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A Historical Review of Fire Engineering Practice and Advances in China

Mingchun Luo*

Department of Building Environment & Energy Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, PR China

Xiaoqian Sun

Arup International Consultants Shanghai Co Ltd, Shanghai, PR China

Sicheng Li

Department of Fire Engineering, China People's Police University, Hebei, PR China

* Corresponding to mingchun.luo@polyu.edu.hk

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Abstract

In the past three decades, fire engineering has experienced fast development worldwide. Fire regulations for building industry were moved from prescriptive description to performance-based specification. This trend started in the UK in the 1980s and spread to other western countries.

Hong Kong closely followed the UK development and adopted the approach of performance-based design (PBD) for the Hong Kong International Airport and MTR stations in the early 1990s. The Government of Hong Kong SAR formally recognised the PBD approach in the prescriptive codes of practice in the mid-1990s and developed the performance-based code (PBC) in the 2000s. This PBC was promulgated in 2011.

The evolution in fire engineering impacted the fire community in Mainland China. The State Key Laboratory of Fire Science (SKLFS) was established in University of Science and Technology of China (USTC) in 1991. Then fire science and fire engineering stepped into the fast development track. The building industry in Mainland China started to adopt the PBD approach in the early 2000s for the significant developments including large airport terminals, railway and metro stations, super high-rise buildings, and mega commercial centres. However, a structured PBC system is not available within the regulatory framework to date. Adoption of PBD approach is slowing down in recent years.

This paper presents a review of fire engineering development in Hong Kong and Mainland China. The review focuses on the development of the PBC in Hong Kong, and the PBD approach and fire research in Mainland China in the past 30 years.

Keywords: Fire engineering, Performance-based design (PBD), Performance-based code (PBC), China fire regulation.

1. Introduction

1.1 Fire Engineering and Performance-based Design (PBD)

Fire engineering covers a wide range of levels of knowledge and competence. The terminology of fire engineering is also known as fire safety engineering and fire protection engineering in different regions [1]. The definition of fire engineering by the Institution of Fire Engineers (IFE) states: "Fire engineering is the application of scientific and engineering principles, rules (codes), and expert judgement, based on an understanding of the phenomena and effects of fire and of the reaction and behaviour of people to fire, to protect people, property and the environment from the destructive effects of fire". [2] In practice, the design process of a project is called "fire engineering/performance-based approach" or simply "performance-based design (PBD)" if the design cannot fully comply with the codes or prescriptive requirements. From IFE's definition, fire engineering covers both the process of code compliance design and PBD. PBD is a small but important part of the fire engineering field.

In the past 30 years, PBD has emerged and applied for many special buildings to resolve some specific difficulties in practice. Many of the PBD solutions have been regulated and become the clauses of the regulations and codes of practice. Figure 1 shows the relationship among fire science research, fire regulations/codes of practice, fire safety design, and PBD. Fire research results, new concepts, and new technologies can be adopted in practice before they are regulated by legislation body. The process of PBD provides a channel for the application of new research results, engineering principles, and expert judgement to protect people and property from fire.

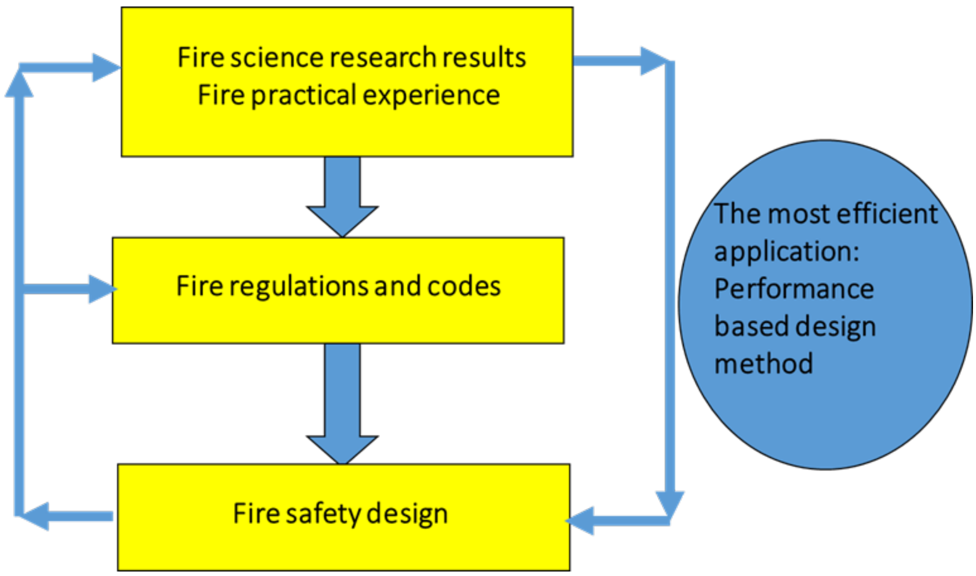

Figure 1. Fire engineering: relationship of research, regulation and practical design.

In Hong Kong Special Administrative Region (SAR) and Mainland China, fire engineering has different meanings. In general, fire engineering approach implies PBD. Buildings Department of Hong Kong SAR issued the Code of Practice for Fire Safety in Buildings in 2011 [3]. Part G of the Code entitled “Guideline on Fire Engineering” provides guidelines on PBD for fire safety or fire engineering approach.

In Mainland China, fire engineering (消防工程) focuses more on fire system installation, inspection, and maintenance. In terms of fire safety design using new methods instead of strictly complying with the prescriptive requirements, a terminology 性能化设计 is used, which means PBD. Fire engineering in construction is related to the installation and maintenance of fire systems and equipment. Fire engineering in consultancy and design institutes means PBD [4].

This review focuses on the development of fire codes, PBD and fire research in China, including Mainland and Hong Kong in the past 30 years.

Compared with the UK, Australia, and the USA, the development of fire engineering and performance-based code (PBC) system in Mainland China lagged behind during the 1990s. Hence the later catch-up in this field was largely influenced by the early progress of the western countries. Due to the demand of innovative design for those projects for Beijing Olympic 2008, Shanghai Expo 2010, and fast economic boost in the 2000s, PBD or fire engineering approach for fire safety of buildings was widely adopted all over Mainland China. However, all the PBD applications were on a case-by-case basis. The national-wide systematic approach of PBD with PBC was not established except that the Shanghai local government developed the smoke code with engineering calculations for the design of smoke control systems [5].

Before 1997, the Hong Kong building code system was deeply influenced by the UK regulations and standards. Application of PBD, or so-called fire engineering approach was started in the early 1990s concurrently with the shift of the UK building regulations from detailed prescription to the performance-based approach. The very early projects that adopted PBD were the Hong Kong International Airport and the metro stations. Hong Kong has been the window of Mainland China to the western world. After 1997, the connection between Hong Kong SAR and Mainland has become stronger. The knowledge and experiences gained in fire engineering and PBD for real projects in Hong Kong were quickly brought into Mainland China.

1.2 International Development of Performance-based Code (PBC)

PBCs allow for greater economic development with the market rather than the government by determining the most efficient way to meet the set of standards. PBCs set up objectives clearly, which lead to more transparent and open regulation. Health, safety legislation generally, and fire legislation in particular, have followed this trend internationally. Over the last three decades, the general development of performance-based rather than prescriptive fire safety codes has been undertaken. Advances in technology, in our understanding of design and analysis tools [6] have led to changes in the way the fire engineering profession approaches fire safety. Around the globe, some countries, including New Zealand, Australia, Sweden, the UK, Japan, the USA, and Singapore, have moved to performance-based regulations [7,8] from the 1990s. The move towards PBCs recognizes that a large number of buildings have actually been designed following PBCs.

1.2.1 UK development

It was stated that the UK's fire legislation is disaster-led, which dates back to the Great Fire of London in 1666, five-sixths of the city was destroyed. As a result, a range of construction measures were developed to prevent wholesale fire spread between buildings. After the Great Fire of London, the first effective regulations specified minimum separation distances between buildings on main streets, as well as placing restrictions on the materials which could be used for construction. Over the following centuries, other control regulations were developed and continued to focus on the prevention of fire spread within and between buildings by containing the fire or by physical separation. The requirements were expressed in a very prescriptive manner and in considerable detail [9].

Up to 1985, the building regulations were very prescriptive, but technical specifications were developed in British Standards (BS). The regulation calls the BS for application. After 1985, the UK adopted a different formal approach for regulating fire safety. The regulations simplified the specification of the requirements. Fewer details were given in the regulations, and the functional requirements were provided for the fire safety provisions [10]. The regulations became performance-based documents. At the same time, the approved documents to the building regulations [11] were developed. The Approved Document B provided the prescriptive requirements and permitted an engineering approach to fire safety system design. At this early stage, fire engineers started to adopt PBD in practice [12,13,14].

In the 1990s and 2000s, new BS Standards were developed by the British Standards Institution (BSI) in relation to PBD. The Approved Document B was continuously updated and extended the practice of calling up the details of the BS Standards. The Chartered Institute of Building Services Engineers (CIBSE) published the CIBSE Guide E for fire engineering in 1996 [15]. The BSI issued a draft for development for fire safety engineering in buildings in 1998 [16]. The PBD approach was widely adopted in practice [17,18,19] since then. The process of the PBD approach involved the whole community of fire engineering, including the regulator, Building Control Officers, Fire Services, and specialist Consultants.

Currently, there are a number of fire legislation and prescriptive guidance documents in force in the UK. The objective of the fire safety provisions in the England and Wales Building Regulations is focused on the safety of people in and around buildings.

The policy line on property protection has been that building owners should be allowed to decide for themselves the strategy to adopt. It is recognised that there are alternatives to taking physical fire precautions. Property owners can adopt financial strategies to offset the loss, e.g. embracing the concept of insurance as a response to the risk of fire affecting properties, or take steps to replicate facilities in separate locations, etc.

1.2.2 Development in Australia

Under the Australian Federal constitution, the regulation of development and building is a responsibility of individual State and Territory governments. Accordingly, as Australia has six States and two Territories, it has eight individual building control systems. In regard to the scope of technical building regulations, there has been a high degree of uniformity in content, hence arising from the development of a national model building code.

In the 1980s, Warren Centre, the University of Sydney, conducted a systematic research programme, namely, Fire Safety and Engineering Project [20]. The research had revealed the need to identify cost-effective solutions for safety design and commenced the investigation on performance-based approaches to design using risk assessment models [21,22]. In the early 1990s, the Building Code of Australia (BCA) was produced and by the end of 1992, this prescriptive document had been adopted throughout Australia as the technical basis of States' and two Territories' respective systems.

In 1994 the Australian Building Codes Board (ABCB) was formed, and this organisation converted the 1990 BCA into a performance-based document that has since become the national basis of technical building control systems. The fundamental goals of the BCA are to enable the achievement and maintenance of acceptable standards of structural sufficiency, safety (including safety from fire), health and amenity for the benefit of the community. Comprehensive property protection (including building contents) is not a fundamental aim of the document; however, a degree of property protection is usually achieved through compliance with the provisions related to the requirements for fire safety and structural stability.

In 1996, ABCB issued the PBC [23]. The performance requirements were introduced in parallel to the prescriptive requirements, so-called the Deemed-to-Satisfy provisions. The PBC provided two process pathways that can be followed to develop building solutions:

<u>Deemed-to-Satisfy Provisions</u>: The Deemed-to-Satisfy Provisions contained in the BCA, including examples of materials, components, design factors and construction methods which, if complied with, are conclusive proof that the Performance Requirements have been satisfied.

<u>Alternative Solutions:</u> Alternative Solutions are proposals that differ in whole or in part from the Deemed-to-Satisfy Provisions, including materials, components, systems, design factors and construction methods that can be demonstrated to:

(a) comply with the relevant Performance Requirements; or

(b) at least perform in an equivalent manner to the Deemed-to-Satisfy Provisions.

In either case, the relevant authority, as determined by the building regulatory legislation must be satisfied that the proposal:

(a) complies with the Deemed-to-Satisfy Provisions; or

(b) where an Alternative Solution is used:

(i) complies with the Performance Requirements; or

(ii) at least performs in an equivalent manner to the Deemed-to-Satisfy Provisions.

In connection to the development of PBC, Fire Code Reform Centre, Australia produced "Fire Engineering Guidelines" in 1996 and recommended the methods of assessment when alternative solutions were proposed during the design process [24]. The ABCB updated the guideline to the 2nd edition, entitled "Fire Safety Engineering Guidelines" in 2001 [25].

In collaboration with the National Research Council of Canada (NRC), the International Code Council (ICC) United States of America, and the Department of Building and Housing, New Zealand (DBH), the ABCB published the 3rd edition of the guideline "International Fire Engineering Guidelines" [26] in 2005. The Guidelines embraced the worldwide best practice and drew upon previous work and parallel work from many groups around the world. It was developed for use in the fire engineering design and approval of buildings.

In 2011, the PBC for fire safety design and the BCA were integrated into the National Construction Code Series (NCC), which incorporated all on-site construction requirements [27].

1.2.3 Development in the USA

Historically, the USA has predominately prescriptive based building control regimes implemented throughout its numerous building control jurisdictions. In the 1990s there was a move toward the development and adoption of performance-based building codes.

A significant development in this move was the formation of the International Code Council (ICC) in 1994. The ICC is an umbrella charged with administering the development and maintenance of the International Codes and coordinating related supporting activities. The mission of the ICC is to promulgate a comprehensive and compatible regulatory system for the built environment, through consistent performance-based regulations that are effective, efficient and meet government, industry and public needs [28,29]. The ICC developed and made available a series of the International Codes, including the ICC Performance Code for Buildings and Facilities (ICCPC).

At the same time, the National Fire Protection Association (NFPA) formed a committee and developed a PBC – the Building Construction and Safety Code (NFPA 5000). By the early 2000s, both the ICCPC Code and NFPA 5000 were available for the construction industry and fire safety design. However, adoption of PBD for fire safety has been slow in the USA [30].

These performance-based codes are to promote innovative, flexible and responsive solutions that optimise the expenditure and consumption of resources while preserving social and economic value. The codes provide a framework to establish minimum levels of safety performance when buildings or facilities are subjected to events such as fires and natural hazards. The minimum performance levels established in the document are based on the types of risks associated with the use of the building, the intended function of the building, and the importance of the building or facility to a community.

For fire safety, the code established the requirements necessary to provide an acceptable level of life safety and property protection from the hazards of fire, explosion and dangerous conditions. The requirements vary with the use and occupancy of buildings, structures, and facilities, and are applicable to the prevention, control, and mitigation of fire, life safety, and property hazards arising from the use and occupancy.

2. Development in Hong Kong SAR

For fire safety, there are two codes of practice in Hong Kong SAR, namely: i) Code of Practice for Fire Safety in Buildings administered by Buildings Department, and ii) Code of Practice for Minimum Fire Service Installations maintained by Fire Services Department. The former prescribes the provisions of passive fire protection and the latter specifies the requirements of active fire provisions in buildings.

Fire safety requirements of the codes of practice followed the UK system and were very prescriptive before the 1990s. The fire engineering approach or PBD was introduced in Hong Kong for large and complicated infrastructure projects in the early 1990s. The prescriptive codes started to recognise PBD as an alternative approach. In the early 2000s, the Buildings Department of Hong Kong SAR commenced the development of PBC and officially issued the code in 2011. Hong Kong has been formally shifted to the PBC system since then.

2.1 Prescriptive Approach

The legislative requirements for the provision of fire safety measures in buildings are laid down in various ordinances, subsidiary regulations and codes of practice published by the Government of Hong Kong SAR. As a general local practice, the provisions of fire safety measures for new buildings are categorised into four main areas:

- Means of Escape (MOE).
- Means of Access for firefighting and rescue (MOA).
- Fire Resistance Construction (FRC).
- Fire Services Installation (FSI).

The standards and requirements of fire safety provisions in buildings are reviewed and updated from time to time to suit the change of society and building innovations. The first documents stipulated the fire safety requirements through various ordinances, regulations and codes of practice are as follows:

<u>Means of Escape (MOE)</u>

- Buildings Ordinance enacted in 1935.
- Building (Planning) Regulations enacted in 1956.
- Code of Practice on Provision of Means of Escape in Case of Fire and Allied requirements issued in 1959 and revised in 1996 (MOE Code) [31].

<u>Means of Access for Firefighting and Rescue (MOA)</u>

- Code of Practice for Minimum Fire Service Installations and Equipment issued in 1964.
- Building (Planning) Regulations 41A, 41B, 41C enacted in 1992.
- Code of Practice on Provision of Means of Access for Firefighting and Rescue issued 1989 and revised in 1995 and 2004 (MOA Code) [32].

Fire Resistance Construction (FRC)

- Buildings Ordinance enacted in 1935.
- Building (Construction) Regulations enacted in 1956 and revised in 1975.
- Building (Lifts) Regulations enacted in 1960.
- Code of Practice for Fire Resisting Construction issued in 1989 and revised in 1996 (FRC Code) [33].

The codes of practice for MOE, MOA, and FRC have been administered by Buildings Department Hong Kong SAR.

Fire Services Installation (FSI):

- Code of Practice for Minimum Fire Service Installations and Equipment issued in 1964 (FSI Code). The code has been administered by Fire Services Department Hong Kong SAR and continuously updated along with the development of new technology. The latest 12th version was issued in 2012 [34].

The Buildings Ordinance (BO) is to ensure that minimum safety and health standards are maintained in the planning, design and construction of buildings. The BO regulates the registration systems for the key personnel in building construction work, including Authorized Person (AP), Registered Structural Engineers (RSE) and Registered (General Building or Specialist) Contractors (RC). The Building (Administration) Regulations governs the procedure for building plan submission, approval and application for consent to commence building/street works, as well as the duties of AP, RSE and RC throughout the submission and construction process. The Building (Planning) Regulations specifies the basic requirements in building planning for amenity and safety purposes, in which fire safety measures include the provision of staircases, fire escapes and access for firefighting and rescue. The Building (Construction) Regulations specifies the requirements on building construction/structural design and construction materials, which include the general requirements of fire-resisting construction such as to inhibit fire spread and maintain stability.

In practice, for day-to-day works of fire safety in the construction industry, the codes of practice are referred for design, approval, and construction. Before the 1990s, these codes were prescriptive in nature. Most clauses originated from practices in the UK when Hong Kong was under the British administration before 1997 [35]. As mentioned earlier, the UK regulation system was moved to a performance base in the later 1980s [10]. Fire engineering approach or PBD was adopted for the design of Hong Kong International Airport [36] and metro stations in the early 1990s, and then extended for the design of commercial development in the private sector in the middle of the 1990s. Both Buildings Department and Fire Services Department of Hong Kong SAR updated the codes of practice under their administration. For MOE Code 1996, MOA Code 1995, and FRC Code 1996, Buildings Department added a clause "Alternative Approach to Fire Safety" in each of the codes and stated, "The Building Authority recognizes that fire safety may be approached in a number of ways the best of which is not necessarily prescriptive. This is particularly pertinent to buildings of special hazards which, because of their size, height, use, design, construction or location, may necessitate special consideration of the fire-safety objectives and the standards to be set". This statement officially opened a door for PBD and its approval.

To further guide and control the PBD process, the Buildings Department of Hong Kong SAR issued a Practice Note for Authorized Persons and Registered Structural Engineers (PNAP 204), entitled "Guide to Fire Engineering Approach" in 1998 [37]. At the same time, the Fire Safety Committee in Buildings Department was formed to provide a forum to evaluate PBD projects on a case-by-case basis.

PNAP 204 provided guidance on the fire engineering approach for the design of new buildings or alteration and addition works in existing buildings to meet the fire safety objectives and performance requirements of Hong Kong building regulations, and as an alternative to the prescriptive requirements set out in the MOE, MOA and FRC Codes, covering fire safety in buildings.

In PNAP 204, it stated that the objectives in adopting fire engineering design are to provide for an overall level of safety that is equivalent to that which would result if fire safety was achieved through full compliance with the prescriptive provisions of the relevant codes of practice. It calls for an "equivalency" with reference to the prescriptive provisions but does not establish how the equivalency is to be measured.

PNAP 204 highlights the performance requirements of the legislation that have to be addressed in the fire engineering design as follows:

(a) Given the function and purpose of the building or installation, the design should not present an unacceptable risk of a fire developing and spreading.
(b) Occupants should have time to reach a place of temporary and/or permanent safety without being dangerously affected by heat or smoke from a fire.
(c) A fire should not spread to adjacent property.
(d) A fire/smoke should not spread beyond the compartment from which the fire originates.
(e) Firefighting personnel should be able to gain access and mount firefighting and rescue operations without undue risk to their health and safety.
(f) The stability, insulation and structural integrity of the building should be ensured in a fire of specified intensity and duration.

PNAP 204 had been the major document to guide the PBD process in Hong Kong for over a decade until the Buildings Department issued the Code of Practice for Fire Safety in Buildings in September 2011 (FS Code 2011) [3]. FS Code 2011 is a performance-based code, which combines MOE Code, MOA Code, and FRC Code with additional requirements for Fire Properties of Building Elements and Components, and Fire Safety Management. A section entitled "Guidelines on Fire Engineering" has also been included to guide the PBD.

2.2 Review of Fire Safety Status in Hong Kong

After the practice of fire engineering approach for over one decade, Buildings Department of Hong Kong SAR initiated a programme of a consultancy study on "Fire Engineering Approach and Fire Safety in Buildings" [38] in 2000 and started the work in 2002. The purposes of the study were to review the existing fire protection regulation system, to recommend changes to the existing regulations, and to develop a PBC framework. The authority commissioned a consultant team to undertake the consultancy study and to form the technical basis for regulatory reform in Hong Kong.

The study was divided in a number of stages, including:

- to review the status of fire safety design worldwide. The USA, the UK, Japan, Australia, Sweden and Hong Kong were chosen for review.
- to recommend changes and amendments to the prescriptive regulations.
- to draft the PBC of practice and design guidelines.
- to try the PBC with real projects for one year.
- to finalize the PBC and plan for implementation.

The overall fire safety risk and expenditure provide guidance on the objectives for the PBC. Any changes to the present building environment would impact the community, the government departments and the construction/building industry. All recommendations are required to be specifically tailored to the Hong Kong building environment, reflecting the nature of the industry and the culture.

The aim of the recommended alterations to the prescriptive regulatory environment would improve the processes of documentation for the relevant authorities. The changes should ensure that the new regulatory framework provides a greater level of control and enforcement with an overall improvement to the design and approval process. The PBC would also offer flexibility in design, which is especially important for alterations to existing buildings.

It was considered whilst changes occurred to the regulations that guide fire safety design with the existing regulation, no performance-based regulatory framework for fire safety would be workable without retaining a prescriptive-based approach as one option for designers. A performance framework must be made up of a majority of prescriptive components, which were used for the majority of building designs. The PBC and framework were designed as an "open" code and allowed fire engineered solutions as an alternative to prescriptive design. PBD is a small part of fire engineering both in total number of projects and in an individual project. Regulations and codes of practice impose the prescriptive requirements and always are the key documents to control the design of buildings for fire safety and its approval process.

It was suggested that for any changes in the prescriptive code system, the impact on the designer should not be significant. Buildings would always be designed with a significant portion of "prescriptive design" and some aspects of "performance design", similar to the practice of fire engineering approach for over a decade in Hong Kong. On this basis, the change to a PBC was not significant for the designer and builder. The overall aim of the recommendations was to:

- Provide for regulatory change to streamline the process of fire safety design, for all the government departments involved.
- Rationalise the existing regulatory system and introduce a modified framework with a simpler and easier system for government employees and members of the building industry.
- Minimise the level of change to the building industry but introduce greater opportunities for the building industry to undertake PBD.
- Understand better the level of safety, give flexibility in design, and result in greater cost-effectiveness with the PBD approach.

The reviews and studies assessed the status of fire safety within Hong Kong and compared with other countries, specifically the UK, the USA, Australia, Sweden and Japan. The aim was to assess the prescriptive requirements in Hong Kong and ascertain the level of safety, with regard to the fire risk in Hong Kong. The basis of the process for decision making was:

1. How adequate were the existing prescriptive requirements?
2. What was the basis of the existing prescriptive codes of practice?
3. What were the fire safety trends in other countries?
4. What was the world's best practice?
5. What recommendations should be made based on the assessment, using collective knowledge and experience?

The risks from fires were represented by the number of fires in different types of buildings and the number of fatalities and injuries in these buildings. In regard to the overall level of fire safety in Hong Kong when compared with the overseas countries reviewed, Hong Kong had a good record if adopting the number of fire deaths per million population per year as shown in Table 1 as a benchmark.

Table 1: Number of estimated averaged fire deaths per year [39,40,41,42]

Hong Kong	3.5 deaths per million population
Australia	10.0 deaths per million population
Sweden	15.4 deaths per million population
Japan	16.0 deaths per million population
UK	18.1 deaths per million population
USA	26.3 deaths per million population

The study and review in relation to the risk to life and property from fire in Hong Kong revealed that:

1. The risk to life and property had been relatively low in global terms and compared well with other countries and cities of similar populations. There was no need to lower the risk significantly through more stringent fire safety provisions for the construction of all new buildings.
2. There were concerns on greater fire risk to occupants of older residential buildings (pre-1975).

3. There were concerns about the risk of fire associated with unauthorised building works (UBW), illegal change of use, lack of maintenance of fire protection systems and inadequate fire safety management programmes. The existing legislation was adequate for controlling UBW and illegal changes of use, but needed the legislation for continuous fire safety management and maintenance (passive system in particular) for occupied buildings.

Based on the risk to life from the threat of fire presented by the available statistics, Hong Kong has been very good, compared with other countries. The key aspect is the low number of deaths in residential fires. It implied that the existing prescriptive requirements were adequate. The reasonable high expenditure on fire safety resulted in a low fire risk.

2.3 Development of Performance-based Code (PBC)

The study and review of the existing prescriptive code system and the status of fire safety in Hong Kong led to a number of recommendations, including:

1. It was recommended that Hong Kong introduce a performance-based framework for fire safety design, which would allow more flexibility in design for some buildings and an alternative for designers to develop more cost-effective building solutions.
2. There was no evidence to suggest that expenditure be increased significantly on additional or more stringent fire safety measures for new construction in Hong Kong.
3. There was a need for further inspections, maintenance and potentially fire system upgrades to reduce the risk of fire in existing buildings constructed before the 1970s.
4. It was recommended that an awareness, education and training program be established and undertaken at all levels of the construction industry in relation to the new performance-based fire safety framework and codes of practice. The programme was to provide high level education and practical exposure to the new performance-based fire framework and code.

The aim of code is to provide an adequate level of fire safety to occupants, without having an undue level of resources spent from the building industry and general society. The framework of the performance code is shown in Figure 2 [3].

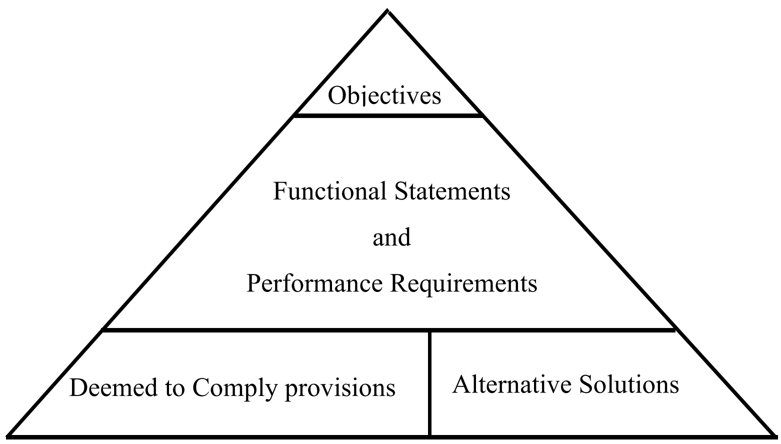

Figure 2. Framework for Fire Safety in Buildings

The hierarchy of the framework is based on the performance-based regulatory systems of Australia [23], the United States of America [28,43] and New Zealand [44]. With reference to the relevant legislations, the framework for fire safety in buildings was formulated as follows:

(a) Buildings Ordinance provides an over-arching goal [45].

(b) Regulations provide the detailed Objectives and Functional Statements for fire safety as well as Performance Requirements for achieving the objectives of fire safety [46,47].

(c) The Code provides the means of compliance (Deemed-to-Comply provisions) and guidelines for adopting the fire engineering approach (Alternative Solution).

The review process revealed that life protection was the primary objective in Hong Kong existing regulation system. The long title of the Buildings Ordinance [45] stated that the objective is "*to provide for the planning, design and construction of buildings and associated works; to make provision for the rendering safe of dangerous buildings and land*", where the life safety was addressed. But property protection was not addressed explicitly. It was recommended to include property protection as an objective of fire safety. Hence, the objectives in the new code become:

<u>Life Safety:</u> Fire safety provisions should be provided for:

1. protection of the life of building occupants
2. minimization of fire spread between fire compartments
3. prevention of building collapse as a result of fire
4. facilitation of firefighting and rescue by fire services personnel

<u>Property Protection:</u> Fire safety provisions should be provided for:

1. minimization of fire spread between fire compartments
2. prevention of building collapse as a result of fire
3. minimization of fire spread between buildings
4. facilitation of firefighting and rescue by fire services personnel

The fire safety provisions in a building should achieve the fire safety objectives. The functional statements clarify the fire safety objectives in detail. These statements were spread in the existing regulations. The new PBC repeated these function statements and included these statements at one location for easy reference. For example, the function statement for means of escape was provided in the Building Regulation [46], stating "*Every building shall be provided with such means of escape in case of emergency as may be required by the intended use of the building*." It was repeated in Part A of the PBC in front of Section "Performance Requirements" for means of escape.

The Performance Requirements provide the criteria by which a solution for fire safety can be formulated. The Performance Requirements consists of two parts: (i) the Performance Requirement itself; and (ii) the guidance to the Performance Requirements, which provides the factors to be considered for demonstrating compliance. A new set of performance requirements and guidance were developed for each of the codes, namely MOE Code, FRC Code, MOA code, Fire Properties of Building

Elements and Components, and Fire Safety Management, which become an important part of Part A of the new PBC.

As a result of the review, the requirements of the existing codes were kept or updated with the new development as Deemed-to-Comply provisions, and formed Part B (MOE Code), Part C (FRC Code), and Part D (MOA code) in the new PBC system. To fill in the gap of legislation on management and maintenance of the occupied buildings, the new PBC system incorporated two new sections of Deemed-to-Comply provisions, namely: Fire Properties of Building Elements and Components (Part E) and Fire Safety Management (Part F). The Deemed-to-Comply provisions provide a benchmark with respect to the acceptable level of fire risks to life and property. Alternative solutions can be assessed against the benchmark and/or the pre-set acceptance criteria. The relationship between the acceptance criteria and the relevant Performance Requirements may vary in different scenarios and must be considered on a case-by-case basis, which is part of the PBD process.

The process of formulating an alternative solution is called PBD or fire engineering approach. Part G "Guidelines on Fire Engineering" of the new PBC was developed to: i) provide guidance for complying with the fire safety objectives in the Buildings Ordinance and the Performance Requirements; and ii) provide a framework for fire engineering to develop an Alternative Solution.

3. Development of Regulation in Mainland China

3.1 Development of Fire Protection Standards

After World War II and the end of the civil war in 1949, Mainland China experienced the first wave of fast development of the economy. Design and construction of industrial facilities and residential buildings were demanding fire safety regulations and design standards. These were not available then. In order to meet the urgent requirement, the Ministry of Construction issued "the Interim Fire Prevention Standards for Architectural Design of Industrial Enterprises and Residential Areas 102-56" in 1956, which was translated from the Soviet Union fire regulations "Standard for Fire Prevention Design of Buildings in Industrial Enterprises and Residential Areas H102-54". Standard 102-56 was the first fire safety regulation of Mainland China.

In 1960, the State Capital Construction Commission and the Ministry of Public Security jointly promulgated "Principles and Provisions on Fire Prevention in Building Design". In order to facilitate the implementation of the provisions, the Government had formulated "Technical Specification on Fire Prevention in Architectural Design" for reference.

In March 1975, the Government, mainly the Ministry of Public Security promulgated "Building Design Fire Code" TJ16-74 for trial use. This code was a revision of "Principles and Provisions on Fire Prevention in Building Design" issued in 1960.

With the reform and opening policy in the 1980s, the economy of Mainland China was in a fast development track, and a large number of high-rise buildings were under construction. In order to ensure fire safety of the high-rise buildings, the State Economic Commission and the Ministry of Public

Security jointly approved “Code for fire protection design of high-rise buildings GBJ45-82” in 1982. The Code laid down the foundation for the standardization of fire safety design of high-rise buildings in Mainland China, and played an irreplaceable historical role. With over 10-year implementation, the Government revised the Code and issued as “GB50045-1995” in 1995 [48]. The code was revised in 1997, 2001 and 2005.

In August 1987, the Government issued “Code for fire protection design of buildings GBJ16-87”, which was for fire safety design of low-rise buildings. The code was revised in 1995, 1997 and 2001 [49]. In 2006, the Government re-issued the Code as GB50016-2006 [50].

With the rapid development of China's economy, the Code GB50016-2006 for low-rise buildings and the Code GB50045-95 for high-rise buildings became difficult to be adopted for design and construction. Some incongruous issues existed between these two codes. There were also conflicts with other national standards and fire prevention design specifications. In 2014, the Government promulgated “Code for fire protection design of buildings, GB50016-14”, which incorporated the contents of the Code GB50045. It is the first unified code for fire safety design of buildings in China [51].

In addition to the abovementioned codes, the Government also issued fire safety related codes for specific premises and facilities, such as “Code for Fire Protection Design of Garage, Motor Repair Shop and Parking Area GB50067-2014” [52], “Code for Fire Prevention Design of Civil-Air Defence Engineering GB50098-2009” [53], etc.

There are also other technical standards for fire protection system and codes for infrastructures. For example:

- Code for Design of Sprinkler Systems GB50084-2017 [54],
- Code for Design of Automatic Fire Alarm System GB50116-2013 [55],
- Technical Standard for Smoke Management Systems in Buildings GB51251-2017 [56],
- Code for Installation and Commissioning of Sprinkler Systems GB50261-2017 [57],
- Code for Design of Fire Protection for Railway Engineering TB10063-2016 [58], etc.

3.2 Development and Change of Authority Organization

In Central Government, the Fire Bureau of Mainland China was established in 1955, which was a branch of the Ministry of Public Security (MPS). In 1982, the Fire Bureau was shifted to the Chinese People's Armed Police Forces. Fire fighters and fire officers were treated as active military services personnel. Under the authorisation hierarchy, similar organisation structure was set up on the province level at the same time. The provincial Fire Bureau was in charge of their local fire safety issues, including approval, inspection, monitoring the maintenance, firefighting, and rescue.

Before 2019, for the majority of their local projects the provincial Fire Bureau was responsible for approval of the fire safety design prior to construction and for inspection of the completed projects before occupancy.

In March 2019, the Central Government launched the Plan for Deepening the Reform of Party and State Institutions. The Armed Police Force was one of the targets for reconstruction. As the result of the reformation, all the fire fighters and fire officers under MPS were dismissed from their duty as active military services personnel and reallocated to the Ministry of Emergency Management as Civil Servants. Fire Bureau focuses on national wide emergency services, mainly firefighting and rescue. Fire Bureau is still responsible for day-to-day supervision and inspection and deals with unlawful situations, which may violate the fire codes and impact on the safety of public life and properties.

Since April 2019, the duties of approval of fire safety design, commissioning of fire protection systems, filing, and spot check of the projects under construction have been transferred to the Ministry of Housing and Urban-Rural Development.

4. Fire Science and Technology in Mainland China

4.1 Study on Basic Theory of Fire

In the past three decades, Mainland China has experienced rapid development in the construction industry. Different types of buildings such as super high-rise buildings have emerged in many cities. At the same time, due to the needs of energy saving and environmental protection, the industry has faced great demand for external insulation materials and new energy batteries. In order to ensure the fire safety of the infrastructure, vehicles, and energy facilities, many scholars have conducted basic theoretical research on fire protection.

Hu *et al.* [59] investigated experimentally the side wall constraint effect on the features of flame ejected from the facade opening with an under-ventilated compartment fire. Li [60] carried out experiments and theoretical analysis to investigate the motion of buoyant gas driven by stack effect, turbulent mixing and external wind.

Ji *et al.* [61] analyzed the positive pressure ventilation to prevent the smoke from entering the stairwell using Large Eddy Simulation in a sprinklered high-rise building with the heat release rate of 1.5 MW. With the pressurization fan located on the top of the stairwell, a simple method was developed to predict the air mass flow rates at the outlets. Further, the correlation of the average pressure in the stairwell on the fire floor and the pressurization air supply volume flow rate was developed.

For the fire safety of high-rise buildings, Sun [62,63,64] addressed three key issues: (i) the fire characteristics and safety design of exterior wall insulation materials; (ii) the three-dimensional fire spread in high-rise buildings and the mechanisms resulting in damage to the building structures; and (iii) the smoke transport driven by multi forces and its impact on crowd evacuation. The results of the research provide useful information for fire safety design of high-rise buildings.

The numerical simulations were conducted by Zhong [65] to investigate the influence of transverse fire locations on smoke bifurcation flow. The results show that the bifurcation flow is symmetric when fire is located in the central line of the tunnel, and a S-shaped flow occurs when fire is close to the wall.

The critical velocity of smoke bifurcation flow increases exponentially when the fire source is moved to the sidewall.

Through experimental research, combining hydrodynamics and heat transfer theory with experimental diagnosis technology of thermal disaster, Zhang *et al.* [66] studied the principles of fire spread and the internal mechanism of accelerated catastrophe about the coupling action of inclination and roadway effect in the long and narrow underground confined spaces, and the prediction model of accelerated catastrophe theory has been established.

Chen [67,68] studied the mechanism and critical conditions of backdraft in heavy-duty railway tunnel, revealed the characteristics of fire in the tunnel and the backdraft mechanism in the process of asphyxiation and fire extinguishing.

Ping [69] conducted an experimental study on the thermal runaway of lithium-ion batteries in different conditions. The characteristics of temperature, heat generation, gas production and heat release rate were obtained when the battery was out of control, and revealed the mechanism of thermal runaway.

4.2 Study on Fire Safety Design on Building Structures

In Mainland China, the methods of fire safety design for building structures have been established in relevant national codes, such as the fire safety design codes for steel structures, concrete structures and composite structures [70,51,71]. The concrete structures are generally considered as a type of structure with good fire performance and the fire resistance design method is relatively simple. For the steel structures, two types of fire performance design methods, including load carrying capacity method and critical temperature method, were suggested in [70].

Based on the research of fire performance of steel and concrete structures, systematic studies on composite structures, such as concrete-filled steel tubular (CFST) and steel reinforced concrete (SRC) structures, have been conducted [72]. The studies cover the areas of steel tube-concrete interface behaviour at elevated temperatures, fire performance of composite members, structural performance of beam-column composite joints and frames during the combined fire and loading process [72,73,74,75]. The outcomes of these studies have been incorporated into the national codes [70,51,71].

Dong investigated the characteristics of the acoustic emission and vibration of various structural members during fire and developed a method to determine the location of the damage caused by fire [76,77]. The technology can also be used in monitoring the conditions of important projects and provide useful information for fire command in firefighting and rescue.

Shi *et al.* [78] studied the bearing capacity of axially restrained compression members in space truss structures after buckling in fire, and the contribution of residual bearing capacity of the members after buckling, and established the whole process tracking method of fire response of space truss structures.

Yang *et al.* [79] used full-scale reinforced concrete beam specimens for experimental and theoretical research. Under different boundary conditions of shear span ratio, concrete strength and stirrup ratio, he studied the shear performance of reinforced concrete beams during fire and after fire with various fire duration, and established a model for calculation by using ABAQUS nonlinear finite element analysis software. It provides a basis for PBD of building structures, damage evaluation, and reinforcement and repair of structures after fire. Zhang [80] studied the stochastic factors and their probability distribution function in the process of natural fire occurrence and development of large space buildings, and explored the double coupling process of deterministic factors and stochastic factors in the process of fire development by using the Latin hypercube sampling method.

4.3 Study on Fire Detection Technology

In view of the features of forest fire, such as diverse terrain, changed lighting background and large detection area, Zhang [81,82] established a sample database of rich fire video through experimental shooting and computer graphics simulation, studied the characteristics of flame and smoke in forest scenes based on traditional pattern recognition and deep learning methods, and formed a video fire detection algorithm with high accuracy. The video fire detection system has been developed and adopted for identifying the area of a forest fire.

Liu [83] carried out research on key technologies of very early fire detection and non-destructive suppression for important small spaces such as a data centre, and adopted non-contact optical smoke particle detection technology to convert the physical characteristics of fire into electrical signals through specific sensing units.

4.4 Study on Smoke Control Technology

According to the structural characteristics of the subway station and tunnel of a complex three-dimensional transportation hub with longitudinal multi-layer and transverse multi-channel, Jiang [84] and Pan [85] studied the characteristics of the complex flow field in the subway system.

Sun [86] studied smoke movement in staircases of high-rise buildings, and analysed the impact of stack effect and elevator piston effect on smoke control strategy in buildings. The study established a model to predict the temperature distribution in a shaft and the neutral plane height considering the change of the openings on different floors. The results have been adopted for smoke control in high-rise buildings and the formulation of relevant codes.

Compared with a conventional tunnel, Urban Traffic Link Tunnel (UTLT) has a unique configuration, service function and structural characteristics. It poses greater fire risk but has expected higher fire safety objectives. Li [87] analysed the dynamic development process of smoke in UTLT and established a model for smoke temperature distribution, smoke layer spread and stratification characteristics of UTLT through theoretical analysis, full-scale test and numerical simulation. The study extended the critical wind speed theory of longitudinal ventilation and the empirical prediction model of "the critical wind speed of annular UTLT" and revealed the influence of tunnel structure characteristics and different smoke control schemes on the smoke transportation process. The research optimised the control scheme of smoke in typical fire scenarios.

According to the characteristics of typical corridor configurations, He [88] established the neutral layer model of air flow in high-rise buildings with time, then calculated the changes of the flow field in buildings and revealed the pattern of smoke diffusion.

Yi [89] studied the natural smoke exhaust and smoke diffusion of a building fire under wind conditions. By analysing the influence of ambient wind on smoke diffusion and natural smoke exhaust, a method was put forward to improve the efficiency of the natural smoke exhaust system. In order to improve the level of fire safety for urban traffic tunnels, Li [90] systematically studied the influence of the tunnel slope on smoke diffusion and the maximum temperature at the ceiling with longitudinal ventilation. The research deduced a formula of wind speed for longitudinal ventilation, which can maintain the stability of the smoke layer and optimise the wind speed for different slope and heat release rates of tunnel fires for longitudinal ventilation.

Based on the collision and adsorption mechanism between smoke particles and water mist particles, Fang [91,92] studied the basic principles of smoke diffusion and spread on the condition of water mist in U-shaped longitudinal section of underwater tunnel, and established the motion equation of water containing smoke particles, so as to predict water mist diffusion and smoke flow in the presence of strong shear wind flow.

Through CFD simulation and experiments, Jiang [93,94] studied the evolution process of plug-holing phenomenon for a centralized smoke exhaust mode in a highway tunnel, the typical characteristics of the smoke layer in the tunnel during plug-holing was analysed, the influence of mechanical smoke exhaust rate, smoke outlet spacing and number of smoke outlets during plug-holing of smoke layer below the smoke outlet was quantitatively analysed.

Aiming at improving fire safety of the subways, Shi [95,96,97] explored smoke diffusion, air distribution and flow field evolution characteristics of fire coupled with different tunnel ventilation and smoke exhaust systems, and studied the effects of different blocking ratios on the critical velocity of tunnel smoke control, the transmission of the ventilation pressure wave and the smoke flow behaviour of a train fire. He also investigated the smoke control modes for fire on different train carriages and the setting of an intermediate air shaft to connect channels and lines. The results provided technical basis for fire prevention and smoke control of subway in Mainland China.

4.5 Study on Fire Extinguishing Technology

According to the characteristics of fire of the floating roof rim seal, compound firefighting equipment has been designed by Lang [98]. Rapid spreading ultra-fine dry powder and pressurised foam with high kinetic energy to resist fire-reignition are used to quickly extinguish the early stage fire of the rim seal.

Gao [99] studied the intelligent fire extinguishing system of a large floating roof oil storage tank. The system is composed of an active protection subsystem and an intelligent fire extinguishing subsystem. The active subsystem uses nitrogen with micro water mist to form an inert mixture to cover the area between the primary and secondary sealing devices of the oil storage tank, which reduces the content of oil gas and oxygen in the combustible mixed gas and the temperature in the concerned area by inert isolation. The intelligent subsystem uses the combination of a fire image monitoring system and an automatic fire monitor control system to detect the fire in parallel, automatically locate the fire source, and extinguish the fire.

By analysing the causes, patterns and characteristics of large tank fires, Dong [100] proposed a concept of a deep prevention system for large oil tank fires, then the program design, product development, performance testing and prototype trial were conducted.

The safety of lithium-ion batteries has become the key factor to vigorous development of new energy vehicles. Yu [101] carried out research in aspects of lithium-ion battery thermal management, battery fire suppression and cooling measures, thermal runaway prevention and control to provide theoretical and data support for the safy design of the battery system.

In order to prevent fires in lithium-ion battery warehouses, Yang [102] used Type-18650 lithium-ion batteries as samples to study the temperature change in the process of thermal runaway through experiments, and set up a three-level early warning scheme with temperatures of 50℃, 100℃ and 120℃, plus 30℃ surface temperature early warning, CO/H_2 early warning, and flame alarm. For the first-level early warning of 50°C, the first-level composite phase-change material with the mass ratio of paraffin, expanded graphite and activated carbon of 21:4:1 was developed for endothermic cooling. Related to the second-level early warning temperature of 100°C, the mass ratio of polyethylene glycol 1500 to methylcellulose was 1.6:1 to form the secondary composite phase-change material for endothermic cooling. For the primary early warning temperature of 120°C, liquid nitrogen spray with 0.03Mpa outlet pressure would be activated to spray liquid nitrogen to cool the lithium-ion battery.

Xie [103] built a lithium battery combustion-inhibition experimental platform, took the ternary aluminium shell power lithium-ion battery monomer with a rated capacity of 150A·h as the research object, induced thermal runaway by electric heating, and studied the fire suppression and cooling effect of perfluoro-hexanone and water mist extinguishing devices on thermal runaway lithium-ion battery. The fire extinguishing time, maximum temperature, quality loss and fire extinguishing efficiency were measured under different working conditions.

In order to solve the technical problems of electrical fire suppression, a new type of automatic fire extinguishing device based on fire detection tube and superfine powder fire extinguishing agent was designed by Chen [104]. Fire suppression performances of the device were studied through fire experiments of full-scale distribution cabinets.

5. PBD in Mainland China

The UK fire regulation system was moved from prescriptive specifications to a performance-based approach in the mid 1980s. During the same period, New Zealand and Australia launched their research programme and were preparing for fire code reform. The international development had a strong impact on the fire safety research community in Mainland China. The State Key Laboratory of Fire Science (SKLFS) was established in 1991.

In the 1990s, many activities, including national and international conferences, were organised by the SKLFS [105] to boost the research work in fire science and to catch up in the development of performance-based approaches to fire safety design in practice. In 1999, an article entitled "*A Performance-Based Approach to Fire Safety Engineering Design of Major Projects"* [106] was presented in the 1999 International Symposium on Urban Fire Safety. For the first time, the terminology "Performance-Based Approach" was translated into "性能设计方法", which means "performance-based design (PBD)".

PBD started in Mainland China in the early 2000s and has been adopted for many large projects in the past 20 years. However, to date a structured performance-based fire safety code is not available within the regulatory framework. Fire safety design was mainly based upon the two major building fire codes before 2015, namely: Code for design of building fire protection, "low-rise code" in short [50], and Code for fire protection design of high-rise buildings, "high-rise code" in short [48]. These two codes were merged into one in 2015 [51].

Application of PBD approaches in Mainland China lagged behind in the 1990s, and experienced a boost during the development of Beijing Olympic projects and Shanghai Expo projects in the 2000s. With over 20-years experience of PBD approach, the authority has periodically updated the code of practice and technical standards. Many PBD solutions and fire research results are incorporated as code requirements. With concerns of non-compliance with fire regulations in design, the authority has tightened the approval process of PBD approaches in recent years. The number of projects with PBD are reducing. Based upon the observation of the construction industry and reconstruction of the authority organisation described in Section 3.2, the trend of tightening the PBD approach will continue in Mainland China.

5.1 Prescriptive Requirements

In the high-rise code, a public building with a floor level higher than 24 m above the ground floor is defined as a high-rise building. For significant developments, fire protection design for most of these buildings is required to comply with the high-rise code, even though the top floor level may not be higher than 24 m. High-rise buildings are categorised as Type A – important buildings, and Type B – general buildings [51]. The maximum fire compartment size is 1000 m^2 for Type A buildings and 1500 m^2 for Type B buildings. For basements, the maximum fire compartment size is 500 m^2. The fore-mentioned fire compartment sizes can be doubled if the building is fully protected with an automatic sprinkler system. The maximum fire compartment sizes for shopping areas and exhibition areas are 4000 m^2 for above ground spaces and 2000 m^2 for underground spaces if an automatic sprinkler system and an automatic fire alarm system are installed.

Table 2: Net widths of evacuation exit and aisle way on ground floor (m)

High-rise	Net Width of each Exterior Door	Net Width of walkway	
		Rooms on one side	Rooms on both sides
Hospital	1.30	1.40	1.50
Residential Building	1.10	1.20	1.30
Other Buildings	1.20	1.30	1.40

The minimum widths of exit doors and corridors are specified according to the usage of the buildings as listed in Table 2. The total width of evacuation exits for crowded halls or rooms is determined on the basis of 1.00 m wide per 100 occupants. The maximum travel distances also vary with the usage of the premises. Three categories are shown in Table 3. For general buildings, the maximum travel distance is limited to 40 m, and that for educational buildings, hotels and exhibition halls is 30 m and that for hospital wards is 24 m. The maximum dead-end distance is half of the mentioned values.

Table 3: *Travel Distance*

High-rise		Maximum travel distance from room door or unit door to the nearest exit or staircase (m)	
		Between two fire exits	Deadend
Hospital	Wardroom Part	24	12
	Other Parts	30	15
Hotel, Exhibition Building, School Classroom Building		30	15
Other Buildings		40	20

With reference to the Chinese fire codes summarized above, it was very difficult if not impossible to design large, significant buildings in the early 2000s. In many cases, these codes cannot cover all situations in practice, particularly for novel or complex buildings. In the last 2 decades, guidelines of PBD have been issued by the Central Fire Bureau. Based on the guidelines the Provincial Fire Bureau controls the process of design and approval. To fulfil the purpose of PBD, new techniques and concepts developed overseas and adopted in Hong Kong were brought in and further developed to suit the mega scale projects in Mainland China.

5.2 Regulation for PBD

In Mainland China, the fire safety regulation system does not recognise PBD and a PBC system is not available. At the national level, the Ministry of Public Security issued Act No 30 in the mid-1990s, in which PBD was not mentioned as the terminology in Chinese did not appear at that time. The Act states if fire safety design for any project does not comply with the prescriptive requirements of the fire regulations, an assessment for the design must be carried out by qualified fire engineering consultants.

The Provincial Fire Bureau will organise an expert panel to review and endorse the design solutions. Act No 30 was replaced by Act No 106 in 2009. In the same year, the Central Fire Bureau issued a temporary guideline for PBD, expert panel review, and management [107]. The recommended procedure for design and approval has been applied for PBD projects in the past two decades.

In Beijing and Shanghai, the local guidelines of fire engineering design were published in the early 2000s. These official documents outlined the areas where PBD could be adopted, the procedure of design and approval process, and the contents of the technical report. In general, for significant developments such as airport terminal buildings, railway and underground stations, Olympic projects, super high-rise buildings, and very large shopping centres, authorities may permit to adopt PBD. For normal office buildings and residential buildings, PBD is generally not acceptable to the approval authorities.

5.3 PBD and Approval Process

The Act No 30 and later the Act No 106 implicitly recognise the PBD and establish the approval process in principle. However, the details of PBD and approval processes are not provided. These detailed processes vary with cities and provinces. The experiences in Beijing and Shanghai are summarised as follows:

<u>Initial agreement on PBD issues:</u> It is essential to agree with the approval authorities at the beginning of the project on the issues that PBD are required.

For a specific project, the PBD issues need to be addressed in the preliminary fire safety strategy report and presented to the approval authorities for agreement. Commonly, PBD is adopted to address large fire compartments, long travel distances, large populations, large smoke zone areas, smoke control systems, fire separation, and structural fire protection issues.

<u>Performance-based analysis:</u> The initial agreement with the approval authorities gives the direction of the detailed PBD and analysis. The timeline analysis technique is well accepted in Beijing and Shanghai. Analysis of fire safety is primarily concerned with time: time of ignition, time at detection, time for evacuation and time to reach untenable conditions. Therefore, rather than examine fire safety in terms of travel distance and fire compartment areas, the level of fire safety is assessed in terms of the time taken for the occupants to evacuate compared with the growth of the fire and time to reach untenable conditions. Therefore, life safety of occupants will be evaluated using a quantitative 'timeline' assessment. This primarily involves determining the time to untenable conditions (ASET) within the fire compartment and compares these with the time required for evacuation (RSET). The requirement for occupant safety is:

$$\text{RSET} + \text{Safety Margin} < \text{ASET}$$

Accordingly, determination of the development of the fire, release of smoke, temperature of the smoke layer, time to reach untenable conditions and time for evacuation form part of the assessment.

Safety of the occupants in a building for a particular fire scenario can be achieved if it is demonstrated that the time taken to evacuate the occupants to an area of safety is less than the time taken for the fire to develop untenable conditions. This relationship incorporates an appropriate safety margin to allow for uncertainties in the assumptions and calculations.

Third party assessment: The requirement of a third party to assess the PBD solutions varies from province to province. In Beijing, a third party is definitely required for any projects adopting PBD. For a large significant development, a fire consultant is normally appointed at the preliminary design stage. The fire consultant will develop a preliminary fire safety report and present to the approval authorities. At this stage, the client is required to appoint a third party for PBD. The third party is another fire consultant recognised by the approval authorities.

Final approval of PBD: When the fire consultant and the third party complete their work and reach the same conclusions, their reports are submitted to the approval authorities. Upon receipt of the reports, the approval authorities at provincial level organize an expert panel meeting. The panel is comprised of Fire Bureau officers, academics, and professionals in fire engineering field.

Both the fire consultant and the third party are required to present the case in detail to the expert panel meeting, and to answer the questions raised by the panel members. The panel meeting normally lasts for half a day to one day per case. For very large and complicated projects, the meeting possibly lasts for two days. The expert panel makes decisions after the panel meeting.

5.4 New Concepts

In the later 1980s, the UK adopted the PBC system. Fire engineers proposed innovative solutions for fire safety design of large scale infrastrature facilities. New concepts based on fire engineering approach, namely “Cabin Concept” and “Island Concept” were developed and applied for Stansted airport in the UK [108], Kansai airport in Japan [109], the Hong Kong International Airport Passenger Terminal [110], and Hong Kong metro stations [111]. The concepts were brought in Mainland China for the Beijing Capital International Airport Terminal 3 and other main airport terminals. With the PBD approach during the high wave of infrastructure construction in Mainland China in the 2000s, various new concepts were proposed and adopted for many mega developments to solve the practical design issues.

5.4.1 Fire separation zone

Referring to the safety belt to stop fire spreading in forests, the ‘fire separation zone’ concept was proposed as a means of fire separation for wide span buildings with a tall roof, in which a physical fire barrier or fire shutter is technically impossible [112,113]. The basic logic of the fire separation zone is to stop fire spreading through a vacant area in the continuous space by lowering the radiation heat flux to the combustibles in the adjacent ‘fire compartment’ from fire source and smoke layer. By using ‘fire separation zone’, the continuous space is divided into several hypothetical ‘fire compartments’. This is an innovative approach to solve the enlarged fire compartment for large span spaces without adding physical fire barriers and whilst keeping the reasonable fire safety level for a building. As a means of alternative fire separation, the fire separation zone should meet the following provisions:

- The fire separation zone has an adequate width to prevent igniting the combustibles in the adjacent 'fire compartment'. Its width is calculated based on the fire and smoke radiation and the critical heat flux of the adjacent combustibles, as sketched in Figure 3.
- To lower the smoke radiation to the combustibles, smoke extraction is provided for the 'fire separation zone', as well as the fire suppression system.
- The fire separation zone is an area without any permanent or temporary combustibles.

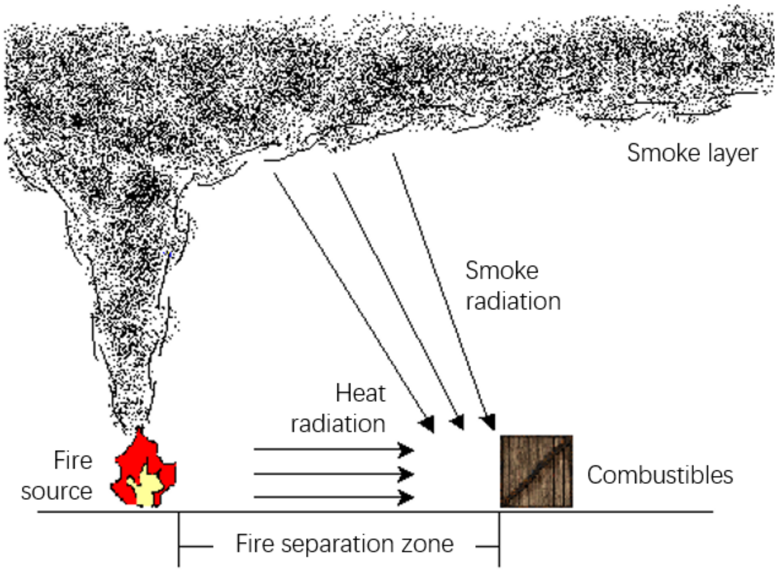

Figure 3. Sketch of 'fire separation zone' concept

5.4.2 Temporary fire safety zone

For large commercial complex with big span in the plan, the stairs are not able to discharge to outside directly on the ground level. The 'temporary fire safety zone' concept was proposed to use the indoor pedestrian street as a temporary safety buffering zone. The provisions for the temporary fire safety zone ensure that the buffering zone is a safety area [114]. With the indoor pedestrian street, the stairs can discharge to the outdoor through the buffering space, which allows flexible design of the layout plan. The temporary fire safety zone concept was initiated for design of large shopping malls and applied for various types of projects with large span. The basic concept is to make it a semi-open space in case of fire by opening the skylights upon fire alarm. The following provisions are imposed:

1. The temporary fire safety zone shall have net width no less than 9 m to prevent the fire spreading from the tenants of one side to the opposite.
2. The length of the temporary fire safety zone shall be no more than 300 m.
3. The tenant shopfront shall be separated from the temporary fire safety zone with fire rated glass or solid partition of 1.0 hr fire resistance rating (FRR).

4. The size of each tenant shop adjacent to the temporary fire safety zone shall be no more than 300 m^2.
5. The total area of the skylight vents on the roof shall be more than a quarter of the ground floor area of the temporary fire safety zone.

Often, the temporary fire safety zone or indoor pedestrian street consists of atria and circulation areas between the shop alleys.

5.4.3 Refuge corridor

The concept of a refuge corridor was proposed as a PBD solution for the mega projects of the Beijing Olympics in 2008. For buildings with large span, a refuge corridor is applied to solve the extended travel distance when it is difficult to allocate direct exit to outdoor in accordance with the code. The refuge corridor is a protected safety area which is equivalent to an evacuation stair. The occupants in the building can discharge to outside through the refuge corridor. The following provisions should be met for the refuge corridor:

1. The partition wall of the refuge corridor shall have FRR no less than 3 hours, and the floor slab shall have FRR no less than 1.5 hours.
2. The refuge corridor shall have at least 2 discharging exits to the street in different directions. If the corridor is connected to only one fire compartment and the fire compartment has at least one additional dedicated exit to street, the refuge corridor can be provided with only one discharging exit. The distance between the door leading to the refuge corridor of any fire compartment and the nearest discharging exit shall not be greater than 60m.
3. The net width of the refuge corridor shall not be less than the total net width of the designed exits leading to the refuge corridor in any fire compartment.
4. A smoke-proof lobby of more than 6 m^2 shall be provided when a room directly open to the refuge corridor to prevent smoke invasion to the refuge corridor.
5. Fire hydrants, emergency lighting, emergency broadcasting and pressurization system shall be provided for the refuge corridor.

This concept with the provisions has been included in the current code of practice [51]. It is one of the examples that the PBD solutions become the prescriptive requirements in code of practice as shown in Figure 1.

5.5 Structural Fire Protection

Fire resistance of structural members and partitions is an important part of the overall strategy in building fire safety design, which is passive means of fire protection. It is required in situations where the active fire protection measures have failed and the fire develops beyond the early stages to post-flashover stage and involves the whole compartment or whole building. The fire raises the temperature of structural members and threatens the safety of occupants and emergency services personnel if structural instability occurs, the potential for huge economic losses to the community also increases.

Traditionally, the fire resistance of structures is assumed to comply with the building regulations, which ensures that all the structural elements have adequate fire resistance and meets the safety requirements. The fire resistance of each element is determined by testing its performance in standard fire resistance tests, where isolated structural elements are exposed to standard fire. The time required for the element to reach failure is defined as their fire resistance. Failure is assumed if temperature of the structural member reaches 550 ºC [115]. On this basis, the fire resistance rating (FRR) for each type of structural member is given in the regulations or code of practice. In Mainland China, the FRR periods are defined as 3 hours for columns, 2 hours for beams, 1.5 hours for floors, and 1.5 hours for load bearing roof structure [51].

Structural design for fire is conceptually similar to structural design for normal temperature conditions, but structural fire engineering (SFE) design retains more load-carrying redundancy. Approach of SFE design can have two stages, namely element design and full-frame verification. However, SFE projects are seldom using the approach of full-frame verification, and likely adopting the element design method to ensure all structural members achieve their fire resistance requirements according to relevant standards.

Based on theory and fire tests mainly conducted by Tongji University and Tsinghua University, Code for fire safety of steel structures was published for SFE design guideline in 2017 [70]. With reference to the SFE design, structural PBD for fire safety has been developed in Mainland China in the past 2 decades, especially for steel structure. The PBD approach considers the credible worst fire scenarios rather than the standard fire curve.

In China, PBD for structural fire protection started with calculating the temperature of individual structural members using simple heat transfer model in the early 2000s. After that, an advanced approach was developed by adopting non-linear finite element tools to analyse the performance of the structural system in a fire environment.

5.5.1 Element design for fire safety

Limiting temperature method and load bearing capacity method are commonly used in SFE element design. The design process consists of various steps:

a) choose a time-temperature standard fire curve to reflect the fire performance of building material and elements in a compartment when affected by heat convection and radiation,
b) a critical temperature for structural elements (such as 550℃) to meet the code requirements based on loading analysis of structural design for normal temperature condition,
c) temperature calculation for unprotected/protected structural members based on heat transfer model,
d) comparison of the critical temperature and the calculated temperature for elements. If an element temperature is higher, additional fire protection measures shall be provided.

Shenzhen Swimming Centre was constructed in Year 2000. The Centre consists of 2 main buildings, swimming/diving halls and a water leisure centre. It houses various facilities, including carpark and plant rooms at basement levels, swimming pools, restaurants, coffee lounge, gymnasium, squash rooms, and a multi-function room. The hall roof is a long-span light-weighted steel structure. Following the code of practice, FRR of 1.5 hours would apply for the whole roof structure above the swimming pool. Fire protection coating for the roof structural members would be required.

The standard fire resistance tests for FRR requirement of the structural members in the fire codes do not reflect the actual fire scenarios in general. Particularly in swimming and diving halls, the fire load is very low with very high roof. The heat release rate (HRR) from a fire will not be severe to cause a failure of the roof structure members.

PBD for the roof structure of the swimming and diving halls of the swimming centre was conducted [116]. It is one of the first PBD projects in Mainland China. Based upon the usage of different areas under the roof, the HRR or design fire size at each location was estimated by considering the combustible materials, ventilation condition, fire protection provision and compartment size. For the worst-case scenario with the conservative HRR and close to the structure members, the steel temperatures of the structural members were calculated by using the simple heat transfer model. It was found that temperatures of various steel structural members of the roof were well below the critical temperature of 550 ^{o}C. The structural members of the steel roof would not be affected by the fire and smoke due to the roof height and low fire load. It was concluded that the fire protection coating to the steel roof structures was not necessary.

5.5.2 Full-frame system verification

Element design for fire safety of the individual structural members provides conservative solutions. The behaviour of the whole multi-building structure or the full structural frame in fire is very different from that of any single element of the structure. The full frame elastic analysis for structural stability considers: i) load transfer from the fire affected structural members to those unaffected members, and ii) tensile membrane action.

Because of complex loading and element interaction, it is hard to analyse the full-frame structural instability in fire using hand calculation. The advanced tools with nonlinear finite element models are required for structural system analysis under fire, such as ABAQUS, LS-DYNA, etc. Three-dimensional geometry of the finite element model (FEM) can be established on the basis of structural 3-D model such as Etabs, SAP2000 and YJK. By importing the worst load combination in normal temperature and fire load onto the FEM, the response behaviour of a full-frame structural system can be simulated and the visualized results provide the structural member's loading state in order to estimate whether structural failure occurs.

The China Central Television (CCTV) headquarter in Beijing is 234 m tall at its highest point and has approximately 400,000 m^2 of floor area including the basement and the podium. It consists of two leaning towers, which are linked together at the top via a 14-storey overhang bridge linked structure. The unique configuration of the building presented great challenges for its safety design to resist earthquake and fire. The approval authorities were very cautious and scrutinised the details during the approval process.

The specifications of fire resistance for the structural members met the code requirements. There were more stringent conditions imposed on design and analysis. For example, the failure temperature of individual structural member was set at 400 °C instead of 550 °C.

To check the level of safety of the overall structural system, 32 critical structure elements were selected for detailed analysis. All were found to satisfy the load bearing capacity criterion within the FRR limits. The temperatures of these individual members were below 400 °C except for 5 key members, which were higher than 400 °C but below 550 °C. Based on the location of these 5 structure elements, full-frame system verifications were carried out for these 5 specific cases with LS-DYNA. The results showed that the performance of the structural system was satisfactory in the worst fire scenarios. The approach was also adopted for Beijing CITIC Tower – the tallest building in Beijing [117], the high-speed rail station in Guangzhou, and more recently the Beijing Daxing International Airport [118].

5.6 Means of Escape

The evacuation safety is a big challenge for super high-rise buildings considering the large occupant number and the long evacuation time. A super high-rise building generally accommodates tens of thousands of occupants. The evacuation time using the stairs as the only means for evacuation is substantial. Occupants are required to travel long flight of stairs before reaching the place of ultimate safety. This is impractical, especially for those who are children, elderly, physically challenged or injured. Other concerns include the reverse flow of fireman and evacuating occupants, which induce a lot of uncertainty.

5.6.1 Lift-assisted evacuation

Lift assisted evacuation was first proposed in Shanghai World Financial Centre (SWFC) project in Mainland China, which was deemed to be one of the means of escape in this super high-rise building. The SWFC tower was the 2nd tallest building in Shanghai, with the height of 492 m. Total of 13 evacuation lifts were installed and served 4 lift transferring floors. These lifts with double deck are operating as shuttle lifts in daily operation. Occupants in the conservatory deck, hotel and office were proposed to adopt evacuation lifts to escape from the refuge floors immediately below the lift transferring floors to the ground. When lift assisted evacuation is being adopted, there are two scenarios for the evacuation:

1. When an event of fire happens, the occupants in the fire affected floor, the floor immediately above and the floor immediately below will be notified. The occupants evacuate to the nearest refuge floors and wait for further instruction. Normally, total evacuation of the entire building is not necessary. The occupants waiting on the refuge floor can choose to leave via lifts or walk down through stairs. The occupants on other floors are not required to evacuate immediately;

2. If the fire is out of control and the fire control centre decides to evacuate the entire building, it is proposed to apply the lift assisted evacuation strategy. The strategy is to manage some of the occupants will walk down via the staircases, and the rest will take the evacuation lifts.

During the fire emergency, designated lift operators will be assigned to operate the lifts for evacuation. Through the evacuation modelling analysis, the whole building evacuation time with lift-assisted scenario is 70 mins using the single-deck lifts, comparing to 110 mins for the scenario with stair evacuation only, as shown in Figure 4 [119]. Only one floor of the double deck lift has been designed for emergency use, the information of the double deck scenario in this figure is for comparison.

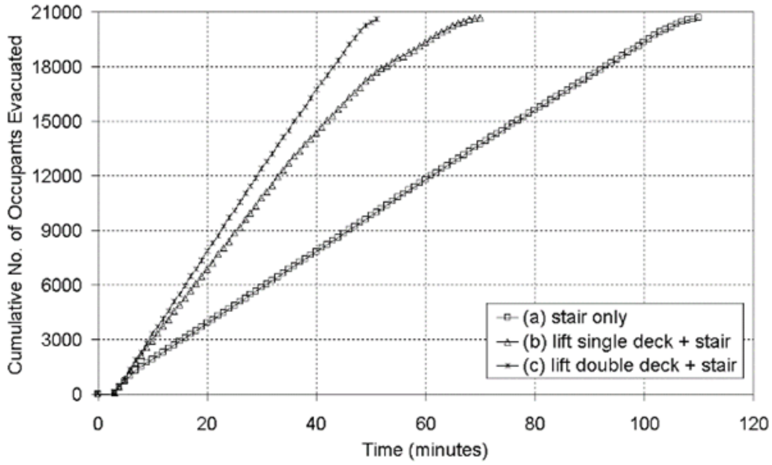

Figure 4. Comparison of whole building evacuation time with stair only to lift-assisted evacuation

5.6.2 Evacuation transition through refuge floor

In Mainland China, many huge mixed-use complexes with conservatory deck connecting multiple towers have been built in recent years. For example, the Chongqing Raffle City [120] comprised of 8 towers, which were connected via a conservatory level on the top and a podium level on the lower floors, as shown in Figure 5. Due to this unique design, the project presented many challenges, especially the evacuation strategy for the conservatory deck. A novel evacuation transfer concept was proposed on the conservatory level merging on refuge floors. With the high occupant load in the area, the proposed design included 15 egress stairs merging into 10 stairs in 5 towers beneath. To enable this design, a connecting refuge area was proposed below the conservatory level which was sized to provide enough space for people which would use it for each connecting stair and so reduce areas of congestion, as shown in Figure 6. Furthermore, the adoption of evacuation lifts was employed to improve the efficiency of the evacuation and also facilitate evacuation procedures for disabled people.

Figure 5. Chongqing Raffle City project night view

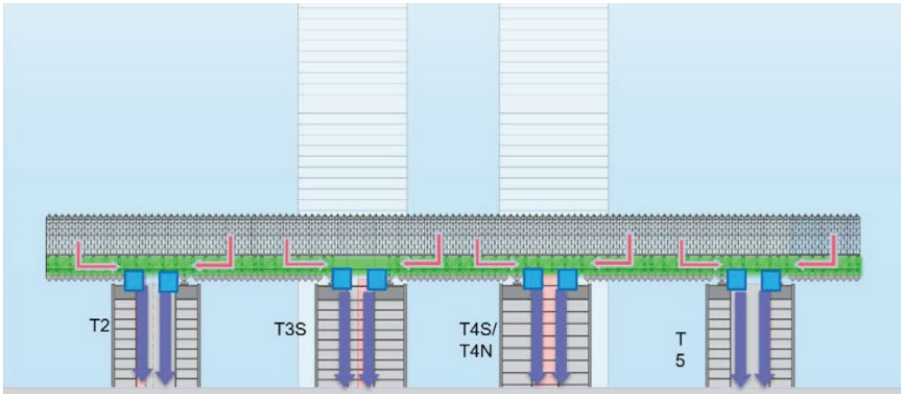

Figure 6. Sketch of evacuation transition through refuge floor

The evacuation stair transfer concept coupled with adopting the use of evacuating lifts on the refuge floor below the conservatory avoided unnecessary stair cores to be added to each tower. The evacuation lifts are used during normal circulation for vertical transport. This provides added efficiency to the design compared to having dedicated fire lifts which take up net lettable floor space with little use during normal operation.

5.7 Application of PBD

PBD has been adopted for a number of significant developments in Mainland China, including very large shopping centres, super high-rise buildings, large complex developments, Beijing Olympic projects, Shanghai Expo 2010, and underground stations. In this review, Beijing Capital International Airport Terminal 3, is used as an example to demonstrate PBD in China.

For architectural and functional reasons, transport terminal buildings are frequently designed to incorporate large un-compartmented spaces. The terminal building of Beijing Capital International Airport was the largest volume of a single building in the world in the early 2000s. The terminal is divided into three sections and connected with an Automated People Mover (APM) system. The length of the building is over 2000 m. The characteristics of the building are in the simplicity of its principal layout, the transparency and the lightness of spaces linked together under a long span roof. The spatial experience of the building is unique, and the design concept is clarity and convenience.

Airport terminals are important buildings. The Chinese fire code classifies the terminal as Type-A building and requires the fire compartment area to be limited 2000 m^2 [51]. To satisfy the operational requirements and the design concept, it is impossible for the terminal building to comply with the limit of compartment size.

Smoke extraction is an important component of the smoke control system. The fire codes require the extraction rate of the system to meet a certain air change rate per hour based on the volume of the space. The terminal building is basically a single space. It is practically impossible to provide an extraction system to meet the requirement for the whole terminal building.

A sprinkler system is required for fire control and life protection. The terminal building has a very high roof structure. The sprinkler heads would not operate for a fire at low level if the sprinkler heads were installed at the roof level. A sprinkler system covering the whole terminal building would require a massive capital investment and be ineffective.

5.7.1 Cabin concept and island concept

The cabin concept is developed to prevent spreading fire and smoke in large spaces. The principle of the cabin concept is to provide protection to the areas of high fire load, whilst permitting flexibility in use of the large space without physical compartment walls. The essential elements in a "cabin" include:

- Smoke reservoir at the area of high fire load.
- Fire detectors in the reservoir and alarm.
- Combined smoke extraction and ventilation systems.
- Sprinkler system.

Figure 7 illustrates the design of the cabin. The front of the cabin is open to allow people movement in all scenarios. A bulkhead and smoke curtains form a smoke reservoir over the protected area. The smoke curtains automatically drop to certain height (i.e. 2 m above the floor) when a fire is detected by the smoke detection system. A smoke extraction system is applied to the protected area and the extraction rate of the system is based on the heat release rate (HRR) of the fire or the design fire, which represents the worst case. Smoke will not spread to the adjacent zones with low fire load. A sprinkler system is designed to protect the areas of high fire load, and installed on the ceiling of the cabin instead of the roof of the terminal building.

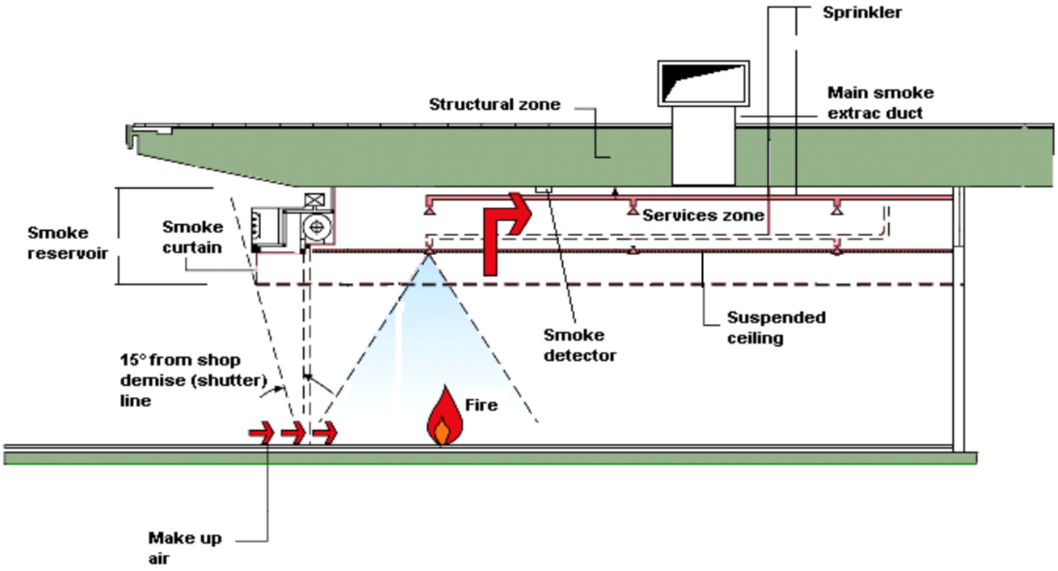

Figure 7. Sketch of open cabin

Fire load in the terminal building is not evenly distributed over the entire floor area. There are small parts of spaces used for shops, restaurants and other purposes, which are classified as high fire load areas. The rest of the areas and public circulation areas have typically a very low fire load. Protection of such low fire load but tall spaces with sprinkler system and smoke extraction system becomes unrealistic, expensive and unnecessary. The cabin concept fits the purpose of protection to the high fire load areas, and at the same time, provides flexibility in use of the large space without physical compartment walls. Figure 8 demonstrates the application of the cabin concept to the concourse of the terminal building of the Beijing Capital International Airport Terminal 3.

Figure 8. Application of cabin concept design to the Beijing Capital International Airport Terminal 3

In areas, which are protected by the cabin concept design, the chances of fire spread away from the area of fire origin are small. However, there is a chance that a sprinkler system might fail to control a fire. The concourse areas in the terminal building cannot be protected by a sprinkler system due to the high ceiling, and interconnection for circulation purposes under very high ceilings. An island concept was introduced to these areas to ensure that uncontrolled fire spread across large areas would not occur [109].

Fire spread between isolated packages of fuel occurs when the heat flux impinging on the fresh fuel is sufficiently high to result in ignition. The fresh fuel outside the plume of hot gases is ignited as a result of radiation heat from the flame of the fire and smoke. In a small compartment, radiation from the smoke layer is of great importance and leads ultimately to flashover. In a compartment with a high ceiling the smoke layer will be relatively cool due to the high level of air entrainment in the fire plume. Radiation from the smoke will be low and fire spread will depend upon radiation from the flame.

The radiative heat flux required for ignition has been studied in detail. The value for instant ignition varies with types of materials from 10 to 20 kW/m^2 [121]. On this basis, a minimum distance between two separated packages of fuel, i.e. seats or moveable kiosks, can be estimated to prevent horizontal fire spread. For the Beijing Capital International Airport Terminal 3, the fire size of an isolated fuel island has been controlled within 5 MW, which is equivalent to an area of a 9 m^2 kiosk in fire. Refer to NFPA 92B [122], the minimum distance between two islands is estimated in 3.6 m.

5.7.2 Phased evacuation and analysis

The terminal building comprises a number of large interconnected spaces. These spaces require special attention as the nature of the space makes it unsuitable to apply the prescriptive requirements in the fire codes. The means of escape from the terminal has been designed as far as possible to follow the normal passenger flows during emergency evacuation. The purpose is to enable passengers to identify logical and obvious escape routes that lead to fresh air. The visibility within the terminal is very good in public areas contributing to the passengers' understanding of the building and allows them to make informed decisions when confronted with an emergency.

This is a major international airport. The overall design is spacious to promote smooth and efficient flow of people at all times. This serves passengers well under emergency conditions. The high degree of management and control of passengers in normal operation of the airport means that people can receive information that allows them to respond appropriately in an emergency.

There are large number of people in the airport terminal. It is appropriate to concentrate on evacuating the area immediately at risk from the fire. Evacuating the whole building is not necessary. Furthermore, it is very difficult to evacuate the whole building because of the large numbers of people involved, the area that needs to be cleared, and the need to prevent mixing of airside with landside, and international with domestic wherever possible. Consequentially, a phased evacuation was adopted so that the evacuation could be managed effectively.

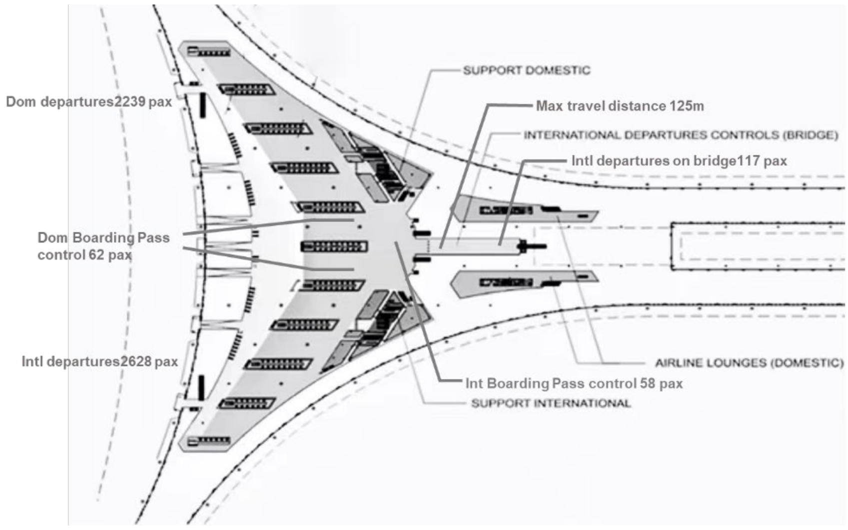

Figure 9. Fire Zone T3A 04, the check-in hall on level 4.

Notwithstanding that, it is undesirable from a management and commercial standpoint, to evacuate the whole building in the event of a minor fire in one area. However, the design of the means of escape provisions was such that total evacuation would be possible if thought to be necessary. This would only be necessary in the case of an extreme event. In general, it was proposed to manage the evacuation in stages with the safety of those who remained in the building being safeguarded. Management of the evacuation and firefighting would be co-ordinated from the Fire Control Centre.

In order to facilitate phased evacuation, the terminal was virtually divided and managed in a number of Fire Zones. Smoke control measures were employed to ensure that an incident in one zone would not adversely affect another. Figure 9 illustrates Fire Zone T3A 04, the check-in hall on Level 4. The phased evacuation approach would not prevent those passengers who felt under threat from using emergency exits. Where evacuation would take place onto the apron on air site, people were led under management supervision to a place of safety, away from the terminal building and away from the aircraft. Evacuation would stop once the initial event was brought under control.

The number of passengers is not governed in any simple way by floor areas. Occupancy density varies considerably with the different areas of an airport and between different airports. In order to obtain the best estimates of passenger loads the population figures based on passenger throughput were used instead of the occupancy load factors prescribed in the fire code. Based on the peak hour passenger flow rate and the dwell time, the number of occupants in each fire zone were estimated. Table 4 gives the results of Fire Zone T3A 04. The number of people at the controlled locations are marked in Figure 9. The total number of passengers in Fire Zone T3A 04 is 5600.

There are 9 protected stairs of 1.5 m width leading to landside exits at ground level, and 10 entrance doors of 2 m width each, leading to the external roadside. The total egress time for all passengers in this area through the exits is 3.3 mins. In this fire zone, the maximum travel distance is about 125m, the maximum travel time is about 2 mins.

Table 4: Number of occupants in Fire Zone T3A 04

Type of accommodation	Traffic	Flow people/hour	Passenger numbers in T3A Level 4
Departure Hall Domestic	DOM Departure (landside) peak hour with greeters, dwell time 30 (mins)	4478	2239
Departure Hall International	INT Departure (landside) with well wishers (50%) at peak hour, dwell time 30 (mins)	5255	2628
Boarding Card Control	INT Departure (landside), dwell time 1 (min)	58	120
	DOM Departure (landside), dwell time 1 (min)	62	
Bridge before Escalator down to APM (Int.)	INT Departure (landside) Dwell time 2 (mins)	117	117
Total Number of Passengers and well wishers			5093
Add 10% staff	**Total Occupants in this area**		**5600**

5.7.3 Smoke management

As the high fire load areas, such as retail shops and services counters, were protected with the Cabin concept design. The smoke extraction system was provided in the cabin. The extraction rate was based on the heat release rate (HRR) or the design fire size in its worst scenario.

However, in the event that an island or a baggage fire occurred in the circulation area or smoke to spill out from the cabins, a smoke clearance system was provided at the terminal roof. The clearance system comprises of aspirating smoke detection system, smoke vents on the roof, and smoke clearance fans. The system was designed for clearing the diluted cool smoke with much reduced capacity compared with the prescriptive requirements.

5.7.4 Fire safety management

Fire safety management is an important part of fire safety engineering design. The management at least covers the following areas:

Housekeeping management: The housekeeping management ensures the fire load in each area to be controlled and to meet the requirement of PBD. For example, the area of an island is less than 9 m^2 and the distance between two islands is greater than 3.6 m.

Evacuation management: For the areas of limited fire load or where the fire load is controlled by active systems, it is unlikely that a fire will spread quickly to affect the areas remote to the area of fire origin. Due to a large population in the terminal building, it is not realistic, or indeed necessary for occupant safety, to evacuate the whole building. A phased evacuation scheme is therefore adopted if a fire occurs. The scheme initiates immediate evacuation of the area of fire origin and alerts the adjacent areas. The remote areas are informed and maintained the normal business. Staff members instruct the evacuation procedure.

Staff training: Staff members play an important role on fire safety management, including fire load control, phased evacuation procedure and other safety issues. It is very important that the staff members are trained regularly to understand the fire safety management, to handle the emergency situation and to guide the passengers to the pre-designed means of escape during evacuation.

6. Summary

Fire engineering as a discipline has experienced fast development since the 1980s. Fire safety requirements for buildings and infrastructure facilities were driving the changes of the fire regulation system. In the UK, the prescriptive fire regulations were simplified and the functional requirements were provided with fewer details after 1985. The regulations became performance-based documents which call the BSI standards for the technical specifications. With the change, the design of buildings was moved to performance-based approach in the late 1980s.

Australia, New Zealand, and some other European countries followed the UK's approach and reformed the prescriptive regulation system and adopted the PBC in the early 1990s. The USA also developed its PBC, namely ICCPC Code and NFPA 5000, in the late 1990s and were available in the early 2000s. Performance-based approach for fire safety design became a global trend in the past 3 decades.

The Hong Kong fire regulations were closely related to the UK system due to historical reasons. The performance-based approach for fire safety design in the UK was quickly introduced in Hong Kong and adopted for significant infrastructural projects. PBD approach has been applied for the Hong Kong International Airport and the MTR stations since 1992. Following the regulation changes in the UK and other western countries, the Hong Kong prescriptive codes recognised the PBD approach for practice in 1995. With over 10 years of experiences in PBD for projects, Hong Kong SAR launched a programme to reform the whole regulatory system in the early 2000s.

In view of the status of building fire safety level, it was revealed that Hong Kong had a very good record compared with the overseas countries in terms of risks to life if adopting the number of fire deaths per million population per year. This finding of the review process formed the basis for developing the PBC in the 2000s. The Hong Kong Government officially published the PBC entitled "Code of Practice for Fire Safety in Buildings" in 2011.

The fire regulations in Mainland China followed those developed by Soviet Union in the 1950s and 60s. Until the 1980s the reform and opening policy boosted the development of the building industry. In the late 1990s and 2000s, super high-rise buildings and mega infrastructural projects emerged in many cities. The Government issued the fire codes for high-rise building and low-rise building respectively in the mid-1980s to meet the requirements of fire safety design. These two codes were revised periodically in the 1990s and merged into one as "Code for fire protection design of buildings, GB50016-14" in 2014.

The abovementioned fire code does not recognise PBD and a PBC system is not available to date. The legal status of the approach of PBD and the approval procedure of the PBD projects are based on the Administrative Act issued by the Ministry of Public Security. In Beijing and Shanghai, the local Government issued the guidelines of PBD. In general, for significant developments such as airport terminal buildings, railway and underground stations, Olympic projects, super high-rise buildings, and very large shopping centres, the authorities agree to adopt PBD. The approval of PBD has been on a case-by-case basis.

The PBD approach for fire safety in buildings created an environment for innovation. Many significant projects have been constructed in Mainland China in the last 30 years, including the Beijing Capital International Airport Terminal 3, the China Central Television headquarter building, the Shanghai World Finance Centre, the Chongqing Raffle City, etc.

Mainland China has not published the PBC as part of the fire regulation system. However, some of the performance-based solutions advanced in the past 20 years have been incorporated in the updated codes of practice and technical standards. The high wave of adoption of PBD for those projects of Beijing Olympic 2008, Shanghai Expo 2010, and other mega infrastructure facilities triggered the concerns of non-compliance with the fire regulations. On one hand the authority updated the codes of practice incorporating the matured PBD solutions, on the other hand the authority tightened the approval process of PBD approach. The number of PBD cases have shrunk in the past few years. This trend may continue.

In the past 30 years, the fire engineering community in Mainland China has made great efforts on research. The work covered broad areas, including fire model, smoke control, detection, suppression, firefighting, etc., with new equipment and new technology.

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