The Goals and Objectives of Project FAIL-SAFE

The addition of redundant layers of safety is a well-established practice within the safety community, and one the National Association of State Fire Marshals (NASFM) has championed for nearly two decades. We are reminded of the aviation industry's duplicative efforts to guard against catastrophic failure, and the automotive industry's exhaustive pursuit of higher levels of safety. As buildings get larger, taller, and more complex, NASFM remains steadfast in our pursuit to ensure buildings are designed and constructed with the same care and concern for safety that we have come to expect from the transportation industry.

The research documents that follow have been produced under the NASFM Fire Research & Education Foundation's Project FAIL-SAFE. This research effort is charged with establishing valid scientific information to serve as a baseline for understanding the effects of incorporating safety layers into the built environment. It must be noted, clearly and distinctly, that this is not a discussion advocating one product over another, or active vs. passive; but rather it is a discussion around safety and resiliency of the built environment. In short, FAIL-SAFE is a research project designed to evaluate existing levels of redundancy to determine acceptable levels of safety should any individual system within the protective envelope fail to function as designed.

Each parcel of the research effort is designed to provide information to advance the understanding of the value of safety layers. As such, they should not be taken individually, but considered holistically with a focus of developing a baseline of knowledge from which further discussion and research will emanate. To that end, the NASFM Foundation commissioned an analysis of tradeoffs in the IBC based on both occupancy and building type to provide focus for subsequent phases of the project. Utilizing the results of the analysis for clarity, the following literature review report was completed by Worcester Polytechnic Institute (WPI). Its goal was to identify what is known scientifically, and what is not known, about how fire protection features interact with one another to increase safety and building resiliency.

Again, building on the direction gleaned from the code analysis and literature review, computer modeling was designed to better understand the knowledge gaps identified by the previous work. WPI was commissioned to continue their work by developing a fire modeling plan designed provide initial answers to the identified knowledge gaps.

Simultaneously, we have undertaken development of the NASFM Foundation Safety Layering MATRIX™. The MATRIX™ is an on-line application that applies standing International Existing Building Code evaluation techniques to understand the overall fire risk associated with existing buildings. Utilizing the data input from the application, an analysis is being performed to study the impact of various fire protection features in the building co and their resultant impact on fire risk.

Evaluating a real-world collection of building inventory from representative areas across the country, with the academic research performed by WPI, a comprehensive picture is being developed to advance the discussion and importance of redundant layers of safety in the built environment.

The principal membership of the National Association of State Fire Marshals (NASFM) comprises the senior fire officials in the United States and their top deputies. The primary mission of NASFM is to protect human life, property and the environment from fire and related hazards. A secondary mission of NASFM is to improve the efficiency and effectiveness of State Fire Marshals' operations. Learn more about NASFM and its issues at www.firemarshals.org.

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A Literature Review of Sprinkler Trade-offs

by

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Abstract

Over the decades, Automatic Sprinkler Systems have acted as a most effective fire protection method, yielding considerable reductions in the number of deaths and property damage in fires. When installed correctly throughout a building, sprinklers are reported as effective in 87% of fires big enough to activate them.

Because Automatic Sprinkler Systems have been deemed by many as providing an adequate level of fire safety, building codes like the IBC and NFPA 5000 have introduced accumulated relaxation or trade-offs of building regulations involving increase of building size, travel distance, exterior wall's unprotected opening area limits and decrease of fire resistance ratings, etc. Although the basic concept of sprinkler trade-offs is that sprinklers can achieve an equal or better fire protection performance compared with the measures being traded off (most of them are passive fire protection approaches), the introduction of them was initiated for cost-savings only. Within the limits of investment, sprinklers are said to be more cost-effective than other fire protection systems, which adds to the appeal of sprinkler trade-offs. However, some researchers believe that fire alarm systems are more cost-effective than sprinklers.

Except for economic considerations, most of the trade-offs are put forward based on descriptive explanations, lacking scientific quantitative analysis. Current prescribed codes stem from human beings' historical painful experiences with uncontrolled fires, thus most of the provisions are empirical. Building codes have been in force for a long time providing a common-sense representation of widely accepted fire safety level. Without support from technical research, the potential risk of sprinkler trade-offs are unknown.

The purpose of this review is to understand current knowledge and suggest what we should do as next steps to fill gaps between building code requirements and the underlining necessary science. It begins with current debates on sprinkler trade-offs, then focuses on topics of interest based on sprinkler trade-offs from employing the NASFM FOUNDATION Fire Incident Risk Evaluation (FIRE) Tool, investigating current published research on sprinkler effectiveness/reliability and sprinkler trade-offs for building size, fire resistance ratings, exterior wall's unprotected opening areas, fire safety systems (manual fire alarm box), and egress (travel distance/dead end length), etc. As a very important aspect influencing tenability criteria and radiation levels, smoke behavior under activation of sprinklers are also addressed as well as the effects of sprinkler trade-offs on buildings' resilience and firefighters' safety.

Major findings from the literature review include: 1) many provisions in the current prescribed codes are empirical; 2) many sprinkler trade-offs are scientifically baseless; 3) sprinkler trade-offs for fire resistance ratings are only partly supported by research using probabilistic risk analysis methods; 4) sprinkler trade-offs for exterior wall's unprotected opening area could be implicitly verified by fire tests designed to study the interactions of sprinklers with smoke layer behaviors; 5) sprinkler trade-offs for travel distance/dead end length are potentially not well founded as sprinklers fail to improve the tenability criteria of visibility, although sprinklers could be very effective in improving other tenability

criteria like heat flux and toxicity; 6) sprinkler trade-offs could be detrimental to disaster resilience of buildings; 7) sprinklers may be very helpful to firefighters' safety in that they are able to reduce the risk of a fully developed fire/flashover, but sprinkler trade-offs may offset advantages from sprinklers in that they will position firefighters in a more dangerous situation if sprinklers fail to be effective.

For next steps, three available approaches are recommended to further investigate sprinkler trade-offs: fire modeling, full-scale experiments, and fire risk analysis. Besides the four major sprinkler trade-offs: building size, fire resistance ratings, unprotected opening areas and travel distance, two other topics are addressed: effective area of sprinkler and baseline tests. The former tries to check sprinkler effective boundaries mainly by employing fire modeling, the latter are to check what sprinklers alone can do without the help of other passive fire protection measures by employing fire modeling and full-scale experiments method.

The literature found during this review is divided into References that directly relate to our main concerns and a bibliography of sources that does so indirectly.

Acknowledgement

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1. Introduction

1.1. Background

1.1.1. History of trade-offs

The term “trade-offs” means to obtain one benefit with the cost of losing another benefit. Although the concept of trade-offs has existed and been adopted for a long time in our ordinary life, in the area of fire protection engineering sprinklers it was first introduced in the Report “America Burning”, first released in 1974[1] and then revisited in 1987[2], advocating reduction of fireproofing requirements by installation of sprinklers. Some proponents even dislike the term “trade-off”, they prefer to use “trade-ups” or sprinkler advantages since they believe an increased level of fire safety could be arrived at by the installation of an automatic sprinkler system [3-5].

Concepts involving sprinkler trade-offs can be traced to changes in the Building Officials Code Administrators International (BOCA) National Building Code in the early 1970s which encouraged sprinkler protections by reason of reduced overall construction costs for tall buildings, since then they have been increasingly adopted by buildings codes [6-11]. It is a challenge to identify the intended minimum level of protection in the code [12]. Historically, BOCA International, the administrator of the BOCA National Building Code (BNBC) and one of the three legacy organizations who merged to form the ICC, was very active in the development of fire protection requirements for the BNBC. In September 1987, BOCA appointed an ad hoc committee to study fire protection systems. One of the tasks was an examination of the requirements for fire suppression and detection systems with a purpose of providing a rationale for each requirement [12]. Many of their conclusions were adopted in the BNBC through the last edition of the BNBC, the 1999 edition, and are currently found in the IBC. Unfortunately, the code development documents from that time period are not currently available in electronic form. For more information on the BNBC, contact Mike Pfeiffer at mpfeiffer@iccsafe.org, who is currently the Senior Vice President of Technical Services for ICC and who worked for BOCA during that time frame. The new International Building Code (IBC) has facilitated the accumulation of sprinkler trade-offs [13].

In the viewpoint of economy, the building code tends to set an equal risk level for all kinds of buildings with different combinations of occupancy groups, type of construction, and fire protection/suppression methods. For each occupancy group or subgroup a different set of fire-protection requirements, height and area limitations, and exit facilities are usually needed in order to achieve equivalent safety in building design. It is reasonable to accept any combination of safety measures as long as it does not decrease the safety level accepted by society [10,14]. Since an automatic sprinkler system is believed to be able to reduce the fire risk level of a building, to achieve “an equal risk level”, the building is allowed by building code to adopt less restrictive regulations on passive fire protection systems. Other financial incentives for installing sprinkler systems include site development incentives and insurance and tax breaks [15]. Since 1988, the National Fire Sprinkler Association (NFSA) has begun to advocate the concept of economic incentive in building codes for sprinkler protection, and these incentives to be achieved by reduction or deletion of other such measures and devices that are deemed to be able to increase total building construction costs without generating an appreciable additional increase in overall fire safety. On the other hand, in the viewpoint of safety, for certain categories of buildings increased levels of fire protection, regardless of cost, are expected and could be achieved by cooperation of passive fire protection systems with automatic sprinkler systems [5].

Apparently, the concept of trade-offs in fire protection engineering is appealing to those focusing more on cost effectiveness than on a higher fire safety level in a building [16]. But the absence of a quantitative method to prove the appropriateness of "trade-offs" accruing from sprinkler systems makes the current existing trade-offs in building codes somewhat arbitrary in nature, which has been admitted by an author who advocates sprinkler trade-offs[17]. The need to identify designed levels of protection, or in other words to confirm the intended minimum levels of fire protection announced by Building Codes, has been a primary challenge for decades.[12].

1.1.2. Debates about trade-offs

Different views on the rationale of trade-offs exist. The proponents of trade-offs believe that the excellent performance of automatic sprinkler systems deserves cost reduction of buildings in passive fire protection features in order to encourage the application of sprinklers. The opponents argue that the main purpose of an automatic sprinkler system should be to enhance the fire safety level including life safety and building conservation, not to reduce the cost of construction by trading-off the passive fire protection features. Most of the trade-offs lack substantial scientific research. Admittedly, even the original regulations about passive fire protection features lack substantial scientific research since they were originally established after incidents of significant scale drawing attention to specific building design issues, but they do provide a widely accepted fire safety level in practice based on loss history data. Since most of the building regulations about passive fire protection features have acted as a cornerstone of building fire safety for a much longer time than the advent and adoption of sprinkler trade-offs, the action to remove them without enough scientific research is arbitrary and potentially risky.

The view points from opponents and proponents are shown in **Table 1** and **Table 2** of APPENDIX 1, from which the contemporary debates about sprinkler trade-offs could be summarized in the following aspects [3,5,6,17,18-31]:

- The effectiveness of sprinklers are widely accepted by both opponents and proponents
- Most, if not all, trade-off opponents advocate a balanced fire protection system including both sprinklers and passive fire protection approaches
- Most, if not all, trade-off proponents believe sprinklers deserve more trade-offs in passive fire protection approaches
- Both the opponents and proponents failed to persuade the other side by demonstrating necessary proofs that are reasonable, scientific, and quantitative

- Sprinklers are effective in protecting both life safety and property.
- Without deeper research that could provide enough scientific and quantitative proof for each side, this kind of debate will continue in the future.

1.2. Experience with the NASFM FOUNDATION FIRE Tool

By applying the NASFM FOUNDATION Fire Incident Risk Evaluation (FIRE) Tool with inputs from different building designs, we find that an Automatic Sprinkler System yields trade-offs in the following aspects if the Occupancy Groups and Types of Construction are within the ranges presented in the NASFM FOUNDATION FIRE Tool flow chart, namely, Occupancy Groups A-2, A-3, B, E, I-1, I-2, R-1 and R-2 are considered.

1.2.1. Building area

- For Type IA and Type IB construction, the building areas are unlimited for all occupancy groups but I-1 whose building area is allowed to triple as a result of sprinkler trade-offs.
- For other types of construction, building areas are tripled as a result of sprinkler trade-offs, with an exception of unchanged building area when S-13R sprinkler systems are installed.

1.2.2. Building height in feet/stories

- For Type IA construction, the building heights are unlimited for all occupancy groups except R Group equipped with S-13R system.
- For occupancy Group R equipped with S-13R system, the building height of all construction types are 60 feet and 4 stories except for Type V-B construction type which allows 3 stories.
- For other occupancy groups and construction types, 20 feet or 1 story increase in height.

1.2.3. Fire resistance rating

- For building elements (non-exterior walls), reduce rating by 1 hour
- For corridor walls, dwelling unit/sleeping unit separations in construction Type IIB, IIIB and VB , reduce rating to 1/2 hour
- For hazardous areas like furnace room greater than 400,000 Btu, reduce rating to 0 hour, only smoke resistance is required.

1.2.4. Exterior wall’s unprotected opening limits

Increase of unprotected opening areas with respect to different Fire Separation Distances (FSD) are:

- 15% for FSD being equal or greater than 3 feet but less than 10 feet
- 30% for FSD being equal or greater than 10 feet but less than 15 feet
- 50% for FSD being equal or greater than 15 feet but less than 20 feet

- Unlimited for FSD being equal or greater than 20 feet

1.2.5. Egress

- Travel distance increase of 50 feet for Group A, E, R, and an increase of 100 feet for Group B.
- Increase of travel distance of common pass is 25 feet for Group B Occupancy when Occupant Load greater than 30 people
- Dead end length increases 30 feet for Group B, E, I-1, R-1, and R-2.

1.2.6. Fire safety system

- Removal of the requirement of more than one manual fire alarm box.

2. Focus Areas and Literature Searching Methods

2.1. Focus Areas

Two types of focus areas were investigated in this review: sprinkler trade-offs and other interesting topics related to sprinklers.

2.1.1. Sprinkler trade-offs

As to each of the five major kinds of sprinkler trade-offs, namely building size, fire resistance rating, exterior wall's unprotected opening area limits, egress, and fire safety system (manual fire alarm box), two fundamental questions will be addressed in this review:

- What we know from the literature
- Literature knowledge gaps in the context of holistic building performance/fire risk

2.1.2. Other interesting topics related to sprinklers

The following areas, due to their importance, will also be discussed in this review.

1) **Sprinkler reliability**
- Definition of sprinkler reliability or effectiveness
- The system-based (incident data) effectiveness/reliability
- Component-based reliability
- Failure modes of a sprinkler system
- Comments on the present studies on sprinkler reliability

2) **Interaction of sprinklers with smoke**
- Different opinions upon the effects of sprinklers on smoke and related studies
- Conclusion of contemporary studies

3) **Building resilience**
- Definition of resilience
- Resilience of built environment
- Effect of sprinkler reliability on building resilience
- Effect of sprinkler trade-offs on building resilience

4) **Firefighter safety**
- Current studies on firefighter fatalities
- Effect of sprinkler reliability on building resilience
- Effect of sprinkler trade-offs on building resilience

2.1.3. Topics out of the scope of this report

The following topics, although to some extent related to sprinklers' trade-offs, will not be discussed in a same depth as listed in 2.1.2 in order to ensure the core concerns to be addressed in some detail:

- Building resilience topics other than fires after disasters, like emergency responder capability and access
- Sprinkler trade-offs for fire service like fire apparatus access road distance and hydrant spacing which are stated in the International Fire Code (IFC)
- Sprinkler trade-offs for fire resistance ratings of specific building assemblies like fire walls, corridors
- Sprinkler's capability of extinguishing a fire
- Consideration of the full intent of building codes including emergency responders' safety, public health and general welfare.

2.2. Search Engines Used

2.2.1. IAFSS.org: fire research engine

The fire research engine in IAFSS.org is a very convenient search engine in the area of fire research. When you input some specific keywords, it will seek what you designate in many different sources (**Table 3** of the APPENDIX 1).

2.2.2. WPI library databases: Science Direct

Some papers listed in the "fire research engine" couldn't be downloaded, in this case Science Direct in WPI library databases works well.

2.2.3. Google/Google Scholar

There are many fire related articles written by engineers, experts, scholars, or even reporters and journalists. Although these articles are less academic, they do present valuable information.

2.3. Sources of Literature Investigated

2.3.1. Peer reviewed articles from journals or conferences

- Accident Analysis and Prevention
- Automation in Construction
- Advances in Engineering Software
- Building and Environment
- Bulletin of Japan Association for Fire Science and Engineering
- Case Studies in Fire Safety

- Engineering Structures
- Fire Safety Journal
- Fire Science Reviews
- Fire Technology
- International Journal on Engineering Performance-Based Fire Codes
- International Symposium on Safety Science and Technology (2014ISSST)
- Journal of Hazardous Materials
- Journal of Loss Prevention in the Process Industries
- Journal of the Council on Tall Buildings and Urban Habitat (CTBUH Journal)
- Land Use Policy
- Mathematical and Computer Modelling
- Progress in Structural Engineering and Material
- Process Safety and Environmental Protection
- Reliability Engineering and System Safety
- The 9th Asia-Oceania Symposium on Fire Science and Technology
- The 23rd Conference on Passive and Low Energy Architecture

2.3.2. Reference texts or textbooks

- An introduction to fire dynamics, 3rd edition
- SFPE handbook, 5th edition
- Practical fire precaution, 2nd edition

2.3.3. Non-Peer reviewed articles from journals or conferences

- Architectural Science Review
- Building Standards
- Fire Engineering
- HERON Journal
- Plumbing Engineer
- Sprinkler Quarterly
- STATYBA
- Ulster Architect Magazine

2.3.4. Government, association, company, etc. reports

- American Iron and Steel Institute (AISI)
- Building Research Establishment (BRE)
- Communities and Local Government: London
- Firestop Contractors International Association (FCIA)
- Fire Research Note of FIRE RESEARCH STATION
- FM Global
- Governor’s Council Task Force Performance-Based Design in Minnesota

- Hughes Associates, Inc.
- International Association for Fire Safety Science (IAFSS)
- International Firestop Council (IFC)
- International Code Council (ICC)
- MST Building and Fire Research Laboratory
- National Fire Protection Association (NFPA)
- National Fire Sprinkler Association (NFSA)
- National Research Council Canada (NRC)
- New Zealand Fire Service Commission
- The Fire Protection Research Foundation
- The Society of Fire Protection Engineers (SFPE)
- Underwriters Laboratories (UL)
- VTT (Finland)

2.3.5. Newspaper articles/newsletters

- http://vincentdunn.com/
- Washington Post

2.3.6. University/College theses/reports

- School of Engineering, University of Canterbury, New Zealand
- Department of Fire Safety Engineering and Systems Safety Lund University, Sweden
- Department of Mechanical & Environmental Engineering University of California at Santa Barbara, U.S.A.
- Department of Building Services Engineering, the Hong Kong Polytechnic University, Hong Kong, China
- Centre for Environmental Safety and Risk Engineering, Victoria University of Technology, Australia

3. Findings in Each Focus Area Relative to Sprinkler Trade-offs

3.1. Building Size (Area and Height)

3.1.1. What we know from the literature and identified gaps in the context of holistic building performance

Scholars have articulated good reasons for the need to set limits for building size, as shown in **Table 4** of APPENDIX 1[32-36,85], from which it could be concluded that building size limitations serve some important functions. First, they limit the amount of fuel available that may be exposed to a single fire incident, limit the fire load, and thus limit the fire severity, and therefore limit the emission of toxic products or greenhouse gases. Second, they limit the number of persons at risk in any single fire incident. Last but not least, they limit the potential fires within the capability of local fire departments

In the past two decades, sprinkler trade-offs about building size in some Occupancy Groups have increased more than 200% [11], but relatively few literature sources have addressed the appropriateness of the extent for sprinklers to trade-off building size limitations, as shown in **Table 5** of the APPENDIX 1 [34-37,85]. Due to the complicated interaction of sprinklers with building size, these authors analyzed the reasonableness of sprinkler trade-offs in a narrative and qualitative way, without developing predictable relationships between sprinkler trade-offs and buildings' specifications (construction types, occupancy groups, etc.). Admittedly, it is hard to relate the benefits of sprinklers to building size. As will be discussed later in this paper, some partly acceptable methods are available to relate the benefits of sprinklers to fire resistance ratings (fire resistance levels). However, the effects of enlargement in building size on building fire safety, although always being negative, are more intangible and immeasurable. A change in building size means changing everything related to fire safety, involving fire load/fire severity, occupancy load, unprotected opening areas, maximum travel distance, etc.

From the literature sources, we know why building size should be limited, but the processes to determine an exact building size are still obscure. Although the cubic capacity concept provided a direct link between the (building size) limit in the building code and the capability of a "well organized" and "properly equipped" fire brigade [14], this kind of link was mainly based on personal experience, not experimental or analytical analysis. The concept of trading-off building size due to the installation of a sprinkler system might be justified but lacks quantified analysis of the exact extent for building sizes to be traded-off. One of the common excuses is that the total fire area of a building is irrelevant when a fire is controlled or extinguished at the point of origin by automatic sprinkler systems [85], which implies a perfect sprinkler reliability. Therefore the common trade-offs of building sizes being 200% or 300% increased as listed in IBC codes are not well founded quantitatively.

Scale is always the most important parameter when we study physical processes. Building size is one kind of fundamental parameter when we are going to contemplate building fire safety, especially holistically. Undoubtedly, the regulations of building size are based on considerations of holistic building performance/fire risk, especially life safety, and capability of fire services. Building sizes are the most important characteristics of a building whose changes will affect almost every function in the building, so further scientific research is essential when size is subject to change no matter what the reasons are.

3.2. Fire Resistance Rating

3.2.1. What we know from the literature and gaps in the context of holistic building performance

In modern building codes, fire resistance is defined, with respect to certain construction assemblies, as the ability to confine a fire to a given area or to continue to perform structurally when exposed to fire, or both [15]. Fire resistance is usually rated by fire endurance which is the time period during which a material or construction assembly continues to exhibit fire resistance and to perform these functions when exposed to fire. Other definitions of fire resistance, its failure criteria as well as its functions, are shown in **Table 6** of the APPENDIX 1[38-41]. According to this table, by providing necessary stability, integrity, and insulation, fire resistance rated building elements could confine fire and smoke within a compartment, limit deflections, and prevent collapse.

Therefore, the main reasons for providing elements with fire resistance are [40]: (1) to protect the escape paths from the building, (2) to prevent fire spreading from room to room on the floor of fire origin; (3) to prevent spread of fire to upper floors of the same building; (4) to control external fire spread to adjacent buildings; (5) to prevent collapse of parts of buildings or the entire building. To achieve these functions, the current U.S.A. codes in practice specify minimum required fire endurance times (or fire endurance ratings) for building elements and accepted methods for determining their fire endurance ratings [39], whereas the fire resistance ratings are in turn set based upon the anticipated fire load for the occupancy (not ventilation or thermal properties of the boundaries), the importance of structural members, as well as the height and area of the building[42,43].

The proponents of sprinkler trade-offs argue that the effects of sprinklers are equal to one hour's fire resistance rating, so fire resistance should be relaxed or eliminated when buildings are equipped with sprinklers[38]. However, active fire protection approaches like automatic sprinkler systems usually work in a different way from passive fire protection approaches. The sprinkler trade-offs for building elements' fire resistance ratings usually are based on lowering safety factors (the ratio of design value to characteristic value) [35]. Due to considerable uncertainties, it is hard to accurately determine safety factors when rating fire resistance of building elements [44]. Therefore it is harder to justify to what extent the sprinkler trade-offs for building elements' fire resistance rate are reasonable.

Safety factors reflecting uncertainties in the design methods are applied to maintain a sufficient safety margin [45]. By balancing safety factors and the effects of sprinklers, **G J Barnes** believes **t**hat safety factors may be allowed to be reduced to just above one, or 33% trade-offs of fire resistance rating if the original safety factors are above 1.5. Further reduction of fire resistance rating that might result in a safety factor less than one shouldn't be permitted [35]**. Jiann C. Yang** mentions a reduction of fire resistance to 60% of the normal value in Eurocode 1 for sprinklered buildings provided that a quantitative fire risk assessment is required to work out the potential benefit of sprinkler [46].

The analysis of sprinkler trade-offs based on safety factors is acceptable in that it accounts for one side of a fire - the probability of fire occurrence. Since a safety factor above 1 is designed to cope with the likelihood of abnormally large fires, and a sprinkler system can reduce to a large extent the probability of a full developed fire which needs fire resistance most, a building equipped with a sprinkler system does not have to be designed with such a high safety factor on fire resistance rating as one without a sprinkler system. .

On the other hand, we should study and establish the correlation between sprinkler performance and fire resistance performance to work out a reasonable extent of sprinkler trade-offs on fire resistance ratings of building elements. Although it is difficult to assess the equivalence between fire resistance ratings and automatic extinguishing systems due to their dissimilar protective methods [34], from the standpoint of engineering it is possible to determine experimentally and/or analytically the hours of fire resistance ratings that could be equivalent to sprinkler performance. Although NFPA 101A has not been designed to validate such an equivalence, its index method known as The Fire Safety Evaluation System (FSES) could be employed to provide an equivalent correlation between sprinklers and fire resistance ratings of building assembles like corridor partitions or walls, doors to corridors, etc.. [47,48,85]. Unfortunately, this type of analysis has not been provided in most of the cases when a proposal on sprinkler trade-offs for a specific building element's fire resistance rating, for example the one-hour requirement for corridors, was approved or disapproved by IBC during its hearing processes [49-52].

Based on the correlation between fire severity/fire load and fire resistance rating, a modulation factor for the sprinkler installation is assigned a value of 0.5[53] or 0.39 [54]. Therefore, the required fire resistance capability of the building structure can be reduced by 50% or 39%, respectively [55]. It is not clear where the values of the modulation factors come from, they might stem from judgments of experts by some unknown reference criteria.

YAPING HE takes the deemed-to-satisfy (DTS) provisions of building regulations as reference in equivalence analyses [56], by assuming the same consequences of fire resistance failure in both the DTS design and the alternative solution. If the outcomes of the two solutions are the same or similar, then the two solutions are said to be equivalent. A probabilistic approach has been worked out to cope with this task [55], but the basic parameters presented as probabilistic density distribution functions also need further experimental supporting data.

Sprinkler trade-offs for fire resistance ratings are said to be very cost-effective. For example, a slight reduction of fire resistance ratings, 1/2 hour, will not introduce any appreciable change to the level of risk-to-life safety, but will represent significant savings (typically 10% for steel-framed buildings) in the capital cost required for fire safety and fire protection in office buildings[57]. This can in part indicate why sprinkler trade-offs for fire resistance ratings are widely adopted.

Fire resistance of building elements is essential to structural fire protection. Due to the severity of fire consequence as well as uncertainties during the standard furnace fire tests and investigation of buildings' fire load densities (which are key factors to determine buildings' fire resistance ratings), safety factors are employed as a generally adopted design format. Similar to structural reliability engineering, first order reliability methods (FORM) have been successfully introduced to derive partial safety factors in structure fire protection engineering, but with many assumptions and judgments from experience [35,44,58]. Some comments on these uncertainties are shown in **Table 7** of the APPENDIX 1 [35,39,40,44]. As addressed in the table, fire resistance ratings tested by standard fire exposures focus only on individual building elements, without consideration of uncertainties as to the performance of a whole building exposed to a real fire. What we can do is to provide safety factors, which by themselves may stem from statistical data or subjective judgments.

The concept of trade-offs comes first from the possibility of achieving an equal risk level by adopting alternative fire protection methods, then from the significant economic benefits when additional fire protection above the code minimums are traded-off, as mentioned in the above example of 1/2 hour reduction of fire resistance ratings . But the effect of trade-offs on performance is not quantified [42].

Although the "equivalent method" of **Yaping He** [55] provides us a more pragmatic way to evaluate sprinkler trade-offs for fire resistance ratings, the basic parameters referred to as probabilistic density distribution functions need further experimental supporting data. Moreover, its basic assumption that "the consequences of fire resistance failure in both the DTS design and the alternative solution are the same", is potentially problematic. Actually with fire resistance failure following sprinkler failure, the alternative solution having sprinkler trade-offs about fire resistance ratings will deliver a much worse consequence than the DTS design due to the compounded effects of multiple sprinkler trade-offs like larger building size, faster flame spread rate, etc..

We have to realize that fire scenarios a sprinkler system can cope with are not unlimited. Besides the reliability issues of the system, some fire scenarios including smoldering/shielded fires, explosions, natural disasters induced fires, intentional actions and fires spreading from outside to inside a building, are generally considered beyond the capability of a sprinkler system [18,60,61,]. If buildings are at high risk of these kinds of fires, few sprinkler trade-offs will be reasonable.

Some people believe that certain buildings need no fire resistance because sprinklers help to get people out quickly. Obviously all the potential benefits from sprinklers are based on an assumed 100% successful performance of the sprinklers. What if the sprinklers don't do their job? Although the probability of this is low, the possible consequences are devastating, especially in tall buildings [40]. Similarly, we have to understand that all code-designed buildings are "not" fire safe, the standard test fire "seldom" simulates real fires, and fire resistance of elements doesn't indicate the fire safety of a whole building.

Although standard fire resistance test has been criticized repeatedly [62], fire resistance ratings of elements in a building could still be deemed as the last resort for maintaining a holistic building performance when a sprinkler system fails to be effective. Although the probability of fires in buildings with sprinkler trade-offs is relatively low when the sprinkler system are present but fail to be effective, as the last layer of building safety the fire resistance of building elements could save people by maintaining the structural stability even after a fire big enough to overcome the sprinkler system. Building designs with safety redundancy and robustness are invaluable in case of abnormal fires and attacks.

The 9/11 disaster to some extent highlights the necessity of safety redundancy of fire resistance ratings, as shown in **Table 8** of the APPENDIX 1[63-65], which indicates the invaluable benefits gained from the built-in safety redundancy.

Due to the environmental differences, the fire resistance performance in a real fire will be different from that in a standard fire test. It is potentially dangerous, even though this dangerousness may not present to us right now, to make a decision of sprinkler trade-offs for fire resistance rate of building elements before we know how the fire resistance performance could be affected by various factors including a sprinkler system's failure.

Moreover, the performance requirements of buildings play a great role on the extent of sprinkler trade-offs for fire resistance rating. Where the collapse of a building is totally unacceptable, for example a tall building in a city center, sprinkler trade-offs for fire resistance rating should be contemplated more carefully than for a single story warehouse on the outer fringes of a city located remote from property boundaries[66].

One less important effect of fire resistance is that it may interact with other structural failure models of the same building. Even if there is no fire, a building element with higher fire resistance rating may possibly perform better than that with lower fire resistance rating. By increasing the fire resistance rating of a building element, its resistance to other damages like weathering or corrosion may also be strengthened. Furthermore a better acoustical isolation performance could also be expected.

3.3. Exterior Wall's Unprotected Opening Area (UOA) Limits

3.3.1. What we know from the literature and gaps in the context of holistic building performance

Exterior walls differ from ordinary interior walls and fire resistance rated walls in that they have to handle fires from inside and radiation from the outside[67]. Protected openings have the mandated fire-protection rating necessary to perform their function. Unprotected openings are simply those exterior openings that do not qualify as protected openings.

An Unprotected Opening refers to a doorway, window or opening other than one equipped with a closure having the required fire-protection rating, or any part of a wall forming part of the exposing building face that has a fire-resistance rating less than that required for the exposing building face[68].

The purpose of limiting Exterior wall's Unprotected Opening Areas (UOA) is to control the fire spread between buildings. Some scholars think that the unprotected opening limits set in the building codes lack sufficient evidence [34]. Most of the time fire spread between buildings is the result of thermal radiation between buildings. Fire spreading to neighboring buildings is very dangerous in dense urban areas. By limiting the UOA, therefore, thermal radiation between buildings is effectively reduced to a value below the critical radiation heat flux that could ignite some specific material on the exposed building face. Due to the exponential dependence of thermal radiation on distance, the percentage of UOA set in Codes[38] increases sharply with distance between buildings (namely Fire Separation Distance, FSD), with the maximum of 100% meaning unlimited Unprotected Opening Areas.

Simply speaking, given a fire scenario three parameters are interrelated to each other: critical radiation heat flux of the exposed building wall, ratio of UOA to the whole exposing façade area, and FSD between the exposing wall and the exposed wall. If two of the three parameters are provided, the third can be fixed. Some experimental work has been done to determine the relationship of UOA and FSD [69-77]. Based on the experimental intensity of radiation from the compartment fire, a critical configuration factor can be calculated. Once a critical configuration factor is chosen, the relationship between UOA and FSD can be obtained from specific graphs, charts or formulae, depending on different methods adopted by different researcher. **Hao Cheng** has completed a valuable literature review about studies on fire spreading between buildings in his PhD thesis [78] In the same thesis, **Cheng** presents some results from his experiments and a fire spread model between buildings based on configuration factor and radiation, which includes a comparison of his results with those required by National Building Code of Canada (NBCC) 2005[79]. This comparison shows some considerable inconsistency between required separation distance in NBCC 2005 and that calculated by the two models of fire spread between buildings when the ratio of aggregate opening area to the exposing building face area varies, this may result from the fact that NBCC only considers the ratio of aggregate opening area to the exposing building face area but not the size of a single opening.

Different percentages of UOA with corresponding openings' distribution can be calculated with a preciseness acceptable in engineering. Such kind of calculations can be found in handbooks and textbooks [80,81]. However, usually they are cumbersome and hard to apply in building practice due to huge diversity of patterns of UOA in external walls. Furthermore, other factors like wind and availability of fire service (except for Automatic Sprinkler System that will be discussed below) could also impose some influence on the consideration of the UOA. Therefore, a more general, convenient, and widely accepted calculation tool is still needed.

Research shows that an automatic sprinkler system could: 1) contain the fire in its original object or room; 2) reduce the temperature of a compartment fire [23,84]. Therefore the sprinkler trade-offs for exterior wall's UOA limits accrue from the possibility of a sprinkler system to reduce the fire severity within the original room and thus to lessen the likelihood of achieving a fully developed fire having the ability to spread to other buildings through these openings. NBCC permits the area of openings to be doubled if a building is sprinklered, which **Buchanan** believes is due to the sharp drop of risk of flashover in a sprinklered building [53]. Possibly for the same reason, IBC codes allow 15%, 30%, 50% or unlimited increase of unprotected opening areas in a sprinklered buildings with respect to different FSD. NFPA 80A goes further by classifying sprinklered exposing buildings as “no exposure hazard” [82]

By limiting the UOA the radiation energy gained from the fire projecting out the openings in the exterior wall could be maintained less than the magnitude needed to initiate another fire. In a sprinklered building, the probability of a fire projecting out of the openings are very low, thus some degree of increase in UOA are allowed by some building codes. But if the sprinkler system fails to perform well, the extent of damage would be larger due to the enlarged UOA generating higher radiation levels. For different buildings, risk assessments should be undertaken to achieve a desirable limit about UOA by taking into account the availability and reliability of a sprinkler system. Therefore, a “one size fits all” UOA limit when a sprinkler system is present is easy to follow but unsuitable sometimes.

3.4. Egress

3.4.1. What we know from the literature and gaps in the context of holistic building performance

For many years, buildings were short enough that stairs provided for access were sufficient for safe and rapid egress for most occupants in the event of fire [80]. Even in single stair (mostly residential) buildings, experience showed that this stair was sufficient for fire egress as long as the fire did not expose or block access to the stair. Fire resistant apartment doors shielded the stair from most fires and exterior fire escapes provided a second egress path beginning early in the 20th Century [83].

The objective of design for escape is to ensure that the life safety performance requirements can be met [53]. It is common sense that the shorter the travel distance is, the faster the escape time to an exit will be[84]. To achieve this objective of safe escape, a maximum travel distance, which is measured “from the most remote point within a story along the natural and unobstructed path of horizontal and vertical egress travel to the entrance to an exit” [38], is required by building codes based on specific occupancy group as well as the availability of sprinkler systems.

Safe egress from fire is assumed to be achieved if the required safe egress time (RSET) is sufficiently smaller than the available safe egress time (ASET), where ASET is defined as the time until fire-induced conditions within a building become untenable [80]. Thus a maximum travel distance could be determined with the constraints of travel speed, S and travel time (ASET), t_{tr}, of evacuees, namely[53]:

$$L_t = S \times t_{tr} \tag{1}$$

Speed of travel depends on the occupant density, age and mobility. At an occupant density less than about 0.5 persons per square meter, the flow will be uncongested and speeds of about 70 m/min can be achieved for level travel and 51-63 m/min down stairs. Conversely, when the occupant density exceeds about 3.5 persons per square meter, flow is very congested and little, if any, movement will be possible. More details about the relationship between speed of travel and density of occupants (people per square meter) can be found in the literature [53].

Relatively longer travel distances of non-sprinklered buildings are permitted in US Codes. In Hong Kong and Macau, travel to an exit must be within 40 m (130 ft). In Australia, the maximum travel distance depends on the type of building, but ranges between 20 m (65 ft) and 40 m (130 ft). For comparison, the maximum travel distance in USA is 61–91 m (200–300 ft) depending on the occupancy served [80].

Most building codes allow some increase in travel distance in a sprinklered building. In New Zealand, 50% increase in open path lengths (travel distance) is permitted. In Canada, single egress paths from each room or suite may be increased to 25 m (82 ft) (up to 100% increase depending on hazard group). In USA, 50 to 100 additional feet of travel distance are permitted in the IBC [38]. **G J Barnes** has analyzed the increase of RSET of occupants as well as the decrease of effective time for fire fighters to control the fire [35]. Although the analysis of **G J Barnes** is undoubtedly right, whether such degree of trade-offs as set in codes are appropriate still needs deeper research by taking into account the benefits (namely the increase of ASET) obtained from the effectiveness of a sprinkler system.

Besides the increase of travel distance, some building codes also permit an increase in allowable exit capacity. For example, in the IBC [38] , 50% of exit capacity is permitted to egress through areas on the level of discharge if area is protected by sprinklers (IBC 1027.1). **James C Spence** believes that the increase of travel distance is more reasonable than that of exit capacity because the latter has a higher risk of crowding at the exits than the former [34]. What supports the analysis of **James C Spence**, although not explicitly stated, is the competence of an automatic sprinkler system to enhance ASET.

Limited information could be found about why a dead end path length should be limited, it seems like it will facilitate rapid egress [53] by limiting the time people will spend in dead-end corridors or being trapped by smoke in the dead-end corridors [84]. Dead-end corridors are an undesirable feature, but for purposes of design freedom and effective space arrangement, dead ends are permissible within reasonable limits [85]. NFPA 101 Life Safety Code states that dead-end corridors should be avoided wherever possible, because they increase the danger of people becoming trapped during a fire[86]. **C. F. Baldassarra and D. J. O'Connor** [85] mention two ways in that people may become trapped in a dead-end: 1) People who occupy the dead-end corridor area could be trapped by the fire or smoke which occurs between them and the point at which a choice of travel is available. 2) People moving within the corridor system could enter a dead-end and become confused under smoky conditions or be trapped by a spreading fire. Dead-end corridors (61 feet long) have been blamed as one of the most significant factors which led to the multiple life loss in the 1977 Rhode Island dormitory fire[87].

The main use of an automatic sprinkler system is to control a fire within its original object or room, not to control the migration of smoke. Although there are several tenable criteria (smoke level or visibility, temperatures, radiative flux, etc.) to determine ASET, criteria of visibility is usually the first one to be met [80]. **Corinne Williams and his colleagues** undertook a series of full scale fires in order to clarify whether a sprinkler system could provide adequate fire control to allow escape/rescue at a reasonable cost. Some of the main general conclusions are shown in **Table 9** of the APPENDIX 1 [88]. To summarize, although it seems that a sprinkler system can improve the tenable conditions other than visibility, as will be reinforced later, this benefit cannot be used to increase the travel distance since it cannot increase effectively ASET.

As a prescriptive design method, the current building codes set different limits on the maximum travel distance if an automatic sprinkler system is used without considering a diversity of buildings' details even in the same occupancy group or construction type. Therefore, for some buildings the means of egress is potentially excessive. For others, however, it might be significantly insufficient. As discussed above, the travel distance has to be set based on the travel speed and travel time (ASET) of evacuees, both of them may vary radically from one building to another. From this standpoint, a performance based design for means of egress, which considers the respective travel speed and travel time of evacuees, is the most suitable.

Knowledge gaps similar to other limits in the building codes exist. Limits about the maximum travel distance/dead end length are necessary since it will be unreasonable for them to be unlimited. However their values set in building codes lack accurate calculations on ASET and travel speed of the occupancy.

From the literature review, we know little about the reasons to increase the travel distance/dead end length of an escape route due to the adoption of an automatic sprinkler system. Whether these trade-offs are reasonable is still inconclusive. It likely depends on the safety factors when estimating the RSET and ASET

Life safety is the most important factor in fire protection system design. When a fire is beyond the capability of a quick extinguishment by occupants or sprinklers, a reliable means of egress becomes the bottleneck of evacuating occupants. Appropriate characteristics about exit access involving travel distance and width of pathway will smooth the process of evacuation, thus helping to achieve holistic building performance for life safety. Any relaxation of these characteristics without sound foundation will leave people in a potentially more dangerous environment when a fire occurs.

What is noteworthy is that different kinds of sprinkler trade-offs like building size, fire resistance rating, and travel distance may interact with each other. For instance, although the critical travel distance becomes relatively insensitive to the room area when the room area is greater than 500 m^2 (5382 ft^2) [89], the increase of building size will inevitably result in a longer travel distance. Therefore, the compounded effects of multiple sprinkler trade-offs on building fire safety (for instance, the increase of travel distance plus removal of area of refuge plus smoke partitions in lieu of fire partitions in [38]) should be further investigated. With inputs from a structured group of experts, the FSES method in NFPA 101A could be considered appropriate to analyze such compounded effects [47,48].

3.5. Fire Safety System (Manual Fire Alarm Box)

3.5.1. What we know from the literature and gaps in the context of holistic building performance

A manual fire alarm box is a manually operated device used to initiate an alarm signal [17]. Manual fire alarm activation requires human intervention, as distinct from automatic fire alarm activation such as that provided through the use of heat detectors and smoke detectors. From the standpoint of safety redundancy, to equip a manual fire alarm system in a building already having an automatic fire alarm system provides more paths to alarm occupants successfully, especially when an automatic alarm system fails to activate. On the other hand, when present, humans can be excellent fire detectors. A healthy person is able to sense multiple aspects of a fire including the heat, flames, smoke, and odors. For this reason, most fire alarm systems are designed with one or more manual alarm activation devices to be used by the person who discovers a fire [90].

According to the IBC, 2012, multiple manual fire alarm boxes are not required where the building is equipped throughout with an automatic sprinkler system correctly installed and the occupant notification appliances will activate throughout the notification zones upon sprinkler water flow [38].

Although an automatic sprinkler system might provide an equal fire alarm as a manual fire alarm box does, it cannot provide an equivalent fire alarm effectiveness if it fails to work. But it seems that the a minimum of one manual fire alarm box is required even when elimination of fire alarm boxes due to sprinklers is allowed [38] . Although NFPA 101A doesn't provide a direct equivalence between manual fire alarms and sprinklers, different credits are set to them based on their existing status. Whether a manual fire alarm system has a Fire Department Connection (FDS) makes differences in that it can influence the response time of firefighters, therefore different credits are assigned to a manual fire alarm system based on the availability of a FDS [48].

As a method to inform occupants of emergencies, a manual fire alarm box is more reliable, robust and easy to use, especially when other automatic alarm devices are out of order.

3.6. Sprinkler Effectiveness/Reliability

3.6.1. Definition of sprinkler effectiveness/reliability

There are several different terms used to describe the successful operation of fire safety systems. According to **Kevin Frank** [91] “reliability”is defined as the probability that a sprinkler system will activate and supply water to a fire demand. “Efficacy”is defined as the probability that the sprinkler system will affect the development of the fire as specified in the system design objectives, given that it operates. Except for Early Suppression Fast-Response Sprinklers (ESFR), other types of sprinklers are designed to control, not suppress or extinguish, a fire [92]."Effectiveness" is a term describing the overall performance of the sprinkler system, combining both the reliability and efficacy. These definitions have been used in other studies on sprinkler systems, such as those by Thomas [93]. "Availability" describes the probability that the system will not be out of service for inspection, testing, or maintenance, and is included in reliability. According to **Daniel Malm and Ann-Ida Petterson** [94], "operational reliability" refers to the probability that a sprinkler system will activate, "performance reliability" refers to the probability that an activated sprinkler system contains, controls or extinguishes a fire, "Reliability" refers to the probability that a sprinkler system will perform as expected. Reliability is the product of operational reliability and performance reliability. In this review, if not specially noted, Effectiveness is used as equivalent to Reliability.

Two general approaches have been used in previous studies taken to quantify sprinkler effectiveness: system-based approach or component-based approach. The component-based approach builds an effectiveness estimate for a system from individual component data. The system-based approach estimates the effectiveness of the entire system directly from past performance in actual fire incidents [91].

3.6.2. The system-based (incident data) effectiveness/reliability

With different backgrounds in statistics, inconsistencies existed in different scholars' research. Since automatic sprinkler systems were originally invented and developed in the 1800s [95], there has been debate as to how effective they are. An early reference to estimates of sprinkler effectiveness can be found in the Preliminary Report of the New York State Factory Investigating Commission, which was released in 1912 following the Triangle Shirtwaist fire. This report estimated a sprinklers' efficacy range of 75% to 95% [96].

There are at least three principal sources of statistical data[97]. 1) The National Fire Protection Association (NFPA) has published data on over 80,000 fire incidents involving sprinkler systems from 1897 to 1969; 2) The Australian Fire Protection Association has published data on virtually all fires involving sprinkler systems in Australia and New Zealand for the period 1886 to 1968 (over 5,700 incidents). 3) Statistics are also available from the City of New York based on a similar number of fires. The three principal sources of statistics on sprinkler performance indicate that sprinklers provide satisfactory performance in 96% to 99% of fire occurrences. While these figures show a remarkably high success rate, the reported causes of failure indicate that the performance of sprinkler systems can be improved if measures are taken to avoid what are considered to be preventable failures. According to NFPA statistics, sprinkler systems did not provide satisfactory performance in almost 4% of the fire incidents. This rate of failure is approximately the same as that reported in the New York study. The Australian-New Zealand statistic, however, reveal a higher reliability rate. Only 0.25% of these systems were considered to have given unsatisfactory performances [98].

A summary of reported reliability estimates for automatic sprinkler systems, collected by **Bukowski, Budnick and Schemel** [99] from various sources is shown in **Table 10** in the APPENDIX 1. However, many of those reported studies are more than 25 years old and hence exclude newer sprinkler technologies such as quick response and ESPR types. Nonetheless, they still represent a relative high level of reliability [100].

According to **Kimberly D Rohr and John R Hall, Jr, 2005** [101], sprinklers failed to operate in 7% of structure fires; when they operated, they were effective in 96% of the time, resulting in a combined reliability of 89% (reported in NFIRS 5.0 in 1999-2002, after adjustment for errors in coding partial systems).

According to **John R Hall, Jr, 2013**[29], Sprinklers are reliable and effective in sprinklered and not-under construction buildings with fires large enough to activate them, with better performance for wet-pipe sprinklers than for dry-pipe sprinklers. In 2007-2011 fires, sprinklers operated 91% of the time; when they operated, they were effective in 96% of the cases, resulting in a combined performance of operating effectively in 87% of reported fires

Kevin Frank (with others) investigated a number of past system studies providing an estimate of sprinkler system effectiveness from fire incident data, and concluded that the estimated effectiveness ranges from a minimum of 70.1% to a maximum of 99.5%, which corresponds to failure rates ranging from 60 failures in 200 fires to 1 failure in 200 fires [91].

Daniel Malm and Ann-Ida Petterson delivered other reliability experiences in various countries, as shown in **Table 11** in the APPENDIX 1 [94]. The values of reliability in the table vary between 38% and 99.5 %. Possible reasons for this are that the quality of statistics (for example the design of the incident report) and management of sprinkler systems (installation, inspection and maintenance) differ between countries. Another important reason is the different scopes of sample spaces employed to calculate sprinklers' reliabilities. For example, the incidents sample space in U.S. is "sprinklered fires" which exclude "fires too small to activate the sprinklers" [101], but that in other country like Sweden, Finland, Norway, etc, is "fires where sprinklers present" which include "fires too small to activate the sprinklers". With pre-1999 data, a past report [102] estimated that sprinklers failed to operate in 16% of structure fires large enough to activate sprinklers. In a later report [101], the same author, Kimberly D. Rohr, admitted that the old data is not perfect in that they could not separate (a) fires in the sprinkler coverage area from fires outside the coverage area (e.g., in properties with partial systems), (b) sprinklers from other automatic extinguishing systems, and (c) human error from mechanical and other equipment problems. After some adjustments he worked out a much lower operating failure rate of sprinklers, 7%. Since nearly all failures of sprinkler were entirely or primarily problems of human error (for example, system being shut-off before fire), it could be concluded that in the future the reliability of sprinklers will possibly be reported as nearly 100% if failures due to human errors are excluded. On the other hand, sprinkler reliability or effectiveness is no more than 40% if fires too small to activate systems are taken into account [102].

3.6.3. Component-based reliability

Different methods of analyzing risk to fire safety in buildings have been developed. One method that has been described in fire safety engineering guidelines (British Standards Institution 2003) [103] and used in fire risk analysis case studies in Australia [104] is Fault Tree Analysis which traces the root causes of a given final event of concern by working backward logically to base events. Individual component reliability probabilities can be combined, or if data on unique failure modes for individual components is known then they can be included as well. The fault tree used for a specific sprinkler system will depend on the components that are present in the system [91]. A general form of a fault tree may look like **Figure 1**. In our case the top event of concern may be sprinkler failure.

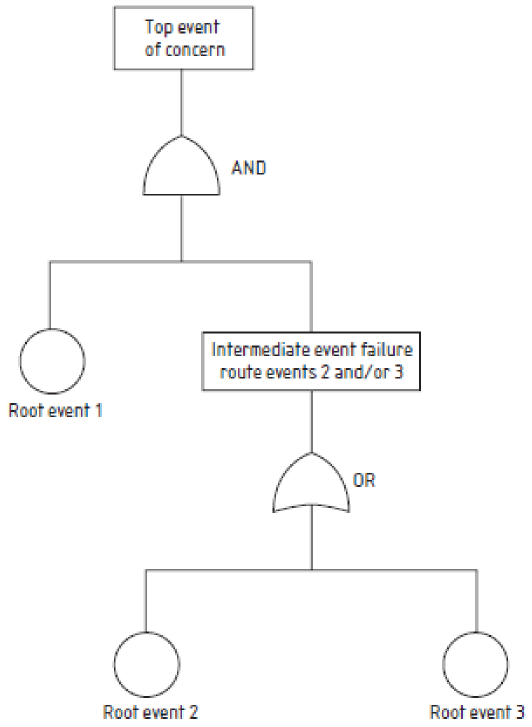

Figure 1: General form of a fault tree [103]

One difficulty with using the approaches discussed above is determining the values that should be used for the probability of the events. Additionally, it can be difficult to determine how a value should be adjusted if the system is modified, which is particularly important in comparative risk assessment. To cope with this difficulty, some identified studies provide some detail sprinkler system component data, which has been classified as related to sprinkler head operation, sprinkler piping, valves, pumps, water supplies, and miscellaneous components [91]. One study shows failure probabilities of 3% to 14% for Australian office buildings which are higher than the commonly considered values in Australia [104].

3.6.4. Failure reasons of a sprinkler system

Failure modes of a sprinkler system could be divided into two categories: Reasons for sprinkler system to fail to operate and reasons for ineffective sprinkler system operation.

The most frequent reason for a sprinkler system failing to operate where the fire is large enough to activate it, ranging from 33% to 100% of the reported failures, is that the system was shut off, indicating that usage failures are mainly critical failures. Inappropriate systems, lack of maintenance, and manual intervention are reported at similar frequencies from 5% to 33%. Damaged components and frozen systems provide the minority of failures, generally near 2% [91,105,106]

The most common reason for sprinkler systems to operate ineffectively was that the water did not reach the fire, ranging from 19% to 55% of the reported cases. An inappropriate system for the fire was the second most commonly reported reason, followed by not enough water released. These reasons are inter-related, and could have different root causes. For example, a partial coverage system may result in any of these outcomes. A change in occupancy or hazard could also result in all three outcomes. For example, a change in fuel package configuration could result in a portion of the fire being shielded, or a system designed for a light commercial occupancy could be insufficient if the use of the building is changed to storage of high-hazard materials [91].

Note that here the reasons preclude fires being too small to activate a sprinkler system. Actually, over half of the sprinklered fires were too small to activate a sprinkler system [105].

3.6.5. Comments on the present studies on sprinkler reliability

According to the researchers' results mentioned above, sprinkler reliabilities vary from researcher to researcher, from country to country. The reasons for the variance include different criteria set to sprinkler effectiveness, different methods of sampling fire incidents, as well as a lot of uncertainty about the reported data. Generally speaking, a higher reported sprinkler reliability may have more inclusive criteria for defining effective sprinkler operation and more exclusive criteria for sprinklered fire incidents. For example, whether fires being too small to activate a sprinkler system are included in the statistics data makes a huge difference on the reliability or effectiveness of sprinkler system.

Note that only pendent sprinklers are discussed above. A BRE report[107] implies a reduced effectiveness/reliability of concealed sprinklers by showing some disadvantages of concealed sprinklers like higher susceptibility to damage, delayed operation, water blockage, leakage of water, and uneven water distribution. Most of the present studies on sprinkler reliability don't consider the situation of persons in intimate contact with a fire, one exception could be found in a report [108] which concludes that sprinklers alone fail to protect lives of a person in bed from being fatally injured, but can help other occupants to survive within the room.

It is clear from experiments that the effectiveness of sprinklers depends strongly on the degree to which the fuel is shielded from the water spray [32]. This dependence, however, has not been well shown in the present studies on sprinkler reliability.

The effects of sprinklers' reporting system, building methods, and fuel loads on sprinkler's reliability are not addressed above. 1) It is important to note that the successful performance ratio of studies included in Table 11 has a relationship to the thoroughness of the reporting system. A reason for the very high successful performance of sprinkler systems in Australia and New Zealand is that essentially all systems are electrically supervised for impairments and for sprinkler water flow [85], 2) Although the construction methods in different countries differ from one to another, it is hard to attribute the differences in sprinkler's reliability to the differences in construction methods. Dominating construction methods in Europe and Australia are concrete, masonry, or solid brick, whereas The United States, and North America in general have historically constructed heavily with wood[109,110]. Obviously, if not sprinklered, wood constructions are more likely to be involved in a high severity of fire than non-combustible constructions. However, if fully sprinklered, buildings only different in construction materials are expected to have similar sprinkler reliability because sprinklers are designed to respond to and control a fire at an early stage when a fire has little impact on the functions of building structures. What make differences might be that the consequence of a fire occurred in a sprinklered wood building is expected to be more destructive than that occurred in a sprinklered non-combustible building provided that the sprinkler systems in both cases fail to be effective. 3) Similarly, although over the decades fuel loads in buildings have increased as a result of the changes in home size, geometry, and interior finishes [111], it is hard to evaluate the effects of this increase on sprinkler's reliability because sprinklers will act to control a fire before it evolves to a considerably severe one, as long as the fire growth rate is under the limits that will overcome a sprinkler system. Once a sprinkler system fails to be effective, however, a fire in modern buildings with higher fuel loads will be much more dangerous to occupants and firefighters than that in legacy buildings with conservative fuel loads, this impact will be further discussed later in this chapter.

It should be noted that an overall sprinkler effectiveness of 87% is hard to be ranked as an "excellent" level. However, an "excellent" or even "perfect" level has been implicated during the cumulative process of sprinkler trade-offs. In a frequently cited report intended to increase fire safety level and reduce the cost of providing public fire suppression services by removing "excessively" redundant fire safety requirements in fully sprinklered buildings, **C. F. Baldassarra and D. J. O'Connor** [85] discussed in some detail the "rationales" for many sprinkler trade-offs including building size, fire resistance ratings of partitions/walls/corridors/doors, travel distances/dead end length, etc., based on the following "evidence": 1) the "excellent" performance history of sprinklers; 2) the long-term existence of sprinkler trade-offs in different model codes; 3) favorable results from many physical tests in which the sprinklers operated perfectly.4) the potential overly redundant requirements in the existing model codes stemming from disastrous fires.

3.7. Interaction Between Sprinklers and Smoke

3.7.1. Different opinions upon the effects of sprinklers on smoke and related studies

Over the years, different opinions have existed on the effects of sprinklers on smoke control systems [112]. Some people argue that smoke control systems are not necessary in a sprinklered building due to the limited fire growth, minimized fire size and negligible smoke production caused by sprinklers. Some state that at least automatic sprinkler protection has a beneficial effect on a smoke control system by reducing airflow rates and pressure differentials needed to achieve effective smoke control[113]. On the other hand, however, some believe that sprinklers deteriorate smoke circumstances in a building by increasing the amount of smoke produced and reduce visibility by carrying smoke down to floor level.

A number of studies related to this debate have investigated the effects of sprinklers on the smoke produced by a fire. This includes studies to determine the effects of the sprinkler spray on the hot smoke layer, the heat release rate, and other parameters for sprinklered fires and smoke movement resulting from a sprinklered fire [114]. The methods adopted by these researchers are either numerical or experimental, or statistical; the fuels used are either solid (wood crib, mattress, etc.) or gas (propane); the fire source locations are directly underneath, or away from, or shielded from a sprinkler. A summary of these study results are shown in **Table 12** in the APPENDIX 1[115-133].

3.7.2. Conclusions of contemporary studies

Although there are different experimental conditions, a general summary based on the review of present studies in **Table 12** could be concluded as:

- Stability criterion of smoke layer: if the total drag force, D, is greater than the total buoyancy, B, the stability of smoke will be overcome.
- Heat Release Rate (HRR): For both shielded and unshielded fires, sprinklers are considerably effective in reducing HRR. Unshielded fires usually could be extinguished or at least be limited to the original objects, but shielded fires could only be controlled to a larger area than unshielded fires. The heat release rate can be over 50% higher than the value at the time of discharging water and up to 80% of the maximum value.
- Temperature: For both shielded and unshielded fires, sprinklers are very effective in reducing the temperature of the smoke layer, indicating sprinklers' capabilities of keeping windows from being broken and of lowering the radiating heat flux even though the windows are broken. Increasing discharge pressure may not be an effective way in cooling smoke layer
- Smoke volume: For both shielded and unshielded fires, sprinklers are effective in reducing the total volume of smoke generated by the fire. But the effectiveness is much less for shielded fires than for unshielded fires.
- Smoke movement: If the fire is not shielded, the sprinkler spray decreases the horizontal momentum of the smoke flow therefore preventing it from flowing out of the spray region. For shielded fires, the smoke, whose volume could be more or less decreased, still presents ability of movement enough to trap the evacuees due to faster descending of a cooler smoke layer, indicating an unyielding demand on smoke control system.
- Smoke and heat venting: If the fire was not ignited directly under a roof vent, venting does not have a negative effect on sprinkler performance, but does limit the spread of products of combustion by releasing them from the building within the curtained compartment of fire origin. If the fire was ignited directly under a roof vent, the average activation time of the first

ring of sprinklers could be delayed. On the other hand, fitting sprinklers in open plan offices may give a major advantage in reducing the capacity required of a smoke ventilation system, but much less of an advantage for cellular offices. Given a capacity of a smoke ventilation system, the increase of operating pressure of a sprinkler has negative effect on smoke venting. Efficiency of smoke venting is controlled by a combination of smoke buoyancy and drag force of the sprinkler spray. Only when buoyancy is greater than drag force can the smoke be extracted by venting. Velocity of smoke venting has been shown to decrease as the sprinkler operating pressure increases.

- Smoke concentration: The activation of a sprinkler in shielded fires could produce more hazardous gases like CO due to incomplete combustion, indicating an untenable condition facilitated by a lower smoke layer.

3.8. Building Resilience

3.8.1. Definitions of Resilience

The term resiliency has been used with increasing frequency in the context of how we build for, plan for, and respond to the variety of events that could interrupt the desired normalcy. Often these disruptive events are characterized as disasters, so disaster resiliency is a common pairing of terms for discussing and defining the concept [134]. Resilience has a wide variety of definitions, with the basic idea of “a community’s ability to absorb disaster impacts and rapidly return to normal socioeconomic activity” [135,136]. There are considerable variations in how different authors define resilience. Different definitions of resilience are listed in **Table 13** in APPENDIX 1 [135,137-151] From the different definitions of resilience listed in the table, it could be found that the major difference between different definitions of resilience focus on whether a definition includes one or more “before the adverse event” components, including resistance, protection, anticipation, and preparedness besides what happens “after the adverse event”.

However, in order to effectively measure and improve resilience, we need to define what things we are trying to avoid. That is, we need to know what we are trying to protect. Generally, the focus is on protecting either lives or property [135]; Losses are divided into four categories by Heinz Center (2000) [152]: the built environment, the business environment, the social environment, and the natural environment.

Except for fires after disasters, building resilience may address more extensive topics like floods, debris, and epidemics which also challenge the capability of an emergency responding system. In this review, based on our concentrations on building fire safety, only resilience of built environment (with special interest in buildings) related to fires after disasters is discussed.

3.8.2. Resilience of built environment

Buildings and utilities in a community together form a built environment of a community, therefore a community's resilience of built environment strongly depends on the interweaved performance of its buildings and utilities system [153].

Hazard events, however, may disrupt services provided by utilities, such as water and electric power, which are required for building functionality. For example, if water pressure cannot be maintained, then fire hydrants, fire suppression, and sanitary systems are out of service, and buildings may not be suitable for occupancy [154].

Different buildings have different social functions needing to be restored in or maintained for different time limits during or after a hazard event. Therefore performance goals are expressed in terms of time to recovery of function for building clusters (buildings with similar functions and performance) following a hazard event. Note that resilience is more than adopting and enforcing the current codes and standards. Due to different emphasis, it is common that some requirements for resilience may exceed those required by model building codes and standards, so future revisions to the model codes may be needed to achieve a community's desired performance, which may add incremental costs but are minor relative to costs associated with repairs, retrofitting existing buildings, or rebuilding 154].

The community may establish a scenario or hazard level based on available guidance or predicted frequency of occurrence. Common hazards for buildings include those that stem from wind, snow, rain, flood, seismic, and fire, etc. Although most of time these hazards are relatively detached from each other, sometimes they do interact with each other. For example, fires could be induced by structure failures from other hazards, which will exert different scenarios that are more difficult for regular fire protection systems to handle based on current building codes.

3.8.3. Effect of sprinkler reliability on building resilience

Usually, when talking about sprinklers' reliability we mean the reliability under common fire scenarios excluding disastrous events like earthquakes, hurricanes, floods, etc. It is from these common fire scenarios that a relatively high reliability of sprinklers has been recorded or reported until now. Sometimes the damage caused by the subsequent fire during or after an earthquake can be more severe than that caused by the ground motion itself [155].

Sprinkler systems are deemed as more vulnerable than the built-in passive fire protection methods in that they are easier to be disabled. A sprinkler system cannot achieve its expected function as a whole system when any part of the system loses its function, which is common in an earthquake. It is reported that the percentages of damaged sprinkler systems among surveyed buildings were 34% in the 1993 Kushiro-Oki earthquake and 41% in the 1994 Sanriku-Haruka-Oki earthquake. The percentage of damaged sprinkler systems in Kobe City was 40.8% and that of fire doors was 30.7%. In the 1994 Northridge earthquake, many commercial insurers have reported that they paid out more losses due to sprinkler leakage than earthquake shake damage due to the extent of damage[156]. Sprinkler systems are very vulnerable to seismic motion even in cases where the level of ground motion has resulted in little or no structural damage. In Kobe City in the Kobe earthquake, there were four fires from the buildings installed with sprinkler systems, two of which resulted in spread fires with burned areas of 3,600 m^2 and 35 m^2 because of non-functioning sprinkler systems [157].

Therefore, sprinkler reliability as well as its effects on building resilience should be investigated not only from common fire scenarios but from the subsequent fires during or after a disaster. Some probability-based tools, for example FiRECAM™ that can assess the impact on life safety of reliability and performance of fire protection systems [158], may be suitable in this case. Also it is believed that seismically resistant sprinkler systems have a significant effect in mitigating fire risks associated with earthquakes[157], indicating a significant improvement of building resilience. Even being equipped with a seismically resistant sprinkler system, a building may still be trapped in an uncontrolled fire due to the shortage of water supply which may occur after an earthquake. To build a seismically resistant water supply system in a community is much more challenging. Moreover the building during a fire event might be inaccessible to fire brigades due to the loss of availability in road systems resulting from an earthquake.

3.8.4. Effect of sprinkler trade-offs on building resilience

As it is hard to evaluate the appropriateness of sprinkler trade-offs, more work is necessary to evaluate the effect of sprinkler trade-offs on building resilience. Studies about this topic are rare. But it will be helpful for us to give some comments on this topic by comparing the reliabilities of sprinkler systems with built-in passive fire protection measures under disastrous events like earthquakes. A reasonable hypothesis here is that if a sprinkler system displays higher reliability than a passive fire protection measure does under disastrous conditions, it will be more convincing to state that sprinkler trade-offs could enhance building resilience. But different conclusions exist about whether a sprinkler system could outperform a passive fire protection measure. Prediction of sprinkler system's reliability directly from the NZ FIRS data was markedly different from predictions based upon datasets which had been reviewed against incident reports. The performance objectives of sprinklers differ to that of passive fire protection systems, therefore it is the specific fire scenario that could tell which system is most effective [159].

3.9. Firefighter Safety

3.9.1. Current studies on firefighter fatalities and injuries

In the United States and its protectorates, approximately 100 firefighters per year are killed while on duty and tens of thousands are injured. From 1977 to 2014, although the number of firefighter fatalities has steadily decreased (except for the year of 2001), the incidence of firefighter fatalities per 100,000 incidents has failed to demonstrate a similar inclination. In fact, from 2012 to 2013, the firefighter fatalities per 100,000 incidents underwent more than 200% increase [160-166].

Reports indicate that the leading nature of fatal injuries to fire fighters is heart attack (44%), followed by trauma (27%): internal and head injuries, asphyxia and burns; whereas the leading types of incidents are structural fire/explosion (46.1%) and wildland/brush fire (20.7%). Regarding the immediate causes of fatal injury, the leading one is overexertion/strain (46.6%), followed by trapped/caught/lost (18.2%), fire department apparatus accident (12.6%). This is consistent with the high incidence of deaths from heart attacks. However, there is almost always a chain of events that leads to fatalities. For example, the reason a firefighter gets trapped and dies may be because of a lack of adequate situational awareness by the incident commander, a dangerously weakened structure that went undetected, the lack of a way to find the trapped fire fighter quickly enough, a shift in wind conditions on a wild land fire, or poor judgment on risk taking [166].

History data indicates that more attention should be paid to structure fires. From 2010 to 2014, 152 firefighters were killed during fire ground operations, of which 95 were at the scene of a structure fire, showing a percent of 62.5% occurred in structure fires. From 2010 to 2012, of fire-related firefighter injures 62.6% occurred in structures on residential property, 13.1% occurred in structures on nonresidential property, showing a total percent of 75.7% occurred in structure fires **[167-172]**. The rate for traumatic firefighter deaths when occurring outside structures or from cardiac arrest has declined, while at the same time firefighter death's occurring inside structures has continued to climb over the past 30 years**[111,173]**. It should be noted that in firefighter fatality incidents where a fire is involved, the most common fire cause is incendiary/suspicious (arson) at 37 % **[**166**]**.

3.9.2. Effect of sprinkler reliability on firefighter safety

Properly maintained sprinkler systems have proven successful in controlling or sometimes extinguishing high-rise fires and protecting building occupants as well as firefighters [174]. However, with increasing reliance on a sprinkler system, its reliability becomes a key factor influencing life safety of firefighters. Once a sprinkler system failed to be effective, built-in fire protection measures must be counted on solely. Some firefighters lost their lives in fires where sprinklers did not activate [166].

3.9.3. Effect of sprinkler trade-offs on firefighter safety

The effect of sprinkler trade-offs on firefighters' safety depends on fire scenarios where firefighter fatalities/injuries occur frequently. Although sprinklers have great performance on firefighters' safety, the trade-offs of other passive fire protection measures may increase the difficulties for firefighters to survive an arson fire, which as mentioned above takes up 37% of total fires involving firefighter fatality. What we should pay more attention to is that an arson fire is sometimes beyond the ability of a sprinkler system which is designed to cope with fires from unintentional accidents. The reason why a sprinkler system could be out of order in an arson fire is that it may be intentionally disabled with little effort.

Another potential effect of sprinkler trade-offs on firefighters is that fire scenarios are more dangerous than before with more sprinkler trade-offs being adopted. Although the total number of fire incidents may shrink if more buildings are equipped with sprinklers, as sprinkler trade-offs, enlarged building size (area and height), lengthened travel distances, weakened fire resistance ratings, lowered fire spread requirements, compromised smoke control system and relaxed UOA limits will together forge a more complicated fire environment that firefighters have to face under conditions of ineffective sprinklers, thus endangering their lives. **Stephen Kerber's** report may partly confirm this point of view [111]. He states that one significant factor contributing to the continued tragic loss of firefighters' and civilian lives is the lack of understanding of fire behavior in residential structures resulting from the changes in home sizes, geometry, contents, and construction materials. Although little explicit evidences show that these changes in the past half century or more accrue directly from the increasingly adoption of related sprinkler trade-offs, they are at least equivalent in effects. According to the experimental results from this report, these effects include: 1) A faster fire propagation. It was very clear that the natural materials in the legacy room released energy slower than the fast burning synthetic furnished modern room. 2) A steeply shortened flashover time. All of the modern rooms transitioned to flashover in less than 5 min while the fastest legacy room to achieve flashover did so in over 29 min. Legacy furnished rooms took at least 700% longer to reach flashover than the modern rooms did. 3) A need for more water and resources to extinguish a bigger fire occurring in modern rooms with more open floor plans and taller ceiling heights. 4) A rapid change in fire dynamics. In most cases the fire has either transitioned to flashover prior to firefighters' arrival or became ventilation limited and is waiting for a ventilation opening to increase in burning rate. 5) A shorter time for a house to collapse. The change in wall linings allows for more content fires to become structure fires by penetrating the wall lining and involving the void spaces. The changes in structural components have removed the mass of the components which allows them to collapse significantly earlier. Modern windows and interior doors fail faster than their legacy counterparts. All these effects together leave significantly less time for occupants to escape and for firefighters to fight the fire, endangering the firefighters in a building possible to collapse soon after their arrival[111,175-177].

Under conditions of ineffective sprinkler systems, the fire environments that firefighters have to cope with may be further deteriorated by sprinklers' trade-offs about fire service aspects like fire apparatus access road distance, hydrant spacing, water fire flow reduction and fire access road limit for multifamily [178], Although these sprinklers' trade-offs are out of the scope of the current project, their effects on the firefighter tactics deserve detailed researches in the future.

3.10. Fires in buildings under construction

3.10.1. Current studies on fires in buildings under construction

Buildings and other structures, regardless of construction type or construction method, are more vulnerable to fire when they are under construction, alteration, or demolition than when completed or when the demolition is finished[clxxix]. A lot of large-loss fires have occurred in buildings under construction. From 2007 to 2014, 165 large-loss structure fires occurred, of which 31 fires (18%) were in buildings under construction. The average loss of a fire in buildings under construction is nearly 30 million [clxxx-clxxxvii]. Fires in buildings under construction can more easily cause severe damage because of incomplete structural systems, lack of applied fire-resistant materials, and the exposed condition of the structure [clxxix].

A lot of causes start fires in buildings under construction, the most notable ones are[clxxxviii]:

- Hot-work related, for example, welding, cutting or soldering
- Careless smoking
- Careless cooking
- Deliberately set fires(arson/vandalism)

3.10.2. Effect of sprinkler trade-offs on buildings under construction

During the whole process of building construction, it is inevitable for the building to experience a time span before the installation of sprinklers. If a building design adopts many sprinkler trade-offs, more attention should be paid to the time span during which no sprinkler system is in order, because fires occurring at this time span could cause a same severe damage as that occurring in an sprinklered building with disabled sprinklers.

3.11. Summary

Sprinklers are a great innovation in the area of fire protection engineering. At the very beginning, however, sprinkler products were not as cost-effective as today. It was hard to popularize them without any incentives because the investment of a sprinkler system was for stakeholders straight forward but the returns or benefits were imponderable. That is where sprinkler trade-offs come from.

Generally speaking, sprinklers have performed well since their advent. It is based on their good performance that some extent of trade-offs are acceptable by the fire protection community. But they are still only “effective medicine”, not a kind of “vaccine”, to fire problems. The accumulated sprinkler trade-offs inherently increase the severity of a potential fire, and in turn increase the dependence of people on the sprinkler system to cope with a deteriorated fire environment. It's not reasonable for people to take off their coats in winter just because they have effective medicines for cold. Similarly it's not reasonable to enhance the fire risk just because people have effective sprinklers to use.

Therefore, although some extent of sprinkler trade-offs are acceptable, the limits of this extent should be technically determined to maintain a balanced fire protection system which is more effective, durable, and robust.

4. Recommended Work for Next Steps

4.1. Available Modeling Approaches

Typically there are three approaches, namely Fire Modeling, Full-Scale Experiments, and Fire Risk Analysis, that can be employed to analyze sprinkler trade-offs. Their relationship is shown below:

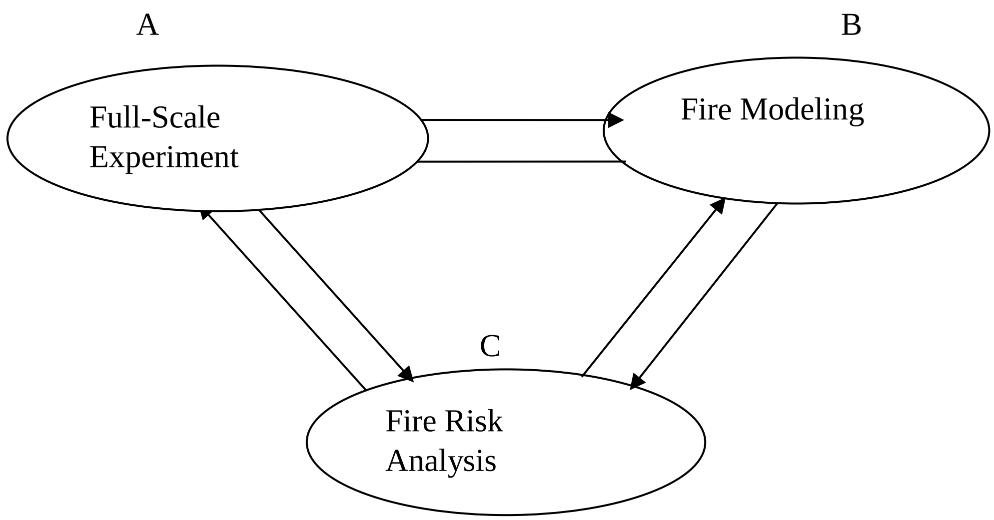

Figure 2: Schematic description of relationship among the three approaches

As shown in **Figure 2**, six edges exist among these three approaches, which mean:

AB = Full-Scale Experiments provide basic parameter inputs to Fire Modeling;

BA = some results from Fire Modeling need to be validated by Full-Scale Experiments;

AC = Full-Scale Experiments provide probabilistic (density) distribution functions of elementary events for Fire Risk Analysis;

CA = some results from Fire Risk Analysis need to be validated by Full-Scale Experiments. For example, if Fire Risk Analysis indicates sprinkler trade-offs of 1 hour's fire resistance rating of fire walls is reasonable, this conclusion needs to be checked by some specific Full-Scale Experiments.

BC = Fire Modeling provides probabilistic (density) distribution functions of elementary events for Fire Risk Analysis, by simulating the critical fire scenarios.

CB = Some Results from Fire Risk Analysis need to be validated by Fire Modeling.

Both Full-Scale Experiments and Fire Modeling could be adopted to validate the results from Fire Risk Analysis, the former being more expensive but more precise than the latter. When cooperating seamlessly with each other, they together allow for more complete understanding of complex scenarios.

It is noteworthy that both Fire Modeling and Full-Scale Experiments mainly focus on a single specific fire scenario, whereas sprinkler trade-offs apply to some range of fire scenarios. Fire protection engineering aims to maintain an accepted fire risk, not to eradicate every fire since it is impossible to do so. Therefore an issue beyond the technical and physical scope has to be addressed: from the viewpoint of statistics, what kind of sprinkler trade-offs is risk-equivalent and cost-effective? Probabilistic fire risk analysis (FRA) might be able to answer this question. FRA has been adopted to analyze the appropriateness of sprinkler trade-offs for fire resistance ratings [56], thus it might also be suitable to analyze other sprinkler trade-offs like (UOA) of exterior walls, travel distance, etc.. FRA needs probabilistic (density) distribution functions of elementary events like RSET/ASET, critical radiation heat flux given a separation distance and UOA, reliability of sprinklers, possibility of a fully developed fire, etc., some of them could be estimated by statistical data, some others could be derived from simulations of Fire Modeling or Full-Scale Experiments.

4.2. Topics for modeling

In this review, five types of sprinkler trade-offs are addressed in some detail: building size, fire resistance ratings, exterior wall's unprotected opening areas, manual fire alarm box and travel distance/dead end length. The trade-off for manual fire alarm box is a management issue more than a technical one, thus will only be discussed in that way in the future. The other four types of sprinkler trade-offs could be further studied by the three approaches mentioned above.

But at the very beginning, it is necessary to obtain information about the effective area of a sprinkler system due to the fact that more than half of sprinklered fires are too small to activate a sprinkler meanwhile some sprinklered fires are large enough to activate many sprinklers that will overcome a sprinkler system[clxxxix,cxc]. Also, baseline tests are interesting in that they could clarify what an automatic sprinkler system could perform on its own, without help from other passive fire protection measures. Additionally, the compounded effects of multiple sprinkler trade-offs are expected.

We focus on two potential effects of these sprinkler trade-offs: life safety and property protection, with more emphasis on the former. Property protection is more easily addressed by a fire risk analysis model than a fire modeling approach, although the damage level of a building in fire could be outputs of some fire modeling simulations or full-scale experiments.

4.2.1. Effective area of sprinkler

It is said that sprinklers can substantially reduce the probability of fire in an area exceeding 100 m^2 (1076 ft^2) but normally have little effect until the fire area reaches 3 m^2[cxci] (32 ft^2). Also sprinklers will fail to be effective in ultra-fast fires [cxcii]. Although usually a larger fire area indicates a higher HRR, there are cases where different fire areas with different fuel attributes may generate the same HRR. The objective here is to determine the combined patterns of HRR and flame spread rates that cannot activate any sprinkler or can render sprinklers ineffective by activating more than N sprinklers. It is reported that sprinkler effectiveness tended to be associated with a small number of sprinkler operating. When more than 10 sprinklers operated, sprinkler effectiveness reduced to only 81% [105]. If this value could be deemed as threshold of ineffective sprinkler, N could be set a value of 10. Potential outcomes would be a chart showing the effective scope of sprinklers, maybe like Figure 3. From Figure 3, all sprinkler trade-offs could only be possibly applied in the "effective area".

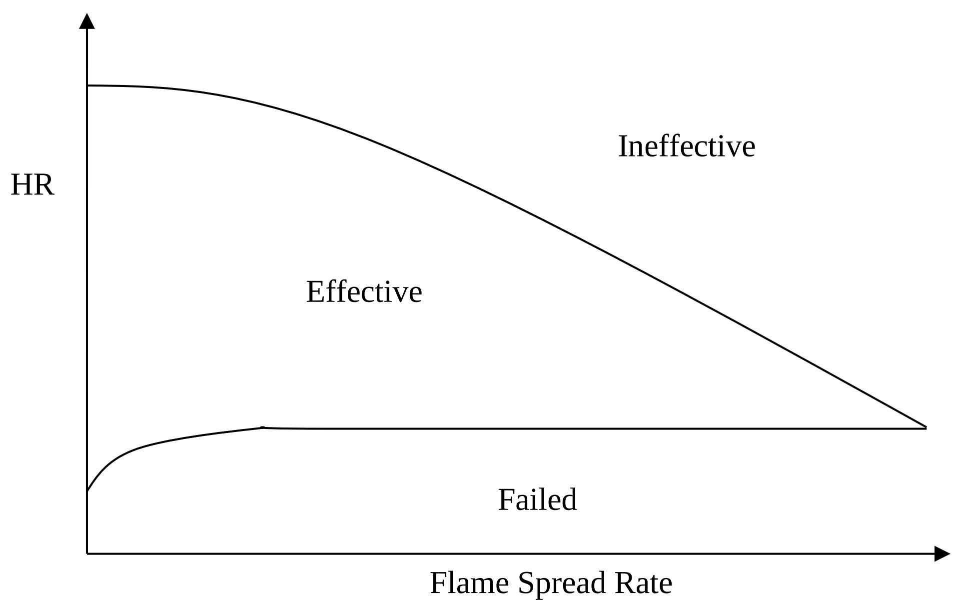

Figure 3: Schematic description of sprinklers' effective area (conceptual use only)

4.2.2. Building size

Probabilistic Fire Risk Analysis would be adopted to analyze firefighters' capability to cope with a sprinklered fire occurring in a larger building size. The basic idea here is, the increase of building sizes will require more ability of the fire department. In non-sprinklered fires, the successful probability for a fire brigade to extinguish or control a building fire decreases with the increase of building size; if sprinklered, a building is deemed to be more likely to survive a fire, thus the probability of a fire brigade to extinguish or control the fire will increase.

Generally speaking, a building size level represents a level of fire severity, which in turn needs a capability level of the local fire department. The probability for a capability level of the local fire department to extinguish or control a fire with a level of fire severity is a random variable and could be simulated by normal or log-normal distribution. The probability for a building size level to represent a level of fire severity is also a random variable and could be simulated by normal or log-normal distribution. Combined together, the probability for a capability level of local fire department to extinguish or control a fire in a level of building size will follow a joint normal or log-normal probability distribution.

Potential outcomes would be a chart showing the correlation between probability for a fire department to extinguish or control a fire and the corresponding building size level, see Figure 4. From Figure 4, sprinkler trade-off for building size could be validated by this kind of analysis. Detailed analytical steps can be found in APPENDIX 2.

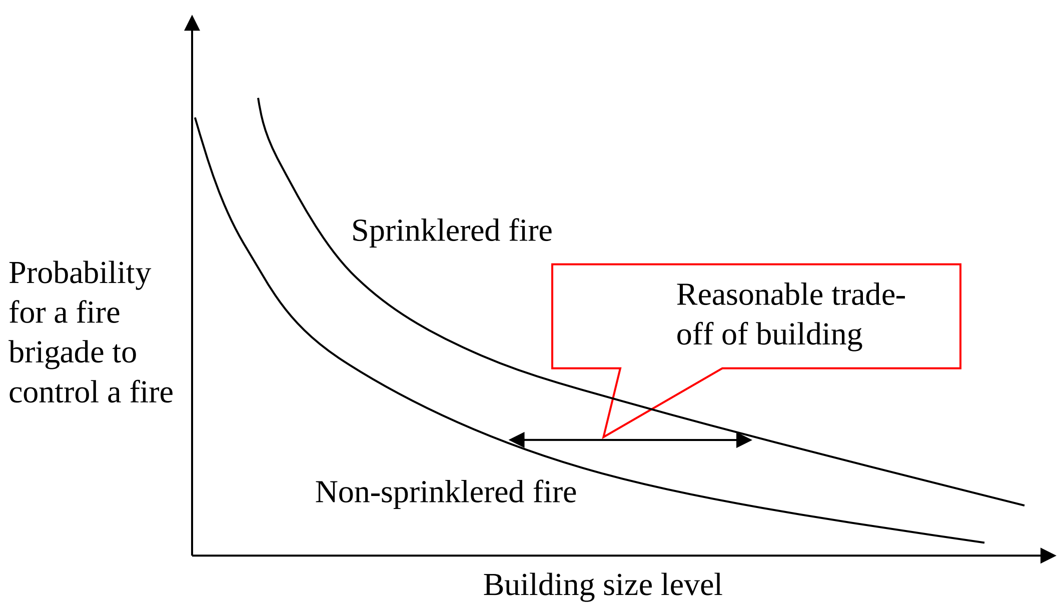

Figure 4: Schematic description of reasonable trade off of building size based on Probability for a fire brigade to control a fire and Building size level (conceptual use only)

4.2.3. Fire resistance ratings

Effects of compromised fire resistance ratings are hard to simulate in fire modeling. It relates to the structure stability and fire spreading beyond the original room. Some network models [cxciii,cxciv] could be able to simulate fire spreading between rooms by having fire resistance ratings as fire spreading resistances between rooms/nodes, but they adopt a random fire propagating direction. Given fire severity of each room and fire resistance ratings of fire walls between rooms, a novel network model is discussed in APPENDIX 3 to simulate the process of fire spreading between rooms.

Although field models such as Fire Dynamics Simulator (FDS) are not good at simulating fire spread, by some special settings it might be partly competent in doing so. Given fires with known HRRs and fire spread rates as well as a wall's fire resistance rating, it is possible to validate if sprinklers could help to stop the fire spreading to another room. It is hard to simulate the integrity failure of a fire wall. For insulation failure, when temperature on the unexposed side of the wall becomes high enough to ignite the wall linings, a new fire will be initiated in the neighboring room, thus the insulation ability of a fire wall is lost. When a wall endures high temperature for a specific time period, the wall will be removed, representing the stability failure of a wall. In FDS the stability failure of a fire wall will be harder to simulate than the insulation failure, so the results might be more approximate. In this way, the possibility of "hot point" ignition in rooms neighboring the original fire room and the possibility of collapse of a fire wall would be approximated, thus the appropriateness of sprinkler trade-offs for fire resistance ratings could be validated to some extent.

4.2.4. Egress

For life safety, once a fire starts, a building mainly depends on its egress system to evacuate its occupants whether a sprinkler system is effective or not. Therefore, whether one kind of sprinkler trade-off could decrease the safety factor of evacuation (the ratio of ASET to RSET) becomes our main concern. The effect of increasing building sizes on the safety factor of evacuation is similar to that of increasing travel distances. Usually RSET could be checked by evacuation models/tools like EXODUS, whereas ASET could be determined by some fire modeling simulations by evaluating the untenable criteria. As detailed in APPENDIX 2, similar Probabilistic Fire Risk Analysis could be employed to validate sprinkler trade-offs for travel distances, by replacing building sizes and capability of fire service with RSET and ASET respectively.

4.2.5. Exterior wall's UOA

Field models like FDS could be employed to simulate radiation heat flux through openings at a distance to a fire source, thus could be used to determine the maximum unprotected opening areas in an exterior wall given a separation distance, with or without activation of sprinklers.

By defining a safety factor of radiation heat transfer (RHT) as the ratio of maximum possible radiation heat flux exerted on another building wall to the critical heat flux needed to ignite another building wall, a safety factor of RHT could be used to determine the unprotected opening areas when varying the separation distance in sprinklered or non-sprinklered fires of prototypical buildings. Potential outcomes could be a chart showing how the unprotected opening areas change with separation distance with a given safety factor of RHT for both sprinkelred and non-sprinklered fires, it may look like Figure 5.

From Figure 5, the appropriateness of sprinkler trade-offs for UOA could be validated. In fire modeling by field model tools, many parameters like fire spread rate, heat release rate, soot yields fraction, radiation fraction, etc., are given as input variables. In fact these input parameters have to be measured through lots of full-scale fire experiments involving complicated scenarios representing interactions of sprinklers with fire plume behaviors.

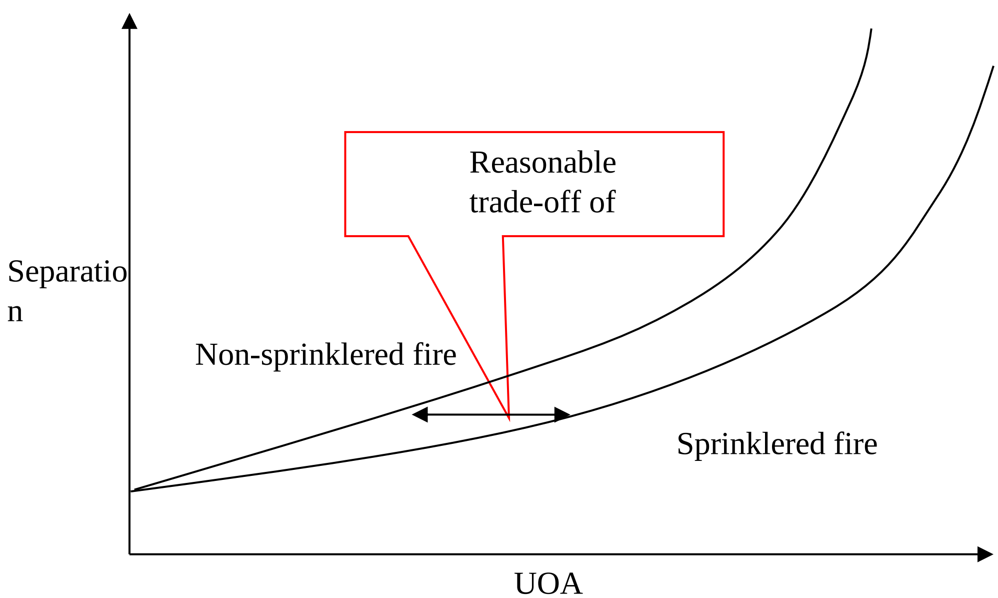

Figure 5: Schematic description of reasonable trade off of travel distance based on separation distance and UOA (conceptual use only)

4.2.6. Baseline tests

Baseline experiments are needed to investigate what an automatic sprinkler system can do on its own without the cooperation of other passive fire protection measures that are considered as excessive in a sprinklered fire. Although passive fire protection measures have a longer history than automatic sprinkler systems do, more and more sprinkler trade-offs have been introduced into model building codes with the increasing recognition of sprinklers' "excellent" performance. To achieve a reasonable sprinkler trade-off, it should be clarified under what fire scenarios an automatic sprinkler system on its own could or couldn't control a fire.

Full-Scale Experiments and field models like FDS could be used to simulate what sprinklers alone can do without any passive fire protection measures, including the conditions of sprinkler operational failure (equal to non-sprinklered fire).

4.2.7. Compounded effects of sprinkler trade-offs

Full-Scale Experiments and field models like FDS can be used to simulate the compounded effects of sprinkler trade-offs including building size, fire resistance ratings, travel distances, unprotected opening areas, flame spread rates, storage of combustible materials, etc. Fires may be located just under a sprinkler in a "standard" building, where all the fire walls reduce to smoke resistance, exterior walls have maximum permitted UOA trade-offs, and materials have maximum flame spread rates trade-offs, simulating a compounded effects of sprinkler trade-offs.

4.3. Example Scenarios of Fire Modeling and Full-scale Experiments

4.3.1. Applications of field model tools or evacuation tools

- Effective area of sprinkler:

Given a series of t-squared fires (HRR will be ramped up to a preset value using a preset time interval and then kept steady) by varying the coefficient of t-squared fires, with the original fire located just under a sprinkler, simulate the number of activated sprinkler heads by varying flame spread rates. If the fire involves most of the floor area but no sprinkler is activated, we consider the sprinklers as failed. If more than N sprinkler heads are activated, we consider the sprinklers as ineffective.

- Egress:

Given sprinklered or non-sprinklered fires occurring in a "standard or common" prototype building without atrium, simulate the ASET and RSET, thus calculate the safety factors for evacuation, with different maximum travel distances.

- Exterior wall's UOA:

Given sprinklered or non-sprinklered fires occurring in a "standard" room with variable area of openings (windows or doors), determine the separation distances associated with UOA that will reach the preset safety factors of RHT.

- Fire resistance ratings:

Given sprinklered or non-sprinklered fires occurring in a "standard" room within a "standard" building, simulate the "hot point" ignition and after that the collapse of a fire wall (just remove the wall in FDS). The thickness of a fire wall set in FDS might be able to represent some level of fire resistance ratings of insulation.

4.3.2. Full-scale experimental approaches

- Baseline tests:

Fires are located just under a sprinkler in a “standard” building, but all the vertical walls are only smoke resistant (no insulation). No smoke control system or elements. Variable fire load densities are deployed on the floor.

- Effective area of sprinkler:

Simulate a fire with intermediate or small HRR, but with higher flame spread rate so that the fire could go out of the original room without activating the sprinklers.

- Arson fires:

Simulate fires ignited by an arsonist at the doorway of a room with gasoline as the fuel, the sprinklers in the rooms and corridors are not disabled.

- Compounded test:

Simulate fires located just under a sprinkler in a “standard” building, with all the fire walls reducing to smoke resistance, exterior wall having maximum UOA trade-offs., materials having maximum flame spread rate trade-offs.

4.4. Other Possibly Interesting Topics:

4.4.1. How do effects of sprinkler trade-offs on fires occurring in old buildings differ from that occurring in new buildings?

- How to define a new building/old building in the view of building fire safety?

In Hong Kong, about 25,000 high-rise non-residential buildings constructed before 1972 are classified as old high-rise where the reliability of sprinkler system is very low[cxcv].

- What is the difference between cellulose (wood) based furniture and plastic based furniture in the view of building fire safety?

4.4.2. The increasing risk to firefighters

Although automatic sprinkler systems could reduce the likelihood of fires with high severity by controlling the fire until the arrival of fire fighters, firefighters will have to confront a more dangerous situation in a sprinklered building having trade-offs of passive fire protection features especially if the sprinkler system is not operating. Over a career, being a firefighter could be more dangerous than before if trade-offs in new building codes are adopted widely.

4.4.3. The vulnerability of an automatic sprinkler system

There are questionable comparisons about the relative vulnerabilities or robustness of automatic sprinkler systems and passive fire protection systems. Some studies believe that automatic sprinkler systems are less vulnerable than passive fire protections, but it is common sense that a more complicated system tends to be more vulnerable than a simple one. Being made of pipes, joints, sensors, valves, heads, an automatic sprinkler system is usually more complicated than a passive fire protection measure. Recognizing the importance of automatic sprinkler systems in disaster resilience of built environments, the vulnerability of an automatic sprinkler system needs more research.

APPENDIX 1

Tables from literature review

Table 1 view points from opponents of sprinkler trade-offs

Opponents	Views
Buettner, D.R,1980[18]	1) Many other systems, such as smoke detectors, might have been equally or more effective 2) Many plastics that give off toxic gases burn at temperatures considerably below those required to activate sprinklers. 3) Earthquakes often destroy the water mains that supply sprinklers. Again, sprinklers without water are just an assembly of useless pipes. 4) Another study by Factory Mutual indicated that in their evaluation of 666 fires, 75% of the dollar losses were related to defects in the sprinkler system. 5) Statistics published by the Oregon State Fire Marshal for the four-year period 1969-1972 show that sprinklers controlled fires in only about 50% of the situations where they had been installed. This is considerably below the 81% effectiveness claimed by the National Fire Protection Agency (NFPA). Statistics from foreign countries indicate similarly poor and questionable performance. 6) Half of the sprinkler systems checked by building inspectors in Milwaukee, Wisconsin were defective. Sprinklers would not have functioned properly in these cases. 7) Arson is the fastest growing crime in the United States. Arsonists, spurred by motives of revenge, vandalism, and insurance fraud, will prevent sprinklers from working.
Jeff Razwick,2009[21]	1) The issue is that sprinklers require a number of steps to activate. Before this can happen, the system must be adequately designed, properly maintained and have sufficient water or power supply during an emergency. NFPA data show that sprinklers fail in about one out of every 10 fires. 2) There are several areas in which the systems can fail, including damage to sprinkler heads, pipe corrosion, and mechanical failure in water supply pumps. Because they may sit for many years without use, absent regular inspection and maintenance, system reliability could be compromised. 3) Exacerbating the problem is the large number of sprinkler

	recalls in recent years. Manufacturers recalled approximately 45 million defective sprinkler heads from the late 1990s through 2006—nearly one in every ten installed in the United States since 1991. 4) In situations where code trade-offs allow reduced compartmentation, sprinkler failure can leave a building and its occupants woefully under protected
L. Twilt and J. Witteveen, 1987[22]	Ideally, the fire safety design concept should allow for a certain equivalency of different design solutions. However, in the traditional concepts, this trade-off is quite impossible. Under certain circumstances this may lead to heavily unbalanced solutions.
J. Walter Coon, 1984 [24]	1) Automatic sprinklers have an exceptional record of property protection, but they are not the panacea of safety to life the sprinkler industry has led many to believe, and many do want to believe for economic considerations 2) Sprinklers are not early warning devices to alert occupants to a fire condition before smoke makes an exit corridor several stories above the fire floor impassable 3) Trade-offs of life safety features for economic reasons are not justified if public welfare is a consideration, nor are they justified to promote a sprinkler installation that can stand alone on its own fire protection merits.
Richard Licht,2005 [6]	1) Changes to the building codes are driven largely by architects, engineers, building owners, construction material manufacturers and others focused on controlling or reducing construction costs. There is surprisingly little testimony from the fire fighters, fire marshals, fire chiefs, fire inspectors and investigators. Among their own peer groups, the various fire services participate in the development of fire codes, but there has been historically little cross-over communication between construction interests and fire services when building codes are revised. 2) We aren't including redundancy, which has been the cornerstone of fire safety over the decades. Everyone agrees that sprinklers are extremely good, but they are not perfect. If you have removed most of your other life-safety devices and then you have a deficiency in your sprinkler or the fire overpowers your sprinklers, you can have real problems 3) If sprinklers fail to operate satisfactorily in buildings built to the newest editions of the model codes, then those who enter a fire scene are going to be working under more stressful and dangerous conditions than ever before…..

	even when sprinklers activate satisfactorily, fire fighters will be exposed to new challenges when forced to deal with fire control in substantially larger spaces. With building codes permitting expanded height and areas, reductions in fire ratings of floors and wall assemblies, longer corridors distances, more combustible materials, narrower stairways, and fewer smoke control features, there is a greater potential for fires to spin out of control and spread to adjacent areas. This, in turn, will complicate the mission of fire fighters
Vincent Dunn [25]	The concept of a fire resistive building has been allowed to slip away. At one time, a fire resistive building was a structure that barring a collapse or explosion would confine a fire to one floor. This is no longer true. In the 1970s, New York had a two floor fire in I New York Plaza; in the 1980s, Los Angles had a five floor fire in the First Interstate Bank building; and in the 1990s, the I Meridian Plaza building in Philadelphia suffered a nine floor fire. So, today there is no longer a fire resistive building. If sprinklers or firefighters do not extinguish the fire, the building will not confine it.
Caroline E. Mayer,2001 [26]	Why not have sprinklers and keep the more traditional, passive fire- protection controls, just as cars now have seat belts and air bags?
Lee G. Jones [27]	1) Sprinklers are not always “properly installed and maintained” as the proponents of sprinklers claimed. 2) Designing and producing defects of sprinklers could result in very severe consequence in an extensive scope, recall of millions of sprinkler heads did happen in the past years. 3) There has been an increase in the occurrence of Microbial Induced Corrosion(MIC) that can completely disable a sprinkler system. 4) Human error is inevitable.
Richard Licht,2001 [6]	1) Sprinkler systems are subject to component failure and human error in a measurable percentage of fire occurrences. 2) Sprinkler systems can be overwhelmed, for example, by a rapidly growing fire. 3) Sprinkler systems can contribute to the generation of toxic smoke, which limits visibility. 4) A sprinkler system will not suppress nor control a hidden or shielded fire, and may be slow to respond in spaces built to increased height and area standards. 5) There is a clear and substantial difference in loss of life, injuries, and property damage between the regions governed by the Uniform, National and Standard Building

	Codes, with the best performance provided by the more balanced fire protection provisions of the Uniform Building Code.
The Association for Specialist Fire Protection(ASFP) [28]	When compared with smoke alarm system, sprinklers are thought as non-cost effective

Table 2 View points from proponents of sprinkler trade-offs

Proponents	Views
America Burning, 1974[1]	Automatic sprinklers can pay for themselves in damages prevented, and the model codes should permit other savings by relaxing requirements for other fire safety features when automatic sprinklers are installed
Russell P. Fleming 1981 [17]	It's well known fact that if you take two steps forward for every step backward, you'll end up ahead of where you started. To stiffly maintain that the belt can't be loosened if suspenders are added destroys the incentive for having suspenders in the first place, and therefore doesn't improve the overall safety factor associated with holding up the pants. Active systems, mechanical and electrical, are subject to occasional failure, and the expected rate should be and is built into the degree of trade-offs available. But passive systems are likewise subject to failure, as demonstrated in the recent MGM Grand disaster.
Kevin J. KELLY 2006 [5];2005[18]	1) A fire which has been successfully controlled by a sprinkler system will result in much less property damage than a fire which has been successfully contained by a passive system. 2) The economic low of diminishing returns comes into play. Once sprinkler protection is provided in a building, the risk to the occupants from fire is minimized-approaching near zero. Each passive fire protection feature provided in addition to the sprinkler protection further reduces the risk, but the reduction in risk with each layer of passive fire protection provided is minimal because the level of risk already approaches zero with the installation of sprinklers. It's a question of how much we are willing to spend on additional passive fire protection features trying to further minimize already minimal risk.
Gene B. Endthoff, 2013 [3]; Jeffrey M. Hugo, 2013[4]	1)In reality, by trading passive protection for active fire suppression, increased fire safety and reduced construction costs are achieved. 2) No data has been presented that the use of any or all of the Trade-Ups has created any additional fire hazard.
Richard C Schulte,2003[20]	1）Although this may be considered to be heresy in some circles, the extent of the effect of "containment area, passive fire protection and automatic fire sprinklers" on the fire safety record of commercial buildings in the United States

	is unknown. 2）Today, it is almost universally recognized that the installation of sprinkler protection in buildings provides far superior protection to that provided by passive fire protection.
S.J. Melink,1993[23]	1）Sprinklers reduce the number of fatal casualties by about half and the number of non-fatal casualties by about twenty per cent. 2）Sprinklers significantly reduce the number of multi-casualty fires.
JOHN R. HALL, JR,2013 [29]	1) Fire sprinklers are highly reliable and effective elements of total system designs for fire protection in buildings. They save lives and property, producing large reductions in the number of deaths per thousand fires, in average direct property damage per fire, and especially in the likelihood of a fire with large loss of life or large property loss. 2) Excluding fires too small to activate a sprinkler and cases of failure or ineffectiveness because of a lack of sprinklers in the fire area, wet pipe sprinklers operated in 92% of reported structure fires and operated effectively in 89% of fires. Three out of five (60%) of the failures occurred because the system had been shut off.
Richard C. Schutle, 2001 [30]	There is no denying that smoke from a fire can be “toxic and deadly,” but the probability of dying in a fire in a high rise building is so small that there should be little concern by the public….. Typically, more people die in the United States as a result of being struck by lightning than as a result of fires in high rise buildings.
Jim Ford,1997[31]	The average fire loss per sprinklered incident was only $1,945, compared to a non-sprinklered loss of $17,067. Automatic protection had a direct role in saving eight lives. One or two heads controlled or extinguished the fire 92% of the time, with the majority of the exceptions a result of flammable liquid incidents. The potential structural fire loss has been dramatically reduced for sprinklered incidents

Table 3 Resources in fire research engine of IAFSS(http://www.iafss.org/fire-research-engine/)

Results Tab Abbreviation	Repository Description and Front Page Interface (not necessarily the URL path where content is stored)
NIST-FIRE	National Institute of Standards and Technology, Engineering Laboratory, Fire Division publications http://www.nist.gov/publication-portal.cfm
NRC-CNRC	National Research Council Canada, Institute for Research in Construction http://nparc.cisti-icist.nrc-cnrc.gc.ca/npsi/ctrl
BRANZ	BRANZ, Fire group publications http://www.branz.co.nz/cms_display.php?sn=92&st=1
SP	SP Technical Research Institute of Sweden, Fire Research publications http://www.sp.se/en/publications/Sidor/Publikationer.aspx
VTT	VTT Technical Research Centre of Finland http://www.vtt.fi/publications/
LNE	Laboratoire national de métrologie et d'essais, France http://www.lne.eu/en/online/publications.asp
CSTB	Centre Scientifique et Technique du Bâtiment, France http://www.cstb.fr/recherche-et-developement-innovation/theses.html
BRE	BRE http://www.bre.co.uk/podpage.jsp?id=1752
CPSC	U.S. Consumer Product Safety Commission http://www.cpsc.gov/en/Research–Statistics/-Technical-Reports-/
NFPA	(U.S.) National Fire Protection Association, Fire Protection Research Foundation http://www.nfpa.org/research/fire-protection-research-foundation/reports-and-proceedings
USFA	U.S. Fire Administration https://apps.usfa.fema.gov/publications/

NZFSC	New Zealand Fire Service Commission http://www.fire.org.nz/Research/Published-Reports/Pages/Published-Reports.aspx
FAA	(U.S.) Federal Aviation Administration http://www.fire.tc.faa.gov/
ERA	University of Edinburgh http://www.ed.ac.uk/home
IAFSS	International Association for Fire Safety Science, Fire Safety Science symposia proceedings http://www.iafss.org/publications/fss/info/
AOFST	Proceedings of the Asia-Oceania Symposia on Fire Science and Technology http://www.iafss.org/publications/aofst/info/
FRNOTES	Archived Fire Research Notes from the UK Fire Research Station from 1952 to 1978 http://www.iafss.org/publications/frn/info/
NATIONAL ACADEMIES PRESS	The (U.S.) National Academies Press http://books.nap.edu/
UNIVESITY/COLLEGE THESES	Fire Safety Engineering Group, University of Greenwich http://fseg.gre.ac.uk/fire/press.asp
	Massachusetts Institute of Technology http://dspace.mit.edu/
	Fire Engineering, University of Canterbury http://www.civil.canterbury.ac.nz/fire/fe_resrch_reps.shtml
UCLAN	uclan – CLOK – Central Lancashire Online Knowledge, University of Central Lancashire http://clok.uclan.ac.uk/
JOURNAL – FIRE SAFETY J.	Fire Safety Journal http://www.journals.elsevier.com/fire-safety-journal/
JOURNALS – SPRINGER	Other Springer journals not individually listed on tabs, where articles are filtered for “fire” http://link.springer.com/

JOURNALS – INTERSCIENCE	Wiley Interscience journals, where articles are filtered for “fire” http://onlinelibrary.wiley.com/
JOURNAL – J. FIRE SCIENCE	Journal of Fire Sciences http://jfs.sagepub.com/
JOURNAL – SCIENCEDIRCT – OTHER	Other ScienceDirect journals not individually listed on tabs, where articles are filtered for “fire” http://www.sciencedirect.com/
JOURNAL – FIRE SCIENCE & TECHNOLOGY	international Journal for Fire Science and Technology https://www.jstage.jst.go.jp/browse/fst/
JOURNAL – J. FIRE PROTECTION ENG.	Journal of Fire Protection Engineering http://jfe.sagepub.com/
JOURNAL – FIRE RISK MANAG.	Fire Risk Management https://www.frmjournal.com/frm_home
OTHER PAPERS & ARTICLES	Global Fire Monitoring Center http://www.fire.uni-freiburg.de/
	Industrial Fire World http://www.fireworld.com/Archives.aspx
	Industrial Fire Journal http://www.hemmingfire.com/news/categoryfront.php/id/141/Spring_2013.html
	International Fire Protection http://www.mdmpublishing.com/mdmmagazines/magazineifp/
	Asia Pacific Fire Magazine http://www.mdmpublishing.com/mdmmagazines/magazineapf/
	International Fire Fighter http://www.mdmpublishing.com/mdmmagazines/magazineiff/

HAZLIT	Natural Hazards Centre Library, HazLit Database http://www.colorado.edu/hazards/publications/
ARCHIVE.ORG	Internet Archive https://archive.org/
OPENLIBRARY	Open Library https://openlibrary.org/

Table 4 Reasons for the needs to set a limit for building size

Authors	Statements
C. F. Baldassarra and D. J. O'Connor, 1983[85]	The threat of unrestricted fire spread and the experience of unsuccessful, hazardous manual firefighting are primary reasons for height and area limitations. The greater the area and height of a building, the greater will be the amount of combustible materials which can contribute to the development and spread of a fire. As a fire spreads and involves larger portions of a building, there will be an increasing demand upon fire department suppression efforts, decreased possibility of successful manual extinguishment or containment, and an increased risk of fire spread to adjacent properties. Larger buildings also increase the hazard to fire fighters due to the greater distances of travel required to reach the fire.
Ramon D. Mallow, 1983[36]	A "strongest fire department" has only a 2% chance of extinguishing a 3,200 square feet fire. Other studies set the practical limit of capability at 5,000 square feet.
Ed Reilly,1984[32]	If 3000gpm is the maximum upper limit of hose stream delivery, then it followed that 0.04 gpm multiplied by 7500 square feet corroborated his assumption of 3000gpm. Lambert insists that all the assumptions upon which his rationale rests are predicated on the common sense experience of chief fire officers that 3000gpm is the upper limit for delivery given his crew sizes, equipment, and physical conditions for Dallas.
Keith D. Calder,2015 [33]	In early times, the risk of conflagration was mitigated by regulating construction type, building separation, and height. These regulations preceded the development of building area limitations; however, area was implicitly regulated through limitations on property size and separation requirements. The increase in building size resulted in fires growing beyond the ability of responding fire services to control, increasing the risk of conflagration.
James C.Spence,1981 [34]	While the fire load is such that fires of an intensity in excess of the fire resistance of the structure may develop, it is necessary to provide for control of the magnitude of a potential fire and limit the exposure to the occupants by height and area limitations. Large buildings present greater fire potential simply because they may have more combustibles exposed to a fire. They also may contain more people who can be exposed to a fire. Evacuation of large buildings is more difficult because of lengthier evacuation routes.

	Further, fires in large buildings may present more difficult fire control problems because of inaccessibility to the more remote interior spaces….. Height and area limits should be designed to limit the fire hazard and potential severity to a reasonably uniform level in all buildings. However, limitations on building heights in building codes are somewhat empirical and have been derived not only from the characteristics of the types of construction and the occupancy, but also consideration of firefighting and evacuation procedures
G J Barnes, 1997 [35]	Although there is no clear objective within the Building Act or Building Code in limiting the fire cell areas doing so will achieve several stated goals. 1) Protection of Fire Service personnel (by limiting the size of the fire). 2) Protection of the environment (by limiting the size of the fire and therefore the emission of toxic products) 3) Control the spread of fire (as required by the Building Act)

Table 5 Comments on sprinkler trade-offs for building sizes limitations

Authors	Statements
James C.Spence,1981 [34]	The rationale for increase in height for sprinklered buildings in model codes is unknown. It appears to be based on the recognition of benefits resulting from sprinklers in improving the conditions for evacuation and firefighting. Justification for height increase is based on the favorable experience in buildings equipped with automatic extinguishing systems
C. F. Baldassarra and D. J. O'Connor,, 1983[85]	The additional risk introduced by allowing greater area for accessory use will be compensated for by the provision of automatic sprinkler systems.
J. Frank Riseden, 1983[37]	Automatic sprinkler protection essentially minimizes the problems of conflagration, manual firefighting and evacuation. Since sprinklers are designed to limit fires to the area of fire origin and have proven able to accomplish this, there is no real reason to restrict the area of the building which is fully sprinklered.
G J Barnes, 1997 [35]	If trade-offs had not been utilized fire cell areas within the building would be limited to fire cells of an area determined by the fuel type. Property losses would be limited as the rated partitions would constrain the fire to a size the Fire Service would be more able to control. Emissions to the environment would be limited and the fire would be less likely to spread to other properties. By partitioning the structure the building would comply better with the Building Act and the property of the owner would be protected from fire and smoke damage

Table 6 Definitions about fire resistance

Authors	Statements
IBC code 2012 [38]	(Fire resistance is) that property of materials or their assemblies that prevents or retards the passage of excessive heat, hot gases or flames under conditions of use.
Long T. Phan,etc,2010 [39]	*Fire resistance* is a measure of the ability of a building element to resist a fire, usually the time for which the element can meet certain criteria during exposure to a standard fire resistance test.
A. Buchanan,2001, [40]	A *building* element is deemed to have fire resistance if it can survive a standard fire resistance test for a particular time, while meeting certain criteria. The criteria are one or more of stability (ability to carry load), integrity (ability to prevent passage of flames) and insulation (ability to prevent passage of heat). Integrity and insulation are containment functions, providing resistance to fire spread, whereas the stability criterion is intended to prevent collapse
Harada, K., 2000 [41]	The role of fire resistance are quite often to: 1) protect escape routes such as stairwell, lobby, temporal refuge area 2) confine fire and smoke within containment 3) structural stability during evacuation, rescue and firefighting.
A. Buchanan,2001, [40]	The expected performance of fire rated elements is that, for a certain time, they can: 1) Prevent smoke spread (not specifically assessed in fire resistance tests) 2) Prevent fire spread 3) Limit deflections 4) Prevent collapse

Table 7 Uncertainties on fire resistance ratings

Authors	Statements
A. Buchanan,2001[40]	…Is the FRR from a single test the most likely time to failure for typical construction, or does it represent the top end of a distribution, the test specimen having been very carefully constructed, especially for the test? What is the statistical distribution of likely post-flashover fires, and where in this distribution should the design point be? A simple start on this path would be to use higher safety factors for very tall or otherwise significant buildings
Long T. Phan etc, 2010[39]	There is also a growing recognition that the current prescriptive, component based method only provides a relative comparison of how similar building elements performed under a standard fire exposure and does not provide information about the actual performance (i.e., load-carrying capacity) of a component or assembly in a real fire environment, nor of the system as a whole or its connections. The prescriptive method also does not provide how the structural system as a whole or its connections will perform in a standard fire exposure, nor does it account for the effects of thermal expansion on the strength and stability of a structural system
P.H. THOMAS[44]	It is noted that data on fire occurrences may be different for different countries and may even vary within one country. The same holds for the efficiency of the various measures.
G J Barnes, 1997 [35]	It is a fact (that) fire engineering is an inexact science, the large number of assumed variables and the unpredictable nature of fire make calculating the exact progress of a fire impossible

Table 8 Importance of built-in safety redundancy

Authors	Statements
David Drengenberg and Gene Corley,2011 [63]	…Undoubtedly, many hundreds of lives were saved because of the redundancy and robustness built into the structures
NIST, 2005 [64]	The WTC towers would likely not have collapsed under the combined effects of aircraft impact damage and the extensive, multi-floor fires that were encountered on September 11 2001, if the thermal insulation had not been widely dislodged or had been only minimally dislodged by aircraft impact….. The procedures and practices used to ensure the fire endurance of structures be enhanced by improving the technical basis for construction classification and fire resistance ratings, improving the technical basis for standard fire resistance testing methods, use of the "structural frame" approach to fire resistance ratings, and developing in-service performance requirements and conformance criteria for sprayed fire-resistance materials
NIST, 2008 [65]	(we need) explicit evaluation of the fire resistance of structural systems in buildings under worse-case design fires with any active fire protection systems rendered ineffective. Of particular concern are the effects of thermal expansion in buildings with one or more of the following features: long-span floor systems, connections not designed for thermal effects, asymmetric floor framing, and composite floor systems

Table 9 Tests on effectiveness of sprinklers [88]

Tests categories	**Main points of tests' results**
30 minutes house fires	1) With sprinklers the fire gases were cooled sufficiently that the occupants of the room of origin would not have experienced extreme pain due to convected heat 2) In all the fires (with and without sprinklers), visibility was lost after 5~7 minutes. Sprinkler activation therefore had no effect on the visibility 3) Tenable conditions (apart from visibility) for the test house could be maintained by sprinklers in the room of origin, or closing the door of the room of origin
30 minutes compartment fires	1) Sprinklers significantly reduced the effect of convected heat from the fire duration of 30 minutes. 2) However, sprinkler did not observably improve visibility 3) Television and bed fires. Sprinklers generally greatly improved conditions in the room of fire origin and maintained tenable conditions in terms of toxic effects; reduced the effects of convected heat but had no observed improvement in visibility. 4) Table fires. For all the sprinklered and unsprinklered fires the conditions became unsurvivable. Sprinklers generally improved conditions in terms of toxic effects, except for one case. 5) In one television fire and one sofa fire, where fire growth was slower than normal, a lot of smoke was produced prior to sprinkler operation and consequently conditions became unsurvivable 6) In another sofa fire, sustained ignition was not achieved, and a lot of smoke was produced but the sprinkler did not operate. 7) For all the unsprinklered fires, the first tenability criteria to be reached was visibility, then convected heat then toxicity effects.

Table 10 Reliability reported by scholars/NFPA [99]

Occupancy	Source	Reliability
Commercial	Milne	96.6/97.6/89.2
	NFPA	90.8-98.2
	Miller	86
	Maybee	99.5
	Kook	87.6
	Taylor	81.3
	Linder	96
General	Miller	95.8
	Miller	94.8
	Powers	96.2
	Richardson	96
	Finucane et al	96.9-97.9
	Marryat	99.5

Table 11 Reliability experience in some country

Country	Reliability
Incidents statistic from Sweden	69%
Incidents statistic from Finland	38%
Incidents statistic from Norway	74
Incidents statistic from London(UK)	85
Incidents statistic from New Zealand	96
Statistics from Industriförsäkring AB for Finland	91
Statistics from AFPA for Australia and New Zealand	99.5
Statistics from NFPA for the U.S.	90
Statistics from six reports and articles	90-99.5

Table 12 Researches on interaction of sprinkler with smoke

Authors	methods of study	intents of study	Conclusions/comments
M.L. Bullen (1974) [115]	Theoretical	To quantify the possible danger of bringing smoke down to a low level and thus impeding or preventing the escape of occupants	Bullen Criterion: the smoke layer lose its stability when the total drag force D is greater than the total buoyancy B.
Marty Ahrens [133]	Statistical	To study if sprinklers provide an adequate defense against smoke	Flame damage is confined to the room of origin in 93% of fires in sprinklered mid-rise buildings and 96% of the high-rise sprinklered building fires. However, smoke damage extended beyond the room of origin in 33% of the mid-rise sprinklered building fires and 31% of the high-rise sprinklered building fires. Although smoke traveled more than the flames, sprinklers clearly helped reduce smoke spread. Smoke spread beyond the room of origin in 51% of the unsprinklered mid-rise building fires and 38% of the unsprinklered high-rise building fires.
Kevin McGrattan, David Sheppard,1998[117]	Theoretical and experimental	To gain insight into the interaction of	1) When the fire was not ignited directly under a roof vent, venting had no significant effect on the sprinkler activation times,

		sprinklers, roof vents and draft curtains through fire experiments and numerical modeling.	the number of activated sprinklers, the near-ceiling gas temperatures, or the quantity of combustibles consumed. 2) when the fire was ignited directly under a roof vent, automatic vent activation usually occurred at about the same time as the first sprinkler activation, but the average activation time of the first ring of sprinklers was delayed 3) when the fire was ignited directly under a roof vent that activated either before or at about the same time as the first sprinkler, the number of sprinkler activations decreased by as much as 50% compared to tests performed with the vent closed. 4) when draft curtains were installed, up to twice as many sprinklers activated compared to tests performed without curtains 5) The significant cooling effect of sprinkler sprays on the near-ceiling gas flow often prevented the automatic operation of vents 6) the first and second sprinklers had a substantial impact on the overall number of activations in the plastic commodity tests
.K. Chow, 2005 [116],2006[118]	Theoretical and experimental	To check the heat release rate for a design fire in sprinkler	In a small office fire the heat release rate cannot be controlled at the value once the sprinkler system is activated. The heat release rate can be up to 80% of the maximum value,

		protected area	and about 50% higher than the value at the time of discharging water. Therefore, in estimating the heat release rate for sprinkler protected area with a t^2 fire, the 'cut-off' value at activation time should not be taken as the design figure. Much higher heat release rates will be resulted, depending on the scenario
Craig L. Beyler and Leonard Y. Cooper 2001[119]	Full-scale experiments	To investigate interaction of sprinklers with smoke and heat vents	1) Venting does not have a negative effect on sprinkler performance 2) Venting does limit the spread of products of combustion by releasing them from the building within the curtained compartment of fire origin 3) Early vent activation has no detrimental effects on sprinkler performance and have also shown that current design practices are likely to limit the number of vents operated to one and vents may in fact not operate at all in very successful sprinkler operations. 4) Curtains should be placed in aisles rather than over storage
DONG YANG, RAN HUO, LONGHUA HU, SICHENG LI and YUANZHOU LI, 2008[120]	Theoretical	To develop a fire zone model including the cooling effects of sprinklers	1) Significant decreases in smoke temperatures were predicted following sprinkler activation. A large decrease in temperature resulted under higher heat release rate. 2) A relatively small decrease in temperature was predicted by increasing the discharge pressure of

			sprinkler from 0.05MPa to 0.1MPa, indicating that increasing discharge pressure may be not an effective way in cooling smoke layer
K.Y. Li , R. Huo, J. Ji, B.B. Ren,2010[121]	Theoretical and experimental	To investigate the discharge rate of a horizontal adjacent smoke vent under sprinkler spray	1) With the increase of the sprinkler operating pressure, the velocity of smoke venting decreases. 2) Smoke venting function of the roof vent is going to be lost from certain operating pressure called “initial logging pressure”, which might cause “smoke venting logging”. 3) The sprinkler spray decreases the horizontal momentum of the smoke flow therefore prevent it from flowing out of the spray region, which leads to an increase of CO concentration. 4) the smoke venting areas would lead to difference of velocities 5) smoke layer temperature rises when smoke venting is not logged and would have no significant effect on the smoke flow state under smoke venting logging.
H.P. MORGAN and G.O. HANSELL,1984[122]	Theoretical	To study how To choose a fire size on which to base the design of a ventilation system	1) Fitting sprinklers in open plan offices may give a major advantage in reducing the capacity required of a smoke ventilation system, but much less of an advantage for cellular offices 2) The British Standard for means of escape from offices is generally successful in preventing

			casualties.
P.L. Hinkley, 1989[123]	Theoretical	To estimate the effect of roof venting on sprinkler	3) The effect of permanent venting on sprinkler activation is small and generally of no practical importance. 4) With short time constant sprinklers, venting was much less likely to increase and more likely to decrease the number of excess sprinklers operating than with long time-constant sprinklers.
C.F. Zhang (2013) [124]	Theoretical	To investigate the cooling effect of water spray	The temperature decrease was almost linear to the working pressure
K.Y. Li (2009) [125]	Theoretical and experimental	To predict the downward descending behavior of the buoyant smoke layer under sprinkler spray	With the increase of the sprinkler operating pressure, the length of the downward ‘‘smoke logging’’ plume increased monotonously and linearly, but the cool effect on the smoke layer was shown to be less effective.
S.C. Li, etc. (2008) [126]	Theoretical and experimental	To measure the cooling of a smoke layer by water sprays	Sprinkler operation has a great effect on the smoke temperature
Morgan and Hansell (1985)[122]	Review	To identifying a "design fire" size for use in designing smoke	Their review indicated that the maximum heat release rates and areas of fire involvement in sprinklered buildings were much lower than in unsprinklered buildings

		ventilation systems for Atria	
Mawhinney, J. R.(1994) [112]	Full-scale experiments on shielded, sprinklered fires	To investigate the effects of sprinkler on shielded fires	Sprinklers are very effective for unshielded fires by reducing both smoke and fire hazard (HRR, temperature, fire pressure, visibility, CO and CO2 concentrations) to negligible levels, but fail to be so effective for shielded fires regarding especially to the visibility and CO, CO2 concentrations
Liu (1977)[127]	Theoretical and experimental	To investigate the cooling produced by a corridor sprinkler system.	the corridor sprinkler system was effective in cooling the hot gas flow. In some cases, the smoke temperature exiting the corridor was less than ambient, resulting in non-buoyant flow.
You et al. 1986, 1989 [128,129]	Full-scale experiments	To investigate the cooling of a smoke layer by sprinkler spray for a fire in a compartment	Empirical correlations for the heat absorption rate of the spray and the convective heat loss rate through the room opening were established
Madrzykowski and Vettori 1992[130] Lougheed 1997 [131]	Full-scale experiments for open-plan offices	To investigate effect of sprinklers on fire size	once the sprinklers gain control of the fire but are not able to extinguish it immediately due to configuration, the heat release rate decreases exponentially
Lougheed et al. 1994	Full-scale fire tests for compact	To investigate effect of	fires in compact mobile systems are difficult to extinguish and large quantities

	mobile storage systems	sprinklers on fire size	of smoke could be produced even after sprinkler activation
Bennetts et al. 1997	Full-scale fire tests for retail occupancies	To investigate effect of sprinklers on fire size	for many common retail areas (clothing and bookstores), the fire was controlled and eventually extinguished with a single Sprinkler, but for shielded fire loads it grew up to large fire.
O’Neill et al. 1980 [132]	full-scale fire tests for patient room	To investigate effect of sprinklers on smoke movement	Temperature was lowered but visibility was lost 60s after the activation of the sprinkler, generating high CO concentrations at 1.5m height throughout the test area
	Full-scale fire tests	To investigate smoke flow into a large volume space as a result of a sprinklered fire in an adjacent compartmen t	approximate heat release rate limits above which hot smoke flow was predominant were dependent on fire location and sprinkler application density ranging between approximately 150 kW to 750 kW for 4.1 (L/min)/m^2 and 8.1 (L/min)/m^2, respectively.

Table 13 Different definitions of resilience

Author	Definitions
Longstaff et al. 2010, [139]	the capacity of a system to absorb disturbance, undergo change, and retain essentially the same function, structure, identity, and feedbacks
Norris et al. 2008; Fiksel 2006 [140]	a process linking a set of adaptive capacities to a positive trajectory of functioning and adaptation after [emphasis added] a disturbance…. resilience emerges from a set of adaptive capacities
	The capacity of a system to survive, adapt and grow in the face of change and uncertainty
National Institute of Building Sciences(NIBS),2006[137]	Drawing upon the work of the National Research Council, we define resilience as the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events.
Allenby and Fink 2005, [141]	the capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must
The White House 2011 [142]	the ability to adapt to changing conditions and withstand and rapidly recover from disruption due to emergencies
DHS 2010 [143]	ability of systems, infrastructures, government, business, communities, and individuals to resist, tolerate, absorb, recover
	from, prepare for, or adapt to an adverse occurrence that causes harm, destruction, or loss
Gilbert 2010 [135]	The ability to minimize the costs of a disaster, to return to a state as good as or better than the status quo ante, and to do so in the shortest feasible time, the ability to withstand a hazard without suffering much harm; the ability to resist to and recover after suffering harm from a hazard
Kahan et al. 2009, [144]	The aggregate result of achieving specific objectives in regard to critical systems and their key functions, following a set of principles that can guide the application of practical ways and means across the full

	spectrum of homeland security missions, including resistance, absorption, and restoration
SDR 2005 [145]	The capacity of a system, community, or society potentially exposed to hazards to adapt, by resisting or changing, in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organizing itself to increase its capacity for learning from past disasters for better future protection and to improve risk reduction measures
Tierney 2003 [146]	The ability to adjust to 'normal' or anticipated stresses and strains and to adapt to sudden shocks and extraordinary demands. In the context of hazards, the concept spans both pre-event measures that seek to prevent disaster-related damage and post-event strategies designed to cope with and minimize disaster impacts
NIAC 2009 [147]	The ability to reduce the magnitude, impact, or duration of a disruption, the ability to absorb, adapt to, and/or rapidly recover from a potentially disruptive event
TISP 2011 [148]	The capability to prepare for, prevent, protect against, respond to or mitigate any anticipated or unexpected significant threat or event, including terrorist attacks, to adapt to changing conditions and rapidly recover to normal or a "new normal," and reconstitute critical assets, operations, and services with minimum damage and disruption to public health and safety, the economy, environment, and national security
NRC 2011 [149]	A disaster-resilient nation is one in which its communities, through mitigation and pre-disaster preparation, develop the adaptive capacity to maintain important community functions and recover quickly when major disasters occur
Boin and McConnell 2007, [150]	the ability to 'bounce back' after suffering a damaging blow
Paton 2007[151]	"the capacity of a community, its members and the systems that facilitate its normal activities to adapt in

ways that maintain functional relationships in the presence of significant disturbances

APPENDIX 2

Analyzing steps of Fire Risk Analysis : an example of Building Sizes

1) Describe probability distribution of fire severity levels based on building size levels, which in turn is based on building areas and building heights, schematic sketches may be shown as figure 6-7 and figure 6-8:

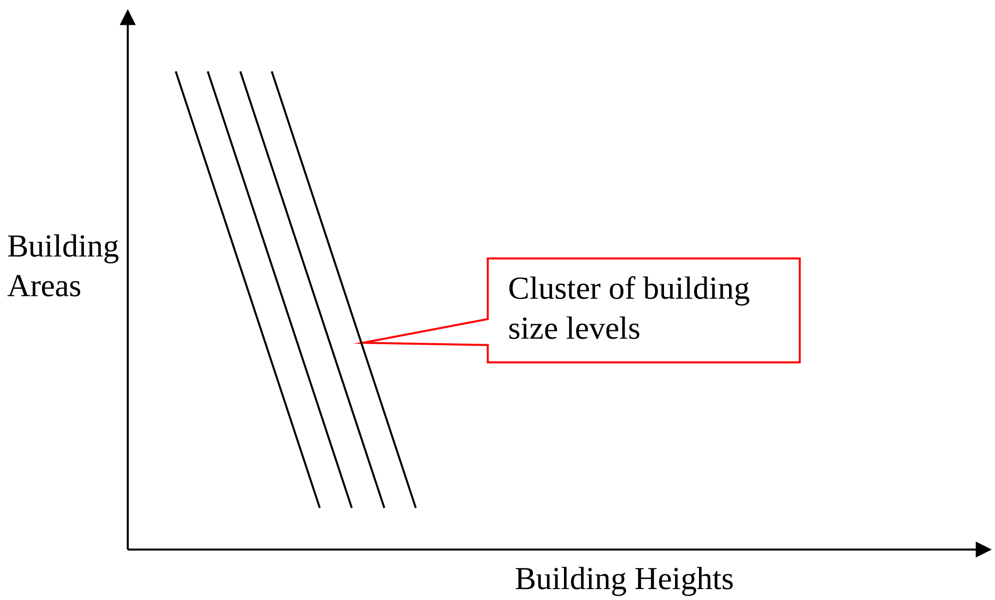

Figure 6: Schematic sketch to relate building area and building height to building size levels.

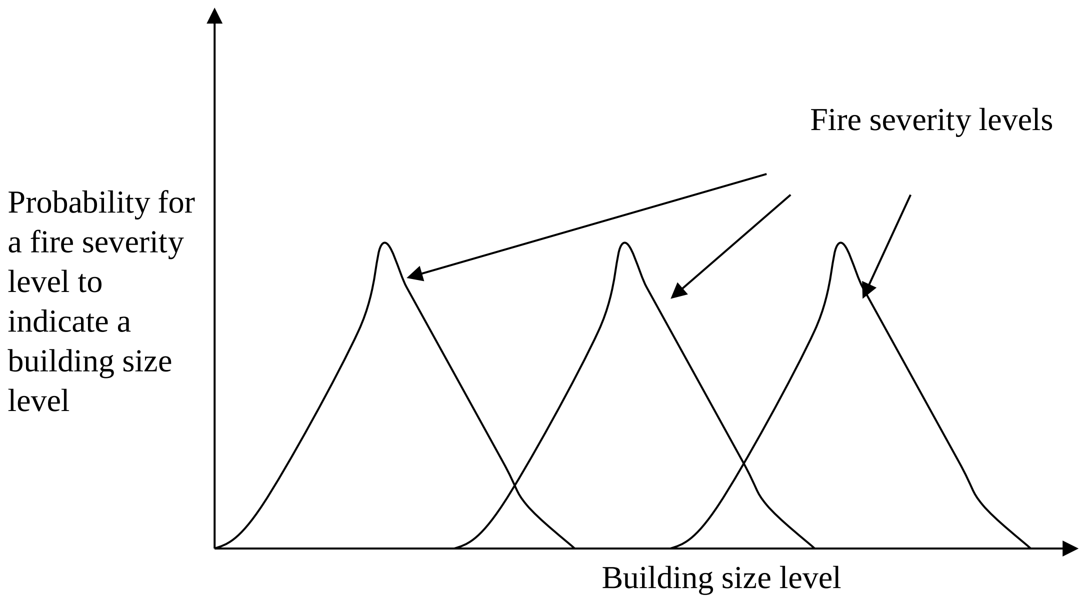

Figure 7: Schematic sketch to describe probability distribution of fire severity levels based on building size levels.

2) Describe probability distribution of a range of capability levels for different fire brigades, as shown in the following figure 6-9

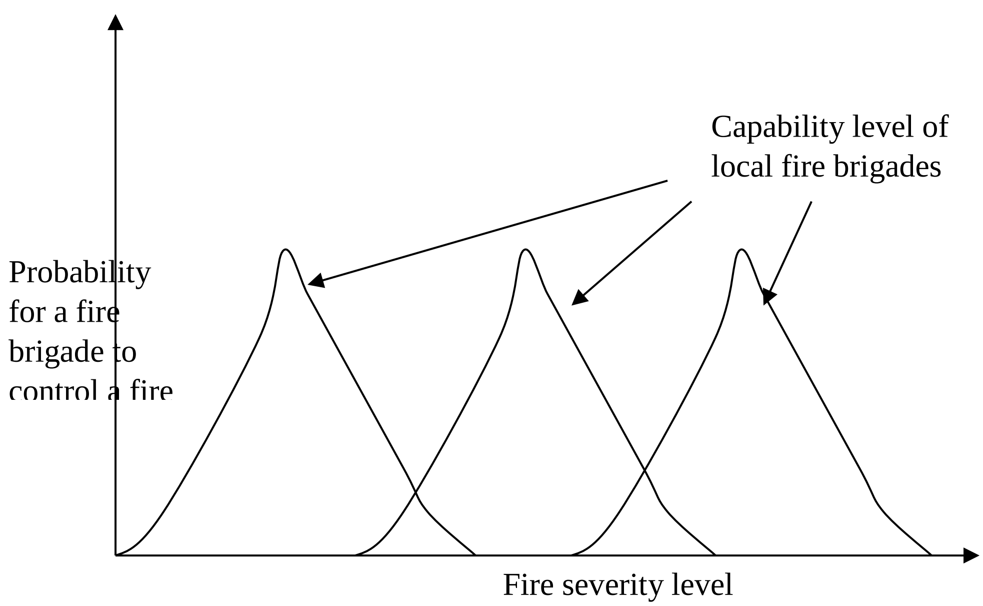

Figure 8: Schematic sketch to describe probability distribution of capability level of local fire brigade based on fire severity levels.

3) Describe the joint probability distribution of capability level of local fire brigade based on building size levels. Note that fire severity level could be measured in the same unit as capability level of

local fire brigades.

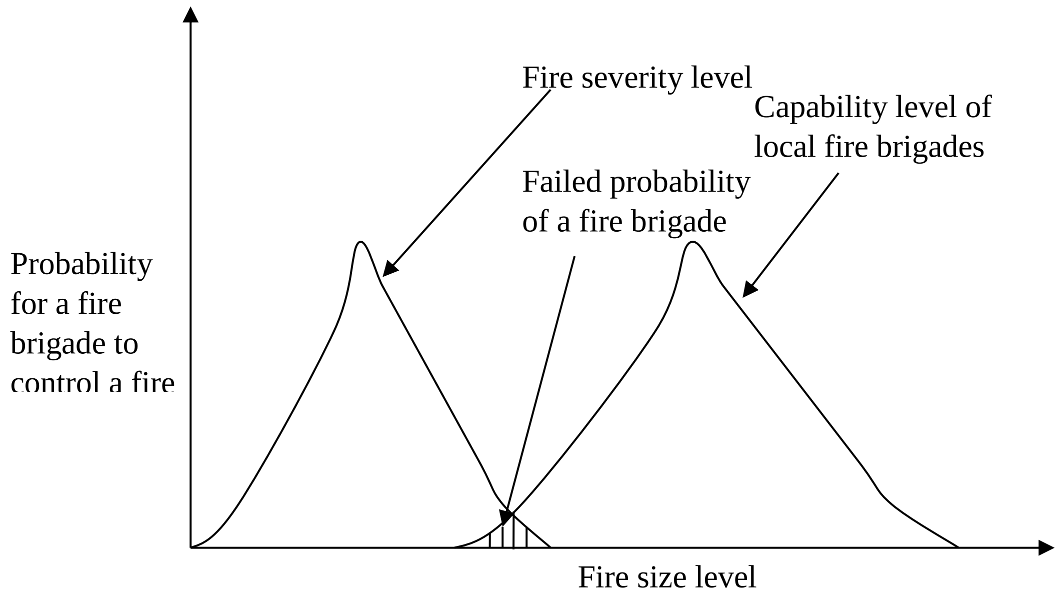

Figure 9: Probabilities of fire severity level and capability level of local fire brigades shown in one figure.

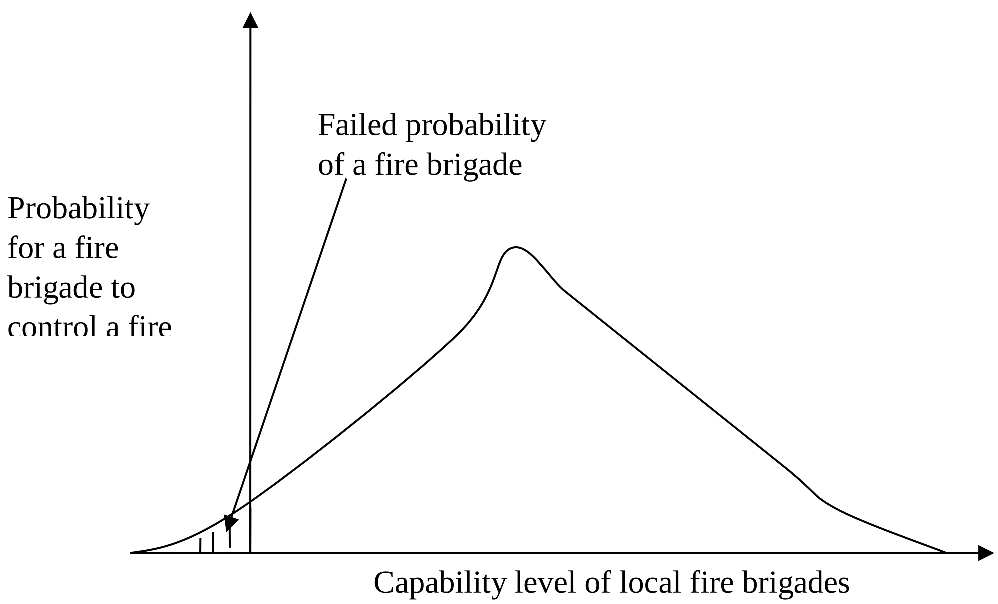

Figure 10: Joint probability distribution of fire severity level and capability level of local fire brigades.

4) Determine the correlation between probability for a fire brigade to extinguish or control a sprinklered or non-sprinklered fire and building size level.

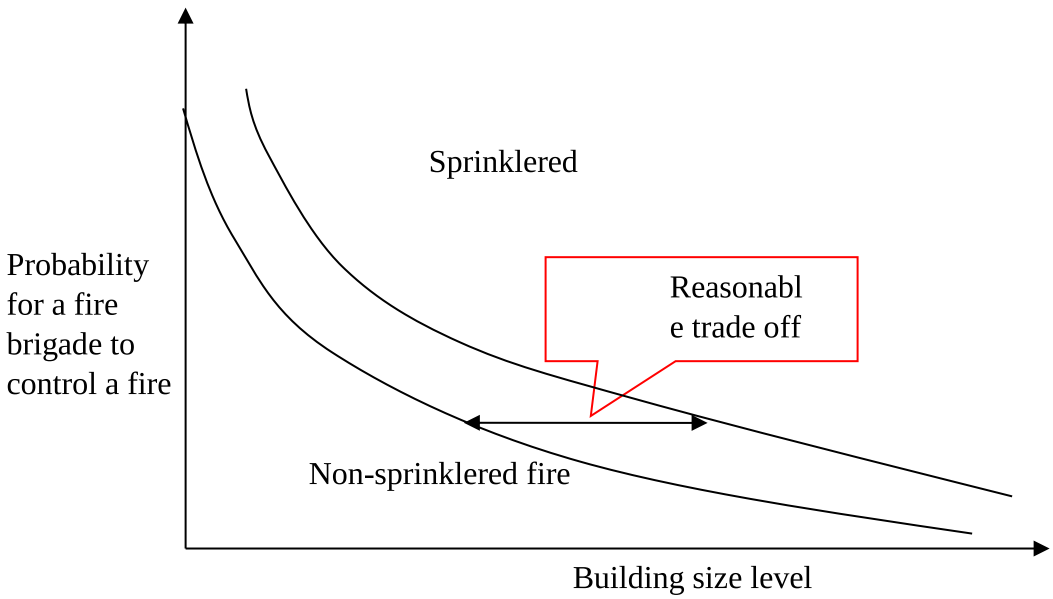

Figure 4: **Schematic description of reasonable trade-off of building size based on Probability for a fire brigade to control a fire and Building size level.**

APPENDIX 3

A network model to simulate fire spreading between rooms

Objectives: Given fire severity of each room and fire resistance ratings of fire walls between rooms, simulate the process of fire spreading between rooms.

Note: the whole building will be simplified to a network, with rooms as the nodes and fire walls as the edges. The heat transfer of fire is all directions, but the different heat transfer coefficient, fire resistance ratings of walls, and the different fire severities will determine which room will be ignited faster than others. The original room will be set a fire temperature much higher than other rooms, and the temperature difference between nodes (rooms) will act as the drive force of heat transfer. One node may be heated by several nodes only if other connected nodes have a fire temperature. Every node is designated a critical heat flux, once a node receives more heat flux than its critical heat flux, it is deemed as a fired room and a fire temperature will be designated to it with some time delay(let's say, 5 minutes). An edge, with both nodes fired, will be deleted after a time period, simulating the collapse of a fire wall. Each node can be sprinklered or not, if sprinklered, a random ineffective probability will be designated to a node at the beginning of every simulation (Monte Cario Sampling). An effective sprinklered node will lose the ability to transfer heat to other nodes. By many times of Monte Cario Simulating, we will be able to grasp the statistics characteristics of fire spreading in a building.

In summary, the network model could be written as G(N,E), where N denotes nodes, E denotes edges. N has such properties :

- critical heat flux,
- fire severity(the time endurance of fire)
- time delay(the time from ignition to fully developed fire)
- sprinklered or not
- sprinklers being effective or not.

E has such properties as:

- Coefficient of combined heat transfer, indicating a faster or slower heat transfer speed;
- Fire resistance ratings, indicating a stability criteria when exposed to fire temperature.

A schematic sketch could be shown as below:

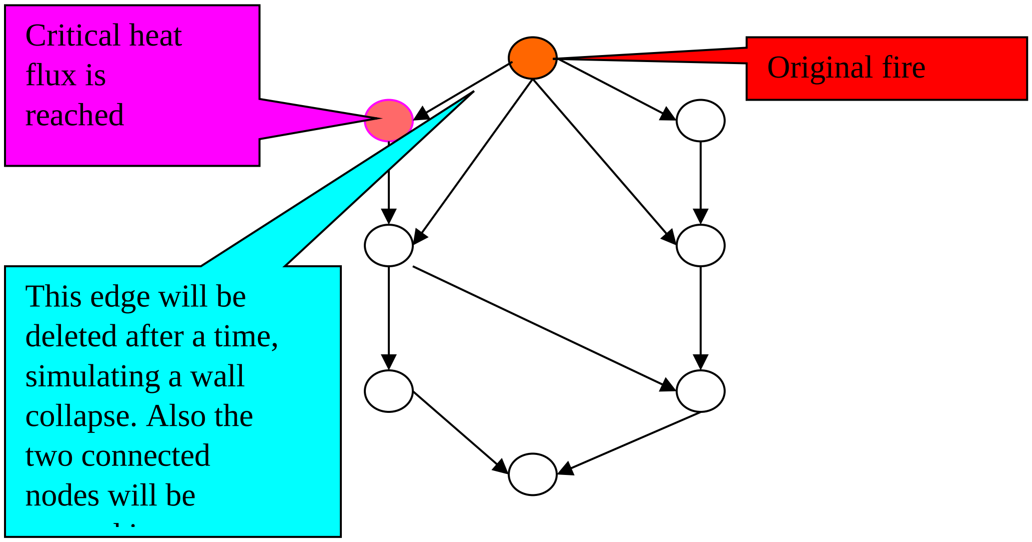

Figure 11: Schematic description of network model of fire spreading between rooms.

Potential outcomes: 1) the possibility of different fire spreading patterns; 2) the effect of sprinklers' reliability on the fire spreading patterns.

Implication: the appropriateness of sprinkler trade-offs for fire resistance ratings could be investigated indirectly combined with the reliability of sprinklers.

Simulation steps:

1) Based on information about a given building, establish a network, assigning different values to properties of nodes and edges;
2) Perform a Monte Cario Sampling to set random effective values to nodes;
3) Select a node to start a fire.
4) Begin the fire spreading simulation
5) Record the simulating results;
6) Iterate from step 2 to step 5 until a preset number of simulation times; is met.
7) Output a simulation report.

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