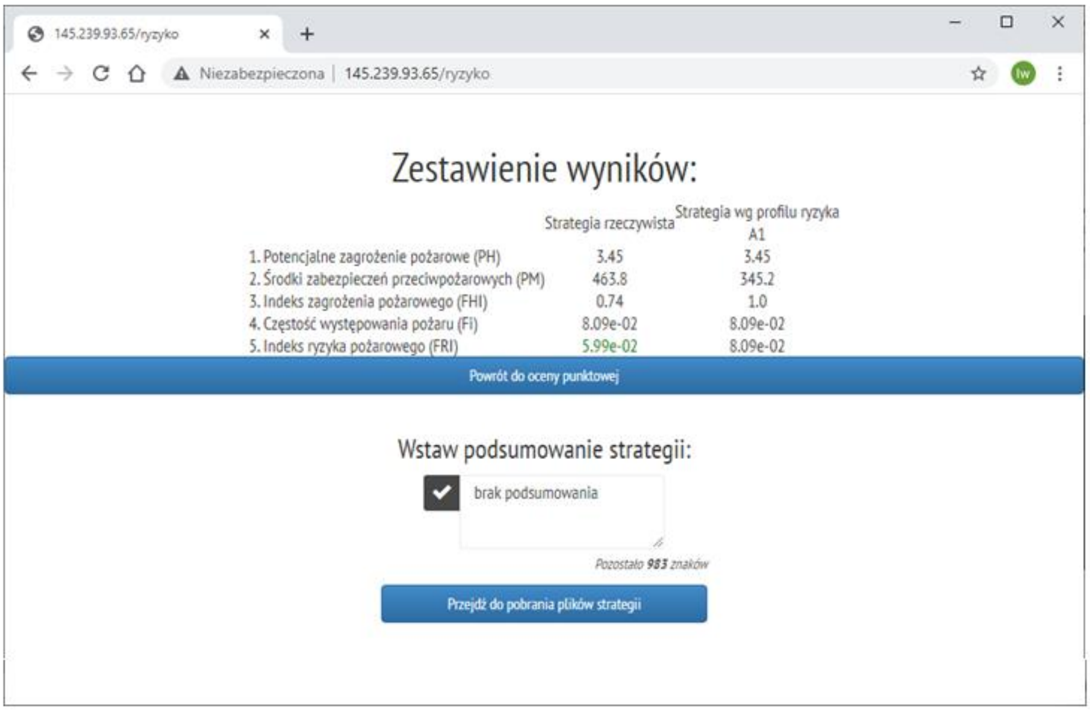
Tabela 5. Zestawienie przykładowych częstości występowania pożarów w różnego rodzaju budynkach, przy założeniu, że posiadają one powierzchnię 1000 m² [3]

Rodzaj budynku	Stałe statystyczne		Powierzchnia budynku [m²]	Częstość występowania pożarów [1/rok]
	a	b	A	$F_i=aA^b$
Budynki produkcyjno-magazynowe PM				
1	2	3	4	5
Napoje, żywność, wyroby tytoniowe	1.00E-03	6.00E-01	1000	6.31E-02
Substancje chemiczne	6.90E-03	4.60E-01	1000	1.66E-01
Artykuły przemysłowe, maszyny, wyroby metalowe	8.60E-04	5.60E-01	1000	4.12E-02
Urządzenia i wyroby elektryczne	6.10E-03	5.90E-01	1000	3.59E-01
Pojazdy	1.20E-04	8.60E-01	1000	4.56E-02
Tekstylia	7.50E-03	3.50E-01	1000	8.42E-02
Meble, wyroby drewniane	3.70E-04	7.70E-01	1000	7.55E-02
Papier i wyroby pochodne	6.90E-05	9.10E-01	1000	3.71E-02
Inna produkcja	8.40E-03	4.10E-01	1000	1.43E-01
Magazynowanie	6.70E-04	5.00E-01	1000	2.12E-02
Budynki zagrożenia ludzi ZL				
Budynki handlowe	6.60E-05	1.00E+00	1000	6.60E-02
Biura	5.90E-05	9.00E-01	1000	2.96E-02
Hotele itp.	8.00E-05	1.00E+00	1000	8.00E-02
Szpitale	7.00E-04	7.50E-01	1000	1.24E-01
Szkoły	2.00E-04	7.50E-01	1000	3.56E-02

Fig. E17. Frequency of ignition.

E.6. Fire Strategy Risk Index calculation

Finally, the Fire Strategy Risk Index is calculated automatically. The final application window also presents the results of the supported parameters used for the FRSI (shown as FRI in the Software) calculation, such as Potential Hazards (PH), Protective Measures (PM), Fire Hazard Indices (FHI) and Frequency of ignition (Fi) for the both baseline and actual fire strategies (*Fig. E18*). When the FSRI is acceptable (*see Chapters 5.3 and 5.4*) the value is presented in green. If the value is too large, it is shown in red. It is then possible to go back to the scoring tables and correct the actual strategy. In this place the User can add their own comments and summarise the evaluation, as well as download a file as a record.



Zestawienie wyników:

	Strategia rzeczywista	Strategia wg profilu ryzyka A1
1. Potencjalne zagrożenie pożarowe (PH)	3.45	3.45
2. Środki zabezpieczeń przeciwpożarowych (PM)	463.8	345.2
3. Indeks zagrożenia pożarowego (FHI)	0.74	1.0
4. Częstość występowania pożaru (Fi)	8.09e-02	8.09e-02
5. Indeks ryzyka pożarowego (FRI)	5.99e-02	8.09e-02

Wstaw podsumowanie strategii:

☑ brak podsumowania

Pozostało ***983*** *znaków*

Fig. E18. Fire Strategy Risk Index calculation.

E.7. Data files

The Software generates data files in PDF, ready for printing, and in a XML format, for subsequent use in the software later (*see Chapter E.1.*). Fig. E19 presents the final widow, where the files can be uploaded.

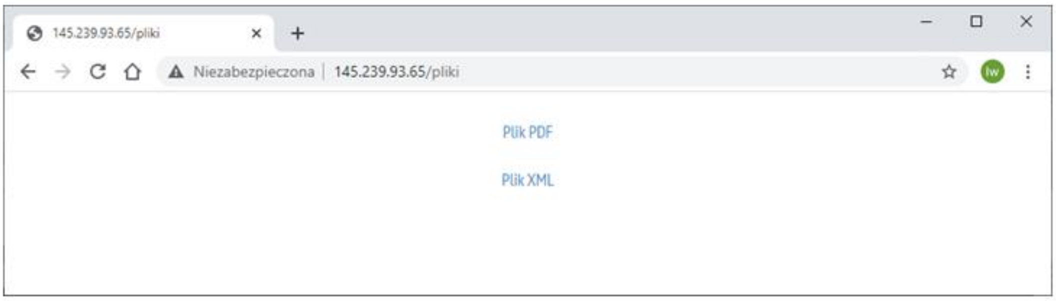


Fig. E19. Fire strategy report data files.