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Fire safety evaluation of multifunctional buildings

Special emphasis on antagonistic attacks
and protection of sensitive areas



LUNDS
UNIVERSITET

Martin Nilsson

Licentiate Thesis

Department of Fire Safety Engineering and Systems Safety
Faculty of Engineering
Lund 2013

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Illustrations and figures: Martin Nilsson

Keywords: *multifunctional building, multipurpose building, antagonism, terrorism, design fire, fire scenario, sensitive areas, electrical appliances room, fire protection, hypoxic air venting, reduced oxygen, fire growth, building code, fire safety engineering*

Abstract:

Multifunctional buildings, often hosting societal important functions, have become increasingly more common during the last years. The combination of many functions within the same building as well as an increased exposure to antagonistic attacks create new, not previously well analyzed problems for fire safety. A method for selection and evaluation of fire scenarios in multifunctional buildings has been developed. The evaluation method is based on the performance-based design approach, using scenario analysis, and accounts for specific identified problem areas for multifunctional buildings and antagonistic attacks. To aid application of the evaluation method a method to quantify fire growth rate of fire scenarios was developed and fire protection using hypoxic air venting was investigated. Finally specific research areas that need further investigation were identified.

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Preface

The research presented in this thesis is part of the project “SAFE MULTIBYGG – Riskidentifiering, analys och åtgärdsmetodik för olycksförebyggande arbete för multifunktionella byggnader med avseende på specifika antagonistiska hot”, carried out during the period 2011 to 2013. The aim of the project is to support accident prevention activities in multifunctional buildings in order to ascertain safety and security for the citizens. The research was supported by grants from the Swedish Civil Contingencies Agency. The research on hypoxic air venting was also part of the project “Kartläggning och kvalitativ analys av möjligheter och risker med reducerad syrehalt i brandceller innehållande elektrisk utrustning”, carried out in 2012. The National Fire Safety Group (Nationella Brandsäkerhetsgruppen, NBSG) also supported the research on hypoxic air venting. The funding is greatly acknowledged.

I would like to thank my supervisors, Professor Patrick van Hees and Dr. Håkan Frantzich for all your help and support. Patrick, you have happily shared your knowledge and despite your busy schedule always taken time to guide me whenever needed. Without your guidance and excellent input my scientific side would not have been what it is today. Håkan, your sense for structure and unambiguousness and your willingness to share that sense has been invaluable. Your comments and straightforward feedback has really helped me improve my work and your support through times of doubt is greatly appreciated.

Many thanks to Mr. Robert Jönsson who gave me the opportunity to do research.

Summary

Multifunctional buildings, often hosting societal important functions, have become increasingly more common during the last years. In contrast to traditional building design there is a trend to have one single building hosting many different functions or occupancies. In addition, there is an increased exposure to antagonistic attacks in multifunctional buildings. These factors create new, not previously well analyzed, problem areas that are generally not considered by the building code.

This licentiate thesis presents research on how the fire safety in multifunctional buildings can be evaluated. Special emphasis is put on antagonistic exposures and sensitive areas, e.g. electrical appliances rooms, often needed to provide continuity of important functions. The research questions are as follows:

- What are the specific problem areas within multifunctional buildings when considering the multifunctional aspects as well as antagonistic attacks?
- How could an evaluation method that identifies and analyzes fire related risks, including antagonistic threats, in multifunctional buildings be designed?
- Are there specific research areas that need further investigation or research questions that need to be answered in order to support such an evaluation method?

Specific problems were that: an incident may have a large impact on society; there are a large variety of and other protection objectives than life safety; a large number of stakeholders; multifunctional buildings are more exposed to antagonistic attacks; the incidents are generally more severe; the public has an aversion towards catastrophic events indicating that a higher safety level may be warranted; fire protection might become impaired and security is of great importance.

Based on the problem areas a method for selection and evaluation of fire scenarios was developed. The evaluation method has its starting point in the performance-based design process and uses scenario analysis.

In addition, to support application of the evaluation method, research was conducted resulting in a method to quantify fire growth rates for fire scenarios, providing useful input to the evaluation method. Also the use of hypoxic air venting as fire protection was further investigated. The hypoxic air venting system is promising for protection

of sensitive areas if the oxygen concentration can be kept at sufficiently low levels. If not there are a number of challenges.

Finally specific research areas that need further investigation were identified, these areas are: safety levels; sensitive areas; fire protection; ignition scenarios and domino effects.

Sammanfattning

Multifunktionella byggnader har blivit vanligare på senare tid. Ofta innehåller dessa byggnader samhällsviktiga funktioner och till skillnad från traditionella byggnader innehåller de flera olika funktioner och verksamheter inom samma byggnad. Dessutom är dessa byggnader i högre grad exponerade för antagonistiska hot. Dessa faktorer skapar nya och inte tidigare väl analyserade problemområden som normalt inte beaktas i de traditionella byggreglerna.

Denna licentiatuppsats behandlar hur utvärdering av brandsäkerheten i multifunktionella byggnader kan göras. Speciellt behandlas problematiken kring antagonistiska hot och skydd av känsliga utrymmen, såsom t ex el-rum, som visat sig vara viktiga för att minska avbrottsrisker för viktiga funktioner. Följande forskningsfrågor formulerades:

- Vilka är de specifika problemområdena kopplat till multifunktionalitet och antagonism för multifunktionella byggnader?
- Hur kan en metod som identifierar och analyserar brandrelaterade risker, inklusive antagonistiska hot, i multifunktionella byggnader utformas?
- Finns det specifika forskningsområden eller forskningsfrågor som behöver utredas vidare för att understödja användandet av en sådan metod?

Identifierade specifika problemområden är: en händelse kan ha stor påverkan på samhället; där är en stor variation i skyddsmål samt även andra skyddsmål än personsäkerhet; många intressenter, högre exponering för antagonistiska hot; händelserna är ofta allvarligare; samhället har en aversion mot katastrofer vilket tyder på att det krävs en högre skyddsnivå; brandskyddssystem har en tendens att ej fungera och säkerhetsfrågor i form av t ex skalskydd är extra viktigt.

Baserat på de beskrivna problemområdena utvecklades en metod för urval och analys av brandrelaterade scenarier. Utvärderingsmetoden grundar sig på funktionsbaserad dimensionering med scenarioanalys.

För att understödja användande av utvärderingsmetoden genomfördes forskning som resulterade i en metod för att kvantifiera brandtillväxthastigheter. Vidare undersöktes system med permanent reduktion av syrgashalten som brandskyddsmetod. Systemet

är lovande för känsliga utrymmen i de fall syrgashalten kan hållas på en tillräckligt låg nivå. Om detta inte är möjligt realiserar en mängd utmaningar som måste hanteras.

Avslutningsvis identifierades områden i behov av vidare forskning, dessa är: skyddsnivåer; känsliga utrymmen, brandskyddssystem; antändningsscenarier och dominoeffekter.

List of appended papers

- Paper I** Nilsson, M., Frantzich, H., & van Hees, P. (2013). Selection and Evaluation of Fire Related Scenarios in Multifunctional Buildings Considering Antagonistic Attacks. *Fire Science Reviews*, 2(3), pp. 1-20. doi: 10.1186/2193-0414-2-3.
- Paper II** Nilsson, M., & van Hees, P. (2013). Advantages and Challenges with Using Hypoxic Air Venting as Fire Protection. *Fire and Materials*. doi: 10.1002/fam.2197. (published on-line).
- Paper III** Nilsson, M., Johansson, N., & van Hees, P. (2014). A New Method for Quantifying Fire Growth Rates Using Statistical and Empirical Data – Applied to Determine the Effect of Arson. Accepted for publication in: *Proceedings of the 11th International Symposium on Fire Safety Science*.
- Paper IV** Nilsson, M., van Hees, P., Frantzich, H., & Andersson, B. (2012). Analysis of Fire Scenarios in Order to Ascertain an Acceptable Safety Level in Multi-Functional Buildings. In *Proceedings of the 9th International Conference on Performance-Based Codes and Fire Safety Design Methods*, Hong Kong, China, 20-22 June 2012, Society of Fire Protection Engineers, USA.

Paper	Author's contribution
I	Carried out the problem identification (i.e. the literature review and the interviews), developed the method for selection and evaluation of fire related scenarios, drafted and completed the manuscript. Conducted approximately 85% of the work.
II	Carried out approximately 50% of the literature review, drafted and completed the manuscript. Conducted approximately 75% of the work.
III	Gathered information on fire growth rates, developed the method together with one other author (50% each), carried out the statistical analysis, drafted 75% of the paper and completed the manuscript. Conducted approximately 65% of the work.
IV	Carried out the literature review, developed the method, drafted and completed the manuscript. Presented the paper at the conference. Conducted approximately 90% of the work.

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Abbreviations

AASW	All Active Systems Working (scenario)
ASET	Available Safe Egress Time
CC	Cone Calorimeter
CCF	Common-Cause Failure
CDF	Cumulative Distribution Function
DE	Domino Effect
FP	Fire Protection
FPA	Fire Propagation Apparatus
HRR	Heat Release Rate
IS	Ignition Scenario
OASI	One Active System Impaired (scenario)
PBD	Performance-Based Design
QRA	Quantitative Risk Assessment
RQ	Research Question
RSET	Required Safe Egress Time
SA	Sensitive Area
SL	Safety Level
WCC	Worst Credible Consequence (scenario)

1 Introduction

1.1 Background

Multifunctional buildings have become increasingly more common during the last years. In contrast to traditional building design there is a trend to have one single building hosting many different functions or occupancies, for example hosting theatres, a subway station, a shopping center, restaurants and offices within the same building.

For the purpose of this thesis a multifunctional building is defined in accordance with the terminology used in Paper I. A **multifunctional building** is

“One or several connected buildings hosting several functions (e.g. societal) or occupancies (e.g. office, restaurant) where the facility and its function is one integrated whole. The definition also includes underground facilities.”

Multifunctional buildings often host societal important functions such as transportation centers, municipality offices etc. Due to the large variety of functions and businesses hosted, a multifunctional building often has a large number of stakeholders, is often open to the public and could potentially contain a large number of visitors as well as many different tenants. Furthermore the building design is often complex, for example open with intermediate floors in atria, complicating evacuation in case of fire as well as contributing to a large potential for significant smoke spread. All these factors contribute to the overall complexity and vulnerability, and potentially unacceptable consequences if a fire was to occur. An incident in such a building may result in significant consequences as a result of death, property damage and impaired functions or services that may be essential to societal or business operations. The impairment of functions or services may also have an impact outside the affected building such as a delay in transportation services, as illustrated in figure 1. Another such example is production sites, where one site is dependent upon material produced at a sister site. This effect where one infrastructure is dependent upon another infrastructure, which could be both due to spatial and functional interconnectedness is often referred to as interdependencies (Utne et al, 2011), and may be a significant parameter affecting the societal consequences in case of an incident in a multifunctional building.

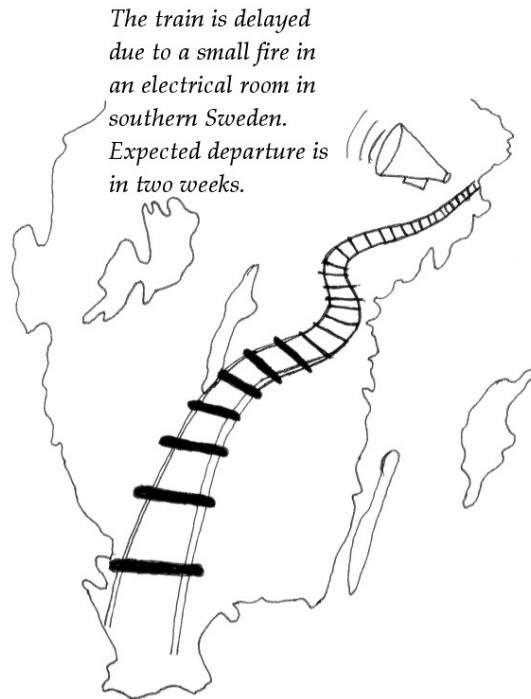


Figure 1. Illustration of the effect of interdependencies.

Adding to the above-described complexity, with potential for significant consequences, is the increased exposure to antagonistic attacks for multifunctional buildings (Paper I). Due to the fact that many functions are gathered within a small area in a multifunctional building these buildings are more vulnerable to attacks and other accidents. An attack on a multifunctional building would inflict significant emotional and/or economic damage and may result in impairment of societal functions making these buildings more likely to be selected as targets for antagonistic attacks (Brown & Lowe, 2003).

For the purpose of this thesis the definition of an **antagonistic attack** is

“A manmade attack, against a specific target to which the aggressor bear hostility, with the intention to achieve a specific goal as a consequence of the attack, e.g. a terrorist attack such as an explosion or arson fire”

According to the oxford dictionary (Oxford English Dictionary, 2013) antagonistic is “showing or feeling active opposition or hostility towards someone or something”. Coster and Hankin (2003) state that antagonistic attacks are deliberate and malicious. However

they further state that studies of terrorism commonly refers to the difficulty in defining what terrorism is. Holmgren et al (2007) discuss the nature of antagonistic attacks. They state that the aggressor chooses the target and that the purpose can be to cause large damage, to impair important societal functions, to make a symbolic demonstration, to spread fear and that the attack may be designed in order to reach higher goals (political, economical etc.). No univocal definition of what an antagonistic attack is has been found in the literature. However some of the characteristics are that they are deliberate, conducted against a chosen target, includes bearing hostility and has a specific goal. These characteristics are captured by the definition above. It should be noted that the definition does not include anything about the scale of the attack, i.e. it does not have to be a large-scale attack or an attack that cause large damage in order to be an antagonistic attack according to the definition. For example an arson fire against a school building would be classified as an antagonistic attack according to the chosen definition.

Terrorism and attacks on buildings have increased during the last years (Brown & Lowe, 2003) and the probability of an antagonistic attack is for example suggested to be between 10^{-6} and 10^{-7} per building and per year on a US commercial building (Stewart, 2008). This frequency is in the same order of magnitude as acceptable risk criteria proposed by Det Norske Veritas (DNV) (Davidsson et al, 1997) where acceptable individual risk is between 10^{-5} and 10^{-7} per year and for societal risk between 10^{-4} and 10^{-6} per year for $N=1$. Since the proposed frequencies by Stewart (2008) relates to single buildings and the criteria proposed by DNV considers risk from one hazardous activity the two should be fairly comparable, indicating the need to analyze antagonistic attacks. Furthermore arson, included in the definition of an antagonistic attack, is a common fire scenario, for example Richards (2008) suggests that 15% of all fires in New Zealand are deliberately lit, Hall (2007) concludes that 6% of all US fires are intentional and Simonson (2007) states that in Sweden the number is as high as 25%. Examples of fairly recent antagonistic attacks are: the Boston Marathon bombings in USA 2013 (Winter et al, 2013), the underground explosion in London, UK 2005 (Handley et al, 2009), the subway fire in Daegu, Korea 2003 (National Emergency Management Agency, 2004), the attack on the World Trade Center in New York, USA 2001 (Gutierrez et al, 2005), the gas attack in Tokyo, Japan 1995 (Pangi, 2002) and the World Trade Center bombing in New York, USA 1993 (Isner & Klem, 1993). In Sweden the bombing in Stockholm 2010 can be mentioned (Skarin & Högström, 2010) as well as the arson fire in Gothenburg 1998 (Eksborg et al, 2001) and the arson fire in Vellinge 2007, (Strid et al, 2007; Trelleborgs Allehanda, 2007) where a variety of functions were affected such as school functions as well as other businesses.

Many of the above referenced antagonistic attacks are high consequence events, which are impossible to control for the people exposed. The general public perceives

risks that are considered dreadful, i.e. uncontrollable, catastrophic, not equitable compared to the perceived benefit, not easily reduced and/or have a high dread factor as higher risks (Slovic, 1987). The higher the perceived risk the more people want to see its current risks reduced (Slovic, 1987). Furthermore if the risk is considered to be unknown, i.e. the risk is unobservable, unknown to those exposed, new, the effect is delayed and unknown to science the risk is also perceived as higher than if it is characterized as the opposite (Slovic, 1987).

It is clear that antagonistic attacks in general, especially when considering large-scale events, are considered dreadful and rank high on that scale. However, the effects of an antagonistic attack such as arson or an explosion might be well known but on the other hand terror attacks are fairly new risks and in one essence unknown to those exposed. It is therefore not easy to pinpoint antagonistic attacks on the unknown scale. Slovic (1987) however states that the dread factor is the most important factor impacting how risks are perceived. Therefore it is highly probable that the general public would like to see a higher safety level against antagonistic events than what may be possible to economically justify by regular cost-benefit analysis. Slovic (1987) makes this point by stating *“The point is that traditional economic and risk analyses tend to neglect these higher order impacts, hence they greatly underestimate the cost associated with certain kind of events.”* What he talks about in this instance is the increased cost due to stricter regulation, public opposition and reliance on more expensive energy sources as a result of the Three Mile Island nuclear reactor accident in 1979. In this instance the costs that are generally neglected are economic costs that couldn't be foreseen but also increased costs in terms of e.g. changed behavior as an effect of the event, increased fear among the public, and further restrictions to personal integrity as a result of the event (e.g. security checks). Such costs are hard to estimate and foresee and this may be the reason they are neglected. One example of this effect for antagonistic attacks is illustrated by the long-term effect the underground explosion in London, UK 2005, had on the population's use of the public transportation system after that accident. Eight months after the bombings the population had reduced their use of the public transportation system with 19% (Rubin et al, 2007) and 45% of those directly affected by the bombings reported disabling travel anxiety (Handley et al, 2009).

Wolski et al (2000) also discuss these effects with respect to fire and that people in general require a higher protection level against large fires and catastrophic events. Wolski et al (2000) discuss nine risk factors that can be used to describe the public attitude towards differently perceived risks: volition; severity; effect manifestation; familiarity; controllability; benefit; necessity; exposure pattern and origin. When considering these factors, which have much in common with the characterization made by Slovic (1987), they point towards a required higher safety level in multifunctional buildings, especially if antagonistic exposures exist (Paper I).

An interesting aspect is then how the society handles accidents through regulation, both traditional accidents and antagonistic events. The building codes traditionally focus on life safety considering accidental fire events (Klason et al, 2011) and generally scenarios incorporating antagonistic events are not considered (Gilbert et al, 2003). Klason et al (2011) and Richards (2008) state that building codes, especially traditional deemed to satisfy fire safety design, do not account for arson fires since they do not consider the actions of the individual lighting the fire. The antagonistic events however may be more severe, carefully planned and there is a potential for large consequences. In addition, to the exclusion of antagonistic events in the building code, protection of functions is generally not considered. The Swedish building code (Boverket, 2011b) for example focuses on life safety as well as the NFPA life safety code (NFPA, 2012a). The requirement for continuity of business and essential functions, as well as protection of property is generally up to the relevant stakeholders, i.e. business owners, to specify, and is not regulated by authorities. As a result the prescriptive design methods do not cover these types of protection objectives. Furthermore, since prescriptive rules cover a wide range of buildings and antagonistic attacks incorporate an almost infinite number of possible events, deemed to satisfy solutions taking into account antagonistic attacks would be very expensive. Also due to the fact that prescriptive rules cover such a wide range of buildings the rules are not able to capture the uniqueness of a multifunctional building and the problems that presents. Performance-based design methods, however, would be able to capture the uniqueness of multifunctional buildings, relevant possible events and account for different protection objectives, see e.g. (SFPE, 2006, 2007). However these guidelines do not explicitly include antagonistic exposures, are broad and not very detailed, meaning that they give limited guidance on evaluation of such complex buildings as multifunctional buildings.

The increased number of multifunctional buildings where a lot of functions are gathered in a small area, together with the increased exposure to antagonistic attacks, creates new, not previously well analyzed, problem areas that are generally not considered or regulated by the building code. These new problem areas need to be analyzed, while also considering the potential for significant consequences, especially societal, in case of fire or other incidents. The presence of protection objectives other than life safety, together with the public's aversion to catastrophic events and their requirement for a higher safety level in multifunctional buildings also need to be accounted for. These factors together with today's limited guidance on evaluation procedures, and lack of well-established analysis methods, create a demand for a method analyzing the fire safety level from a holistic view in multifunctional buildings.

1.2 Aim

The aim of this thesis is to support accident prevention and consequence mitigation in case of an accident or antagonistic attack in multifunctional buildings.

1.3 Goal

The goal of the thesis is to develop a method that identifies risks in multifunctional buildings and analyses them. The developed evaluation method shall focus on the consequences from antagonistic threats or accidents such as fires and explosions. Furthermore the goal is to identify specific aspects of multifunctional buildings and antagonistic attacks that presents problems that need to be evaluated in order to make a holistic evaluation of a multifunctional building. Finally the goal is to identify the need for further research and input in order to be support use of the developed evaluation method and to investigate a few of these areas deeper.

Two areas were chosen for deeper investigation, quantification of fire growth rates and hypoxic air venting as fire protection measure. Regarding fire growth rates the goal was to develop a method that quantifies the fire growth rate of building fires in terms of a probability distribution. The goal with the study, of hypoxic air venting as a fire protection measure, was to determine advantages and challenges with the system as well as further research needs.

1.4 Research questions

The main area of interest in this thesis is to develop a method that identifies and analyses risks in multifunctional buildings. Such an evaluation method needs to be able to account for: the uniqueness of the building; different protection objectives; antagonistic attacks and other specific problems associated with multifunctional buildings and antagonistic attacks. The following research questions (RQ) were formulated:

RQ 1: What are the specific problem areas within multifunctional buildings when considering the multifunctional aspects as well as antagonistic attacks?

RQ 2: How could an evaluation method that identifies and analyzes fire related risks, including antagonistic threats, in multifunctional buildings be designed?

Furthermore, for the developed evaluation method to be practically usable there may be research areas that need to be further developed in order to support the use of a developed method. This raises the following research question:

RQ 3: Are there specific research areas that need further investigation or research questions that need to be answered in order to support such an evaluation method?

Answers to research question 3 actually contain new research questions or areas in need of further research. It is not the intention of this thesis to address all those identified questions and areas, just to document them. However two topics were further investigated within this thesis: quantification of fire growth rates for building fires and hypoxic air venting as a fire protection measure.

1.5 Working method

To obtain the answers to research questions 1-3 the methods and working process presented in figure 2 were used. The working process generally followed the solid arrows in chronological order. However input to research question 3 was also given directly from the literature review, semistructured interviews and field visits (cross-hatched lines).

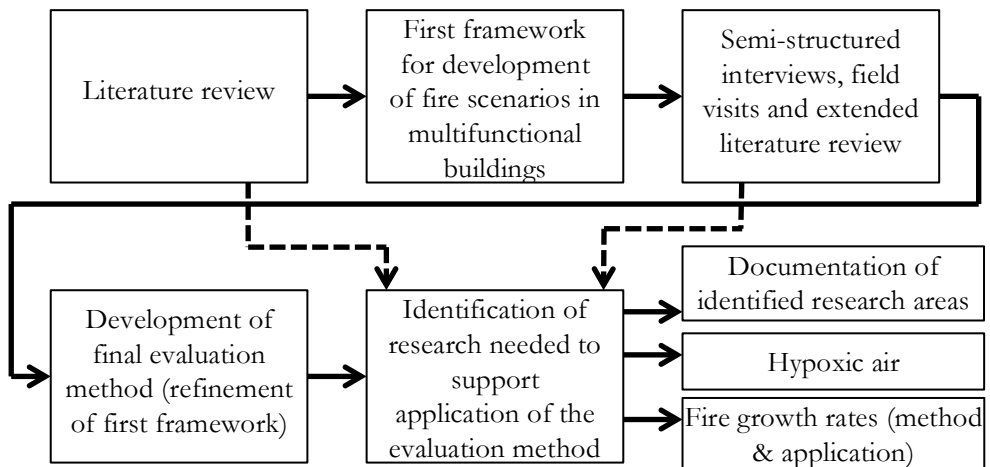


Figure 2. Illustration of working process.

The main focus of the literature review was the problem identification with respect to multifunctionality and antagonism that is related to fire safety. Within the literature review fire safety design guidelines were also studied to obtain input on possible evaluation procedures for multifunctional buildings. The literature review included review of the following subjects: performance-based design guidelines; design fire guidelines; papers regarding multifunctional/multipurpose buildings; design guidelines regarding antagonistic attacks and review of occurred antagonistic attacks and their implications. This literature review resulted in a first framework for development of fire scenarios in multifunctional buildings. The framework and results from the literature review are presented in Paper IV.

Once the first framework was established, semi-structured interviews were conducted with stakeholders in a selected multifunctional building. A total of nine interviews were conducted. Semi-structured interviews have the benefit of ensuring flexibility in how and what sequence questions are asked, for the interviewees to be able to develop their thoughts and for the interviewer to ask follow-up questions, this so that unexpected themes can emerge (Mason, 2004). In connection to the interviews, that were held at the selected multifunctional building, field visit to the building was conducted as well in order to capture specific fire related problems with the layout (architectural, fire protection etc.) of a multifunctional building. Based on the interviews and field visits an extended literature review was conducted on specific topics that were found relevant. The above-described activities resulted in answers to research question 1 and the first framework for development of fire scenarios was refined and further developed with the new input. This resulted in establishment of the method for selection and evaluation of fire related scenarios in multifunctional buildings, answering research question 2. The full description of and findings from the interviews can be found in Nilsson and van Hees (2012) and a summary of the first literature review and the interviews as well as the final evaluation method can be found in Paper I.

Based on the layout of the final evaluation method as well as input from the literature reviews, interviews and field visits, identification of research needed to support application of the method was made (answering research question 3). Firstly the identified research areas were documented and then two research areas were chosen for further investigation. The first was the use of hypoxic air venting as a fire protection measure, which was found to be a suitable risk mitigating fire protection system in multifunctional buildings. The second was the quantification of fire growth rates as input data when analyzing fire safety.

1.6 Limitations

The focus of this thesis is on fire related events. The identification and analysis of risks/hazards are therefore limited to fire related risks/hazards. No consideration has therefore been given to for example antagonistic attacks incorporating spread of toxic gases, armed attacks etc. In terms of antagonistic events mainly arson, explosions, attacks on fire protection equipment and associated support systems etc have been considered.

The effects considered, as a result from an event, are only the effects on and within the building itself. This means that the effect that a function is lost for several months is considered explicitly, however it is not considered how that propagates in the society.

Focus in the thesis is on multifunctional buildings containing societal important functions.

Special considerations for evacuation and structural performance in case of an incident is another part of the SAFE Multibygg project and is not treated specifically in this thesis.

1.7 Thesis outline

A summary of the specific problem areas facing multifunctional buildings with respect to multifunctionality and antagonistic attacks is given in chapter 2, i.e. the answer to RQ 1. In chapter 3 a presentation is given of the developed method for identification and evaluation of fire related risks in multifunctional buildings, i.e. the answer to RQ 2. Chapter 4 presents the areas where further research is needed in order to support application of the evaluation method, i.e. the answer to RQ 3 is presented. Chapter 5 presents research results related to hypoxic air and fire growth rates, i.e. an in depth study of two of the areas identified in chapter 4. In chapter 6 the need for further research is discussed and finally the work is concluded in chapter 7. The four papers, upon which this thesis is based, are included in Appendix 1.

2 Problem areas in multifunctional buildings

The specific problem areas connected to multifunctionality and antagonistic attacks have been identified during the whole process up until the evaluation method (presented in chapter 3) was developed. Hence input has been collected during both literature review, interviews and field visits.

Table 1 summarizes the problem areas identified. These are explained in full detail in Paper I, but some of the issues are discussed and elaborated on below. The identification of specific problem areas with respect to multifunctionality and antagonism serves two purposes. Firstly it provides input on what to put specific emphasis on during analysis of the fire safety in a multifunctional building and when considering antagonistic attacks. It therefore provides input to what an evaluation method needs to address. Secondly the problem identification serves to identify research areas that need to be further explored.

The identified problem areas have been given a designation whether they are associated with multifunctionality, antagonism or both. The designation is sometimes not easy to make and is up for discussion. However pointing in one direction is believed to help the thought-process of the end-user when identifying problem areas in a specific building and designations have therefore been included.

Table 1. Problem areas specific to multifunctionality and antagonism (Paper I)
(M=multifunctionality, A=antagonism).

Aspect that needs to be considered/addressed in the evaluation method	M/A
Flexibility so that a large variety of protection objectives can be addressed	M
Large number of stakeholders	M
Stakeholders with a high exposure to antagonistic attacks (exposing less exposed stakeholders)	A
The initiating event might impair both passive and active fire safety features	A
Common-cause failure due to large number of protection systems and increased probability for common-cause failure due to larger initiating event.	A/M
A lot of different functions provided, however not all are of main concern and the most important ones need to be determined	M
The fire severity, fire development or growth rate might be higher than what is usually designed for (including what protection systems are designed for)	A/M
Support systems that are important for functions and fire safety features	A/M
Domino effects (e.g. fire following explosion)	A
Location of fire (critical locations, e.g. sensitive areas, smaller fires where fire protection do not achieve the protection objective)	A/M
Security features (surveillance, access control, easy access areas etc.)	A
How to determine relevant antagonistic attacks (both large scale and small as arson)	A
First priority should be life safety then the core function of the building	A/M
Core functions of the building and relevant stakeholders need to be determined	A/M
Areas or functions needed to handle an ongoing event need to be analyzed	A/M
Guidance on firm and measurable protection objectives	M
Flexibility to take into account emergency management plans and action plans	M
Higher tendency for failure of protection system due to maintenance issues	M
Passive protection might be inadequate due to maintenance problems	M
External exposures such as a bomb threatened vehicle brought into the building for evacuation	A
The evaluation method needs to be simple enough to identify and determine scenarios to be analyzed during a site visit	-

2.1 Multifunctionality

Multifunctional buildings involve a lot of different stakeholders (Paper I & IV) presenting problems in terms of determining the acceptable fire safety level. This is because there may be different economical prerequisites, a variety in consequence severity for the different stakeholders in case of an incident or simply due to the large number of stakeholders. Including all of them in an evaluation is time consuming. In addition the number of stakeholders also presents problems because there might be fundamentally different views and opinions between different stakeholders. For example on the need for fire protection and what safety level that should be achieved, i.e. different protection objectives that should be achieved. In a multifunctional building, with many tenants located next to one another, the tenants are actually exposing each other. For example, even if one tenant aims for a very high safety level they may be exposed to other tenants aiming for a lower safety level. In addition to the nearby exposures it was indicated during the interviews that the tenants were not aware of what other tenants had for routines and plans regarding fire safety. Furthermore, in the studied building, there was no communication of such plans between tenants (Nilsson & van Hees, 2012; Paper I).

Even though a building is multifunctional there is generally a main purpose or main purposes of a building, e.g. providing transport, municipality functions or production. Of course a multifunctional building will include additional sub-purposes, otherwise it would not be a multifunctional building. The interviewees, in the studied building, considered the core function of the building to be the most important function to protect after life safety (Paper I). Many such core functions depend on support systems such as electricity, water, telecommunications etc. Since these support systems seem to be essential to the core function, there are indications that there is a need for good fire protection for these support systems. Most often the support systems were associated with electrical appliances rooms, server rooms, control rooms etc. These sensitive areas are generally prone to fire damage even by a small fire that would not endanger life safety. Hence, the evaluation and protection of such sensitive areas is therefore generally not considered during normal fire safety design according to building codes. Even if the magnitude of the fire is small it can cause great damage if it occurs in a critical location. Due to the need for continuity of operations/functions, the location of the fire becomes more important than for buildings not hosting important functions.

The complex building design of multifunctional buildings, as discussed in chapter 1, often requires a variety of different fire safety systems to achieve an acceptable safety level (Paper I). When such systems are integrated with each other there is a risk of common-cause failure (CCF), i.e. a single fault disabling several protection systems

(Lundin, 2005). In addition to the, often, complex design of fire safety systems in multifunctional buildings the interviews indicated that one issue with multitenant buildings is the global management of fire safety and the maintenance and limitations of fire protection systems. In the studied building, the responsibility for the maintenance of fire protection systems was not clarified resulting in maintenance not being conducted for some protection systems (Paper I). Furthermore, not knowing the limitation of fire protection systems would most likely increase the probability of the occupancy hazard exceeding the limits of the system, e.g. storage height exceeding the design value in a sprinklered area. During the field visits it was also seen that there are often unprotected areas next to protected areas (e.g. sprinklered areas next to unsprinklered areas). This presents the challenge of the protection system not being able to reach the seat of the fire. Another example of this would be a sprinklered subway station where the sprinkler system will not be able to reach a fire inside a train car, hence the effect of the protection system is fairly unknown.

Multifunctional buildings share some of the problem areas with other types of buildings. For example the need for support systems could be compared of that with the production industry or IT industry where the output is highly dependent upon support systems as electricity, steam, cooling, computers etc. Hence input from how these industries work with business continuity and business impact provide useful information.

2.2 Antagonism

The large number of stakeholders also has a bearing on the exposure to antagonistic attacks. If one tenant experiences a higher exposure, than other tenants, to antagonistic attacks this will create a higher exposure to otherwise “unexposed” tenants. Furthermore a multifunctional building often contains societal important functions and hosts a large number of people. An attack on such a building could cause significant economic and emotional damages, increasing the probability of an attack (Brown & Lowe, 2003).

In addition to the increased probability of CCF as a result of multifunctionality there is also an increased probability for failure of fire protection systems, both active and passive, if an antagonistic attack was to occur (Paper I). A large initiating event, such as an explosion, may damage fire walls, active fire protection etc. For example in the bombing of the World Trade Center in New York, USA 1993, the explosion damaged firewalls and doors (Isner & Klem, 1993). But also loss of both normal and emergency power resulted in a CCF affecting sprinkler system and emergency lighting (Isner & Klem, 1993) as well as the smoke management system (Quenemoen et al,

1996). This indicates the importance of support systems as well as protection systems. There are several other examples where the initiating event has impaired protection systems, see Paper I. However, the loss of protection systems may not always be due to the severity of the initiating event. The loss may be as a part of an antagonistic attack where fire protection systems are bypassed or attacked (Thompson & Bank, 2007; Richards, 2008). The situation where a scenario escalates and amplifies the scale of the accident is sometimes referred to as domino effect (Gómez-Mares et al, 2008). This is pointed out in Paper IV, e.g. a fire following an explosion, where the protection system has been damaged needs to be taken into account when considering antagonistic events.

When designing buildings to obtain code compliance, focus is on life safety considering accidental fire events (Klason et al, 2011). Antagonistic events are generally not considered (Gilbert et al, 2003) and traditional prescriptive design does not take e.g. arson into account (Richards, 2008; Klason et al, 2011). The fire can be much more severe when considering antagonistic events. If for example flammable liquids are used the fire growth rate can be much higher which could endanger life safety as well as other protection objectives (Paper I). Furthermore it may also render fire protection systems ineffective (Paper IV). Buildings are generally not designed for arson fires; the consequences of the Gothenburg fire in Sweden (Eksborg et al, 2001) as well as the Daegu subway fire in Korea (National Emergency Management Agency, 2004) illustrate this. Certainly the antagonistic events can be much more severe and unexpected as the plane crash into the World Trade Center in New York, USA 2001 (Gutierrez et al, 2005). The matter of deciding what safety level that should be achieved is difficult and the question “How safe is safe enough?” certainly becomes relevant. Also as seen by the examples of antagonistic attacks they can take many different forms depending on what the aggressor wants to achieve. If the aggressor wants to interrupt the train transportation in one part of the country the attack against that building will probably be very different from if the aggressor wants to create a lot of casualties in the same building. Hence it is difficult to determine how an antagonistic attack will develop and the location of the attack is also something that will vary depending on the purpose of the attack. The severity and location of an attack is also linked to security features, which is the main protection against antagonistic attacks (Brown & Lowe, 2003; Paper I). For example if there is no possibility to drive vehicles into the building the amount of explosives that can be brought into the building may be limited.

In a broader perspective the problem areas associated with antagonistic attacks may in general be applicable if evaluation of antagonistic attacks is to be done for a building, i.e. not just multifunctional buildings.

3 Method for fire safety evaluation of multifunctional buildings

As described in the previous sections there are a large variety of problem areas that a method for evaluating fire safety in multifunctional buildings needs to cover. On an over-all level these problem areas can be characterized into problems associated with multifunctionality and antagonism as done in chapter 2. With respect to multifunctionality the over-all concluded problems are:

- an incident may have a large impact on society,
- there are a large variety of and other protection objectives than life safety (that is generally the one considered),
- a large number of stakeholders and
- multifunctional buildings are more exposed to antagonistic attacks.

Further with respect to antagonism the over-all concluded problems are:

- the incidents are generally more severe and not explicitly considered by building code,
- the public has an aversion towards catastrophic events demanding a higher safety level,
- fire protection might become impaired and
- security is of great importance.

All of the above points contribute to an overall complexity and vulnerability presenting the potential for unacceptable consequences if an incident was to occur in a multifunctional building. A method for evaluating fire safety in multifunctional buildings needs to address these issues from a holistic view and the main basis for the evaluation method is the problem areas identified in chapter 2.

In figure 3 and the paragraphs below the overall evaluation method is briefly described, a full and more detailed description of the method can be found in Paper I. Below, it is also specifically described how the evaluation method addresses the problem areas that were elaborated on in chapter 2.

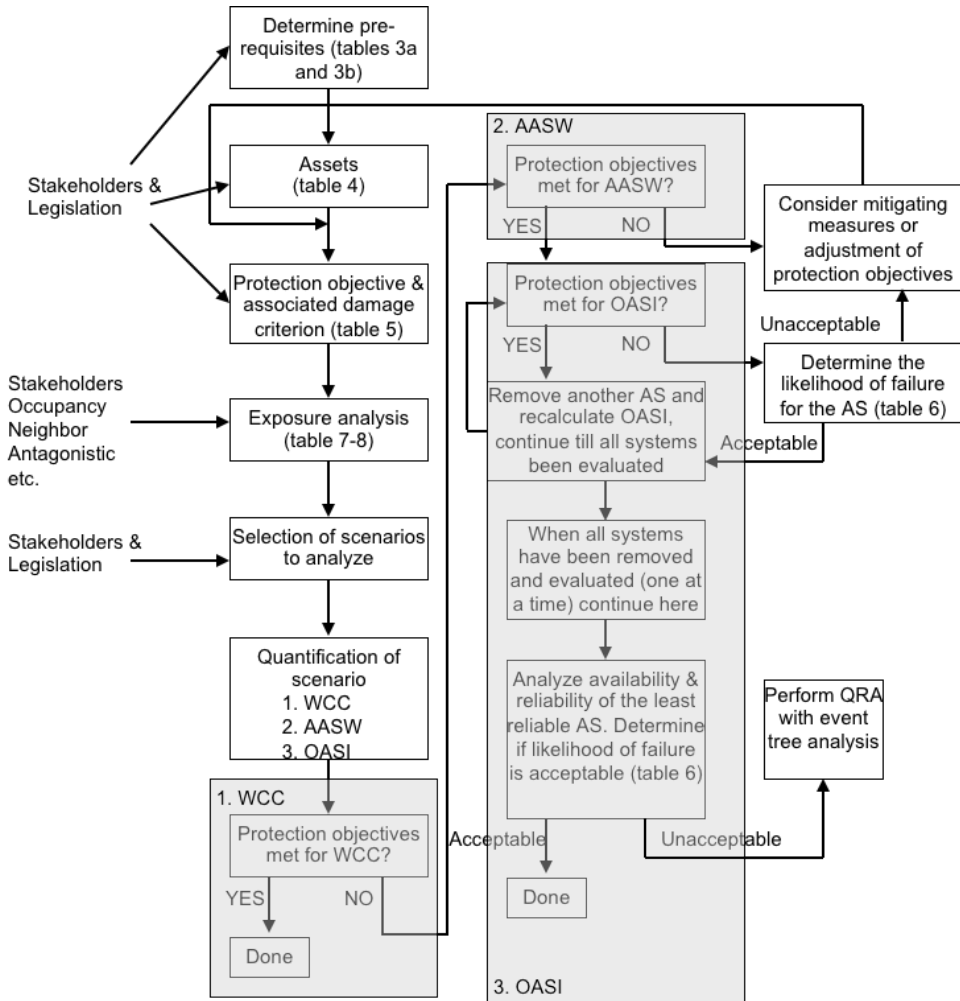


Figure 3. Overview of method for development and evaluation of fire scenarios in multifunctional buildings(Paper I) (table numbers refer to Paper I)

The evaluation method starts with **determination of prerequisites**, basically determining the core functions and the relevant stakeholders of the building. This is

in order to determine where the focus of the evaluation should be. Further building and occupant characteristics are determined and all this information forms the basis for the evaluation (Paper I). In the light of the core functions of the building the **assets**, i.e. what need to be protected, should be determined, this is divided into *life safety, property, environmental and functions*. Once the assets in need of protection and evaluation have been determined, **protection objectives and associated damage criterion** need to be determined for the assets. For example the protection objective for a function could be that the function should not be interrupted for more than 8 h and the associated damage criterion could be that the inner core temperature of the data cable should not exceed 180°C. The damage criterion describes at what point of exposure the protection objective is exceeded.

The following step is the **exposure analysis**; here it is determined what exposures/hazards/threats that has the potential to cause failure to meet the required protection objectives. In the evaluation method the exposures have been divided into two categories: *accidental/natural exposures* and *antagonistic exposures*.

Based on the determined **assets**, the **protection objectives** and the **exposure analysis**, an evaluation of the fire safety is to be performed. In the evaluation method it has been chosen to do the evaluation as a scenario analysis. This means that uncertainties are treated by choosing conservative values for uncertain parameters. Hence, the analyzed scenarios are what is referred to as “worst-credible case” scenarios and there is no explicit probability assigned to each event. This way of treating uncertainties is equivalent to what Paté-Cornell (1996) refers to as Level 2. This way of treating uncertainties has the benefit that it is transparent what scenarios that have been considered and if these scenarios can be handled or not. It is also straightforward and easy to use which is desirable when conducting an analysis in the field (Paper I). Generally a large number of fire related scenarios challenging the protection objectives will be identified, hence a **selection of scenarios to be analyzed** has to be made. The selection is made by clustering similar or worse scenarios together, and thereby choosing representative scenarios, i.e. if the protection objectives are met in the chosen scenarios the objectives are also met in the other scenarios. The final steps of the analysis incorporates **quantification of the chosen scenarios** by developing **Worst Credible Consequence (WCC)**, **All Active Systems Working (AASW)** and **One Active System Impaired (OASI)**. The reason for developing three different “versions” of the same scenario with combinations and failures of different active fire protection systems is to determine the vulnerability of the fire safety strategy and its dependence upon active fire protection systems. Finally the success of the scenarios is **evaluated towards the determined protection objectives**.

Since the risk is not quantified when using scenario analysis there is no way to determine cost effective mitigating measures or to prioritize what scenarios to address

(Paper I). Due to these reasons there is a possibility that the first scenario analyses, i.e. the level 2 analyses, do not give satisfactory results, i.e. it cannot be concluded that the situation is acceptable (Paper I). This means that the analysis is now outside the area of validity for the evaluation method presented in figure 3 and the analysis has to be taken to a higher level. In such a case the evaluation method will recommend that a **Quantitative Risk Assessment (QRA)** be performed (Paper I). QRA corresponds to what Paté-Cornell (1996) classifies as Level 4 regarding treatment of uncertainties. The reasoning behind this approach is that it is ineffective, unpractical and time consuming to perform a full QRA if it is not warranted and sufficient information can be obtained using simpler methods (Paper I). A full and detailed description of the evaluation method is provided in Paper I.

The evaluation method was developed in order to support accident prevention in multifunctional buildings. It is mainly supposed to be used for evaluation of existing buildings (Paper I). The end user of the evaluation method can be the municipality, government or other authorities when the considered multifunctional building has societal importance. For example the municipality is required to conduct a risk and vulnerability analysis as part of their planning processes for emergency management (Eriksson, 2008). The method for selection and evaluation of fire related scenarios could be a part of such an analysis when the considered building creates a vulnerability to the municipality. Furthermore the end-user can also be the stakeholders (business owners, municipality, etc.) of the considered building. They may want to analyze their exposures, present safety level, the need for protection in order to ascertain an acceptable safety level etc.

The strength of the evaluation method is that it presents a systematic way of evaluating the fire safety in multifunctional buildings considering aspects of fire safety that is normally not considered when designing buildings according to the building code. Such a method has not previously been presented for such a specific application. In addition to normally considered aspects such as life safety and third party damage, it incorporates aspects of antagonistic attacks, multifunctionality and continuity of operations for essential functions. It should be noted that the evaluation method is using the performance-based design (PBD) approach and is in essence a PBD. Therefore the content of the evaluation method can be fitted into framework presented in guidelines such as the SFPE Engineering Guide to Performance-Based Fire Protection (SFPE, 2007). However the evaluation method presented here is more specific in the sense that it specifically addresses the aspects of multifunctionality. However the evaluation method is also broader since it considers antagonistic exposures. This focus has been chosen in order to increase the likelihood that all relevant aspects are considered during an evaluation and to provide support for the engineer.

The evaluation procedure needs to be performance-based in order to be able state protection objectives to be achieved (Frantzich, 1998) whereas prescriptive rules only consider protection objectives accounted for during the code development process. Often prescriptive rules are also based upon previous accidents and the experience from antagonistic attacks is often limited. As stated previously, scenario analysis has been chosen as the method in order to tackle some of these issues. However the chosen scenarios are based upon judgment by the engineer raising the question “How safe is safe enough?”. As Paté-Cornell points out, it is unknown how conservative the chosen values actually are, which presents shortcomings in the risk management phase (Paper I; Paté-Cornell, 1996).

The problems presented by the large number of stakeholders in the evaluation process is addressed in the evaluation method by first determining the core functions that the building is providing. Next, the stakeholders associated with the core functions are included, hence limiting the issue with involvement of a too large number of persons in the evaluation process. The focus on core functions also limits the problem regarding different views on what level of fire safety that should be achieved. By focusing on the core functions the required level by the stakeholders (associated with the core functions) determines the acceptable safety level. Neighbors, which may aim for a lower safety level than what is acceptable for protection of core functions, are dealt with, in the evaluation method, by the possibility of handling their presence as an exposure and threat to the determined protection objectives. Even though all these aspects minimize the problem with agreeing on an acceptable safety level there is still an issue for the stakeholders involved of determining the severity of the scenario to be analyzed. Finally, the effects of emergency management plans can be included into the process when quantifying the scenario, for further discussion see Paper I.

The core functions of a building, e.g. transportation, municipality functions etc. are highly dependent upon support systems often located in sensitive areas (e.g. electricity, telecommunications etc) as determined in chapter 2. Evaluation of these areas is often omitted during normal design due to the fact that they might not be relevant to life safety. Not to say that they are always omitted, there may be situations where these areas are essential to fire protection systems, e.g. evacuation alarm and emergency lighting and then they may be included. However they are often omitted, but also essential to the functions provided and therefore in need of evaluation in a multifunctional building. The evaluation method has its starting point in the relevant assets and to capture support system an asset evaluation form has been developed that helps to identify support systems (table 5 in Paper I). By focusing on the assets that need protection, and what is needed to provide the function the asset is delivering, relevant fire locations can be identified, whether such a fire will be affecting a support system or the asset directly. Further, potentially relevant fire

locations, both from accidental fires and antagonistic attacks will be captured by this approach since it does not only consider the exposure, rather it is considering the vulnerability of the system. This can somewhat be compared to What-if analysis or Hazop. If the fire or incident location should be evaluated or not is then dependent upon the determined exposure (likelihood, severity etc) and the protection objective and potential of the exposure to exceed the damage criterion. Since these sensitive areas are of great importance to the functions provided in multifunctional buildings there is a large need to be able to thoroughly analyze the impact a fire in such an area may have and suitable protection options to mitigate the impact from such a fire.

The increased probability of failure of fire protection systems is addressed in the evaluation method in different ways depending upon if the system is an active or passive system but also depending on the reason of failure. The reason for failure could be due to the initiating event or due to availability/reliability issues. The reliability and availability issues for active fire protection systems are handled by means of developing three different scenarios, WCC, AASW and OASI. These scenarios test the need for the active protection systems and the sensitivity of the fire protection solution, see Paper I for further discussion. In addition, for every scenario the evaluation method requires that it should be determined if the initiating event causes impairment of any protection system (both active and passive). For example, an explosion damaging a firewall or someone bypassing active protection systems as part of an antagonistic attack. Finally when evaluating the assets the evaluation method directs the user to determine the adequacy of passive fire protection as well as active fire protection systems. For example verifying that there are no holes in fire separating construction or determining whether the sprinkler system is designed for the hazard in the room.

As discussed it is difficult to anticipate how an antagonistic attack will be initiated or how it will develop. To provide guidance the evaluation method points out a couple of principles. First, only locations of attacks that threatens the protection objectives should be considered, secondly the security for that location is of importance. An example of a security issue may be unguarded areas with easy access where the aggressor can work undisturbed. The severity of an attack may also be connected to security, e.g. if a car cannot enter the area the amount of explosives may be limited in comparison to if a car could enter. Brown and Lowe (2003) suggest an approach where the existence of a threat, the capability of the aggressor, history of attacks and intentions of the aggressor is evaluated. This approach has been adapted within the evaluation method with the additions suggested in Paper IV, i.e. the aspects of security and examples of threats from Thompson and Bank (2007) and Brown and Lowe (2003).

4 Identified research areas supporting the evaluation method

In order to apply the evaluation method (presented in chapter 3) a variety of information is needed to be able to analyze the fire safety level within the building to be analyzed. The information can be related to input data, protection objectives, damage criteria, the effect of different fire protection systems, etc. During the interviews, the development of the evaluation method and the field visits, areas where lacks of such information exist were identified. Lack of knowledge and information creates uncertainties and in order facilitate the use of the evaluation method it is beneficial to decrease these uncertainties. Therefore, identified gaps of knowledge and their relevance to the evaluation method have been documented in this chapter and categorized into five different research areas (section 4.1 – 4.5). The categorization is not a clear and easy to do and there is some overlap between the categorized research areas. The categorization could maybe have been done in another way but the categorization below represents the approach angle of this thesis. First a short description of the background and the research area is provided. Then, within each research area a number of specific research questions have been formulated. The documentation of the research areas in this chapter answers research question 3 formulated in section 1.4. The common theme for the formulated questions is that the answers are of importance to support application of the evaluation method. A further discussion on some of the research areas can be found in Nilsson and van Hees (2012).

4.1 Safety levels

The resulting fire safety level in a building is highly dependent upon the severity of the chosen design fire scenario (Paper III). Or, when evaluating an existing building highly dependent upon the fire scenario against which the building is tested. The issue

with deciding the severity of a scenario becomes a reality in the evaluation method (presented in chapter 3) when quantification of the scenario is to be done. It includes determining e.g. heat release rate, production rates of gases, and fire growth rates of the fire. The use of scenario analysis, which corresponds to level 2 according to Paté-Cornell (1996), has its benefits as discussed in chapter 3. However, as Paté-Cornell points out, there is the matter of determining how conservative the chosen scenario is, which actually determines the achieved safety level within the building. Furthermore, the scenario analysis presents shortcomings not only when quantifying the severity of a scenario, but also when trying to quantify the effect of a more severe event such as antagonistic attacks. Since multifunctional buildings are more prone to antagonistic attacks (Brown & Lowe, 2003) it would be beneficial to be able to quantify how this exposure affects the resulting safety level. Especially since there is evidence for a required higher safety level in these types of buildings, see discussion in chapter 1 and in Slovic (1987).

The acceptable safety level for societal important functions and life safety is generally a political decision. To some extent the safety level is specified for life safety in building codes, see for example Boverket (2011b), BSI (2001) and NFPA (2012a). However the building codes generally do not consider antagonistic attacks and for societal important functions and for other functions as well there are not as defined criterions and safety levels. As discussed in chapter 3, the evaluation of an aggressor and security related features provide some guidance when developing an antagonistic scenario, however a reasonable severity of a scenario is still very hard to determine. In reality, the safety level in a building is therefore up to the judgment by the engineer, resulting in a non-quantified safety level possibly being undesired by the stakeholders (too low or high). A more quantified scenario would aid the stakeholders in making qualified and informed decisions regarding safety levels and would probably make it easier for them to agree upon an acceptable safety level.

According to Babrauskas and Peacock (1992) the most important variable in fire hazard is the heat release rate. Therefore, in the early stage of the fire, the fire growth rate is important and in the later stage of the fire the maximum heat release rate is important. Growth rates and maximum heat release rates are specified in some performance-based building codes, for example Department of Building and Housing (2012) and Boverket (2011a). However these growth rates and maximum heat release rates are based upon experience and it is not determined what percentile-fire they represent and they are not quantified. Since damage levels most often become critical during the growth phase of the fire, i.e. early in the fire rather than when the fire reaches its maximum heat release rate, the growth rate is decisive. When considering antagonistic events there is a large variety in possible events. However as pointed out arson fires are common (Richards, 2008; Hall, 2007; Simonson, 2007) as opposed to other antagonistic attacks such as bombs. Due to the importance of the growth rate

as well as the fact that arson is a common antagonistic event, it would be beneficial to be able to determine percentile values of the growth rate as well as quantify the effect of arson.

Specific research questions

With the background described above the following research questions addressing safety levels (SL) were formulated:

- SL 1. How conservative is the chosen fire scenario?
- SL 2. How does antagonistic scenarios affect the safety level?
- SL 3. What percentile does the chosen fire growth rate represent and how is it affected by arson?

Research question SL 1 and SL 2 are fairly broad and are not specifically addressed in the thesis. Research question SL 3 has been chosen for further investigation and is addressed in section 5.1, the answer to research question SL 3 provides some input to research questions SL 1 and SL 2.

4.2 Sensitive areas

Support systems and associated sensitive areas have been deemed of critical importance in multifunctional buildings (Paper I), see also section 2.1, 2.2 and chapter 3. Due to these areas and systems criticality it is important to be able to determine when the systems are damaged and how such areas can be protected.

To determine when such systems are damaged, when applying the evaluation method, it is necessary to be able to determine appropriate damage criteria, that is at what levels of fire exposure does critical components lose their functional performance. The sustained damage before a protection system is activated and has suppressed a fire is a function of the protection system (activation time, time to suppression, if extinguishment is achieved or not etc.) and the components resistance to fire exposure. There are several known protection options and design guidelines for protection of such sensitive areas, see e.g. FM Global (2004, 2006, 2010, 2012a, 2012b, 2012c,) and NFPA (2012b, 2012c, 2013). However these guidelines do not say anything about the sustained damage if a fire was to occur and the system is operating as designed. This raises the question at what level of fire exposure (smoke, heat etc) critical components are damaged, which is essential to determine if the protection objectives are met or not. Further the referenced protection options are for active fire protection systems, i.e. fire protection systems that activate when a fire is indicated,

meaning that the fire has already done some damage making damage criteria even more pertinent.

Hypoxic air venting, where the oxygen concentration within a protected room is reduced (Chiti, 2009), has been put forward as a suitable protection option for such sensitive areas, see e.g. Jensen and Nygaard (2013) and Jensen et al (2006). Potentially hypoxic air venting provides a suitable protection option since it provides an alternative that may prevent a fire from occurring in the first place. This would provide the benefit of no fire damage at all (also removing the issue with determining damage criteria), as opposed to regular extinguishing systems that need to activate as a response to fire. Hypoxic air systems have already been installed in buildings of societal importance, e.g. in one of the Swedish nuclear power plants (Fredholm, 2012) and also in other industrial applications. However, the achieved fire safety level is dependent upon the provided oxygen concentration. Lower oxygen concentration provides a higher fire safety level but also poses a higher health risk (Paper II). This is because there is a wish to be able to have personnel present in the protected room, e.g. for maintenance, without them wearing personal protective equipment. Therefore the chosen oxygen concentration is a compromise, where the ability to be present in the room is paid with a lower fire safety level and vice versa. Generally an oxygen concentration of 15 vol% is used, but there are different views on whether this oxygen concentration provides a sufficient safety level or not. Chiti (2009) e.g. states, *“The peculiarity of Hypoxic Air systems is that, unlike other firefighting systems, they prevent from a fire”*. Further Jensen et al (2006) states *“At 15.2% O₂ by volume, Class A fires are extinguished and at 14.3% O₂ by volume, Class B fires are extinguished”*. However there are a lot of references showing that fire can still occur at these oxygen concentrations, see e.g. Xin and Khan (2007), Marquis et al (2012) and Mikkola (1993). The completely different views on the achieved protection level as well as the system being fairly new and not well analyzed creates a need for further investigation.

Specific research questions

With the background described above the following research questions addressing sensitive areas (SA) were formulated:

- SA 1. What are the advantages and challenges with hypoxic air venting as fire protection?
- SA 2. At what levels of fire exposure are critical components damaged to the extent that they lose their functional performance?
- SA 3. What is the sustained damage to different equipment in sensitive areas with different types of protection systems?

Research question SA 1 was chosen for further investigation and is addressed in section 5.2. Research questions SA 2 and SA 3 are not addressed in this thesis.

4.3 Fire Protection

During the field visits, situations were identified where a sprinkler system might not be able to reach the seat of the fire (Nilsson & van Hees, 2012). Basically two typical situations were identified, unprotected areas next to a protected area and sprinkler protection in transportation centers where a fire in e.g. a train or bus cannot be attacked by the sprinkler system. If a fire starts in the unprotected area, the fire has a potential to spread to the protected area and there activate the sprinkler system. This creates the possibility of overtaxing the water supply and hence a growing fire spread might occur. The same situation is possible if a fire starts in e.g. a train car and the sprinkler system just sprays water on the top of the car. Furthermore, unsealed penetrations and leaky fire compartmentation were identified during the interviews and field visits (Nilsson & van Hees, 2012). Leaky fire compartmentation might result in extended smoke spread resulting in large damage, e.g. on electronics and control systems. The effect of the installed fire protection is essential when quantifying the scenario when applying the evaluation method and the above identifies difficulties in making such quantifications.

Specific research questions

With the background described above the following research questions addressing fire protection (FP) were formulated:

- FP 1. To what extent do smoke and fire spread between protected and unprotected (e.g. sprinkler) rooms?
- FP 2. To what extent is the fire development limited when a sprinkler system cannot reach the seat of the fire?
- FP 3. How well does regular fire compartmentation resist smoke spread?

The research questions are not addressed in this thesis.

4.4 Ignition scenarios

A common antagonistic threat is an arson fire as discussed in chapter 1. The fire development of a pool fire is relatively well understood, see e.g. Karlsson and Quintiere (2000), furthermore there is a lot of data on fire development of single burning items, see e.g. Babrauskas (2008). However the effect of igniting regular combustibles with a larger ignition source such as a reasonably large amount of flammable liquids is fairly uninvestigated. The effect of a larger ignition source on e.g. growth rates and compartment fire development has not been thoroughly studied. Furthermore there is a potential that a large fire is too challenging for the installed protection system (Richards, 2008). To be able to quantify a fire scenario incorporating the use of flammable liquids when applying the evaluation method more information on the effect of the ignition scenario is needed.

Specific research questions

With the background described above the following research questions addressing ignition scenarios (IS) were formulated:

- IS 1. How is the fire development affected by the size/type of the ignition source?
- IS 2. How is the fire spread affected by a large ignition source when active systems been used to motivate removal/reduction of passive systems?

The research questions are not specifically addressed in this thesis, however some discussion regarding IS 1 is found in sections 5.1 and 6.1.1.

4.5 Domino effects

The potential for domino effects, e.g. a fire following an explosion that has damaged fire walls or other fire protection systems, has been pointed out early in the study of multifunctional buildings and antagonistic attack, see Paper I and IV and Nilsson and van Hees (2012). So far it has been recognized that the potential for such effects is probably larger when considering antagonistic attacks and multifunctional buildings. However this has not been investigated in great depth. Hence there is a need to identify more possible domino effects both with respect to antagonism and multifunctionality since such information is needed when quantifying a scenario when applying the evaluation method. Furthermore the potential for domino effects can

easily be included in the evaluation method but the method does not provide specific guidance on how to calculate or address this issue. As pointed out in Paper I there is a need to investigate this further and to incorporate evaluation procedures of domino effects into the evaluation method

Specific research questions

With the background described above the following research questions addressing domino effects (DE) were formulated:

- DE 1. What are possible domino effects in multifunctional buildings?
- DE 2. What are possible domino effects as a result of antagonistic attacks?
- DE 3. How can the evaluation method be complemented with further guidance on how to handle domino effects?

The research questions are not addressed in the thesis.

5 Research supporting the evaluation method

In chapter 4 research areas and specific research questions were formulated. Obtaining answers to the research questions in chapter 4 will support application of the evaluation method presented in chapter 3. However, it is not the intention of this thesis to address and answer all of the identified research questions in chapter 4. The goal was to further investigate a few of them. It was chosen to conduct further research on two topics and include that research into this thesis. The first topic is quantification of fire growth rates addressing research question SL 3 presented in section 4.1, and the results are presented in section 5.1. The second topic is hypoxic air venting as fire protection addressing research question SA 1 presented in section 4.2, and the results are presented in section 5.2. In chapter 6 the need for further research on these topics are also presented.

The research on quantifying fire growth rates will aid application of the evaluation method by providing input data supporting the determination of the chosen fire scenario and largely affecting the safety level. The research on hypoxic air venting systems will aid application of the evaluation method by evaluating a risk mitigating measure and help quantifying the effect of hypoxic air venting systems as fire protection.

5.1 Quantifying fire growth rates

In order to answer research question SL 3, “What percentile does the chosen fire growth rate represent and how is it affected by arson?”, a method for quantifying fire growth rate was developed. The quantification method uses statistical data regarding fire causes as well as empirical data on fire growth rates for single burning items (Paper III). Further the quantification method was applied to Swedish commercial buildings. Values obtained using the quantification method, presented in this chapter, can then be used as input to the evaluation method presented in chapter 3 when deciding what fire scenario to analyze.

Quantifying the fire growth rate in terms of a probability distribution presents the benefit of providing means to design a building towards a well-defined target, e.g. the building should be designed to be able to handle 98% of all possible fires (Paper III). Further a faster fire growth rate may cause the available safe egress time (ASET) to become shorter than the required safe egress time (RSET) (Proulx, 2008) and it may also cause larger property damage or ineffectiveness of protection systems (Paper III). Quantification of fire growth rates is therefore desirable so that qualified decisions can be made regarding safety levels. Furthermore, a quantification method that can describe the effect of arson is also desirable since the effect may be necessary to include if the particular building has a high exposure to arson.

The developed quantification method is fully presented in Paper III and has the ability to quantify the fire growth rate as well as the effect of arson. The quantification method takes its starting point in the first object ignited and what the fire growth rate is for that single burning item. The basic principle of the quantification method is:

“In certain building types there are a number of recorded fires with recorded first objects ignited. By determining the fire growth rates for all recorded first objects ignited and grouping the fires where the fire growth rate falls in a certain interval a histogram is obtained. The histogram essentially is a discrete distribution to which a continuous distribution can be fitted.”

“Each object ignited has been assigned a fire growth rate and each fire has a first object ignited and therefore the fire growth rates have a frequency creating the distribution for the building type.” (Paper III).

The method, in essence, works by using statistics to determine the probability that the fire starts in a specific first object, called first object ignited, in a certain building category. All these objects are assigned a specific fire growth rate based on experimental data from e.g. single burning item tests. These two pieces of information is combined to create a histogram over the fire growth rate, i.e. a discrete probability distribution for the fire growth rate in the building category. To the discrete probability distribution a continuous distribution is fitted. The fire statistics were obtained from the Swedish Civil Contingencies Agency’s (MSB:s) IDA database (MSB, 2012) and fire growth rates were obtained from experimental data, see e.g. Babrauskas (2008) and Särdaqvist (1993).

The quantification method was applied to Swedish commercial buildings. The application shows that the quantification method can describe the effects of arson. Furthermore it shows that there is a considerably higher fire growth rate for Swedish commercial building if arson fires are included. Figure 4 shows the distributions for Swedish commercial buildings when arson is excluded respectively included. As example it can be mentioned that a fast fire growth rate of 0.047 kW/s^2 , as is the

demanded fire growth rate in commercial buildings according to the Swedish (Boverket, 2011a) and New Zealand (Department of Building and Housing, 2012) building codes corresponds to 97% of the fires if arson is not included (Paper III). However it only corresponds to 91% of all fires if arson is included (Paper III), also refer to table 2.

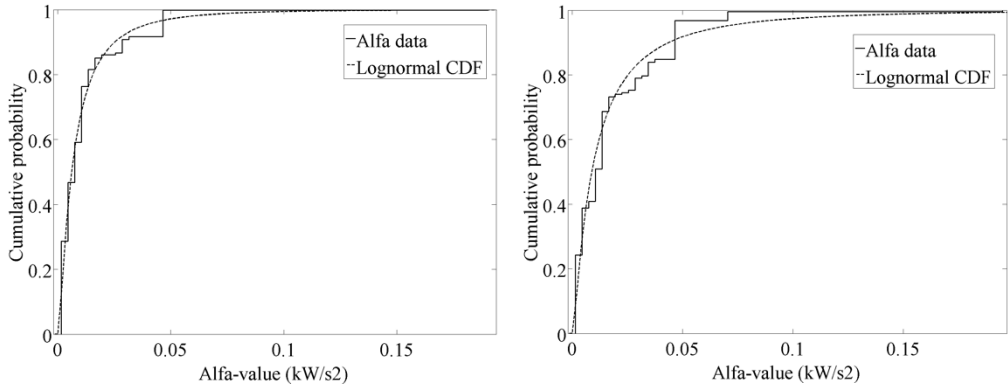


Figure 4. To the left: CDF for the estimated lognormal distribution of fire growth rate when arson is excluded. To the right: CDF for the estimated lognormal distribution of fire growth rate when arson is included. (Paper III)

Table 2. Parameters for lognormal distributions and percentile values (Paper III).

	μ_a (Std. Err.)	σ_a (Std. Err.)	$E(a)$ (kW/s ²)	α_{95} (kW/s ²)	$\alpha_{99.5}$ (kW/s ²)	Percentile for $\alpha = 0.047$ kW/s ²
Accidental fires (arson excl.)	-5.091 (0.0231)	1.100 (0.0163)	0.011	0.038	0.105	97%
All fires (arson incl.)	-4.727 (0.0240)	1.246 (0.0170)	0.019	0.069	0.219	91%

The main benefit with the developed quantification method is that it is able to quantify the fire growth rate for a building by arriving at a distribution for the fire growth rate. This is beneficial for fire safety engineers, business owners, authorities etc since the fire growth rate is decisive for the achieved safety level (Paper III). One strength of the quantification method is that it can differentiate between fire causes

such as arson and accidental fires, this was not possible in other found studies, see e.g. Holborn et al (2004), Angerd and Frantzich (2002) and Nystedt (2011). Another strength is that it in the application on commercial buildings produced log-normal distributions as well as fire growth rates that are supported by other literature (Holborn et al, 2004; Angerd & Frantzich, 2002; Nystedt, 2011).

In the application of the quantification method on Swedish commercial buildings, a deterministic fire growth rate was assigned to each object first ignited. Of course the fire growth rate of furniture will vary considerably (Paper III), e.g. between a metal chair and a sofa and for some categories there might not be sufficient data available. This creates uncertainties and it would be desirable to be able to describe these uncertainties with distributions. Another issue is whether the actual fire is really well described by an α - t^2 fire or not. However this has little effect on the safety level as long as the design fire covers the possible fires within the desirable percentile (Paper III). Also room effects are ignored since the obtained growth rates are for single burning items and the spread between secondary combustible items in the room is ignored as well. Hence, the method is only applicable to the very early stages of a fire. The actual effect on the deterministic fire growth rate that an accelerant has is difficult to assess and there are large uncertainties when assigning a fire growth rate to an arson fire involving flammable liquids, for a more detailed discussion refer to section 6.1.1. There are also uncertainties regarding the statistics associated with the form used for collecting data itself, the variety of persons filling it out etc. For a thorough discussion on uncertainties associated with the quantification method refer to Paper III.

The developed quantification method only defines the severity of the scenario with respect to the design fire growth rate. The heat release rate is the most important variable in fire hazard (Babrauskas & Peacock, 1992). Hence, the fire growth rate is very important in the early stage of the fire and affects the safety level considerably due to the fact that most of the damage criteria fails during the growth period of the fire. However, there are parameters such as production of smoke and gases (toxic and acidic) that are not explicitly considered when using this approach that will have an impact on the severity of the fire scenario as well as the sustained damage. However the production of such gases are generally reported as a yield, i.e. mass units of gas per mass unit of burnt fuel, hence dependent upon the heat release rate. Therefore the heat release rate is decisive. It should be mentioned that since the obtained fire growth rates are from free burning items the obtained growth rates are for well-ventilated single burning items. If the fire becomes under-ventilated the growth rate will change as well as the production rate of gases. In addition, affecting the resulting fire safety level is also uncertainties in e.g. the evacuation scenario when considering life safety, the damage criterion for electrical equipment and so on. The result of this is that the risk level still is unknown and in order to fully quantify the risk level such

uncertainties need to be handled with probabilities as well, e.g. exit choice or cable temperature when the cable loses its functional performance. There may be considerable uncertainties in such parameters as well, however as stated by Babrauskas and Peacock (1992) the heat release rate is a very important variable in fire hazard and it is therefore logical to address the HRR before addressing other parameters.

The quantification method presented in Paper III can be used to make qualified estimates of the percentile the chosen fire growth rate represents, in the early stage of a fire. Furthermore the quantification method is also able to describe the effect of an arson fire. These abilities answers research question SL 3. Furthermore, these quantifications provide one piece of information in a way towards quantifying the severity of a scenario, hence how conservative the scenario is as well as describing the effect of an antagonistic attack. This provides input to research questions SL 1 and SL 2. The obtained distributions of fire growth rates, from the application of the quantification method on commercial buildings, are most useful from a regulatory perspective as they represent an average of commercial buildings in Sweden. Hence the values may not be applicable to a specific building or buildings with other purposes. However the quantification method itself can be used for any building and the statistics regarding first object ignited and room type can be applied. For a certain building the fire growth rates can be estimated with better accuracy since it is known what is in the building or at least it can be determined. For multifunctional buildings it may be necessary to treat the building as many small buildings due to the many different occupancies within such a building. By treating the parts of the buildings as separate buildings (from a statistical point of view) there is an opportunity to make more accurate estimates. Obtaining separate distributions for e.g. office areas, train station, and shopping areas and then using these values for separate parts in the building will make the estimates more accurate. This is probably a helpful way when using the evaluation method presented in chapter 3.

5.2 Hypoxic air venting as fire protection

In order to answer research question SA 1, “What are the advantages and challenges with hypoxic air venting as fire protection?”, a literature review was conducted. In addition an evaluation of the test method used to determine the required oxygen concentrations according to hypoxic air venting standards was evaluated through testing. The full and detailed results can be found in Paper II. The information presented in this section and in Paper II provides input to how installation of such a system affects the fire safety level. This aids application of the evaluation method

presented in chapter 3 when a hypoxic air venting system is installed in the considered building. Further the use of hypoxic air venting systems has been proposed as a suitable protection objective for sensitive areas, commonly found to be critical in multifunctional buildings.

The goal with the literature review presented in Paper II was to present advantages and challenges with hypoxic air venting as fire protection, identify areas where further research is needed and to increase the knowledge about the system as protection in electrical appliances rooms. To provide such information the following questions from Paper II were analyzed:

- *How is the risk for fire affected by a reduction of the oxygen concentration to 15 vol% and how is the potential for ignition affected by a reduction in oxygen concentration?*
- *How is the fire development (heat release rate (HRR), soot production, flame speed) affected by a reduction in oxygen level?*
- *How does a reduced oxygen environment affect a smoldering fire?*
- *What are the advantages and disadvantages with different test methods and how well do they account for different configurations of fuel?*
- *How is the information on reliability and effectiveness of a hypoxic air venting system? Especially considering uneven oxygen levels, experiences from fires and the need for redundant systems.*
- *What are the health risks associated with a reduced oxygen environment?*
- *Are there any specific considerations (temperature, combustible material, functionality of equipment etc.) needed with respect to the occupancy, i.e. electrical appliance rooms?*

Since the oxygen concentration in a room is a balance between the achieved fire safety level and the posed health risks of being present in the protected room without personal protective equipment (see also section 4.2), lower than 15 vol% oxygen concentration is generally not used (Jensen et al, 2006; Paper II). 15 vol% oxygen concentration is generally what is recommended by the standards for hypoxic air venting for most areas (VdS, 2007; BSI, 2011). Therefore a special focus was put on the achieved protection level at 15 vol% oxygen concentration.

The main conclusion in Paper II is that 15 vol% oxygen concentration does not eliminate the possibility of a fire occurring and at that level the system cannot be seen as a substitute to traditional extinguishing systems. However, for important and sensitive areas in multifunctional buildings, hypoxic air venting as fire protection is clearly an option if the oxygen concentration is lowered to a level where fire cannot occur. This is to the inerting point of the fuel, for most fuels around 10 vol% oxygen

concentration, see e.g. Beyler (2008), even though there are fuels requiring even lower oxygen concentrations.

Reducing the oxygen concentration within a room affects the fire development when the oxygen concentration is not lowered to below the inerting point. This presents both advantages and challenges. The main advantages are a lowered probability of ignition due to the fact that an increase in ignition energy is needed (therefore removing smaller ignition sources) (Ackroyd et al, 2011; Blanc et al, 1947; Glor, 1981), and reduction in heat release rate should a fire occur (Marquis et al, 2012; Mikkola, 1993; Xin & Khan, 2007). Furthermore, there are indications of reduced flame spread/speed, see e.g. Fernandez-Pello et al (1981) and Rasbash and Langford (1968), and the system is always operational and does not need to be activated due to indication of fire.

Reducing the oxygen concentration for fire protection purposes also presents challenges or disadvantages. In Paper II it is concluded that the above-mentioned advantages are very material dependent and information is mainly available for generic materials. Furthermore, tests have shown that the configuration of fuel is of great importance (Rasbash & Langford, 1968; Xin & Khan, 2007) and the possibility of reradiation between fuel packages can increase the risk for fire spread (Paper II) as shown in the parallel panel test by Xin and Khan (2007). In addition, when the combustion becomes under-ventilated the production of e.g. soot, carbon monoxide, and other hydrocarbons increases (Tewarson et al, 1993; Tewarson, 1996) possibly increasing damages, especially in sensitive areas. With respect to functionality and reliability it is concluded in Paper II that there is a need for better guidance on how to ascertain even oxygen levels within the protected space. Furthermore, due to the limited number of installations the reliability is uncertain and also health aspects need to be managed. Finally in Paper II an evaluation through testing, of the proposed test method to obtain the required oxygen level for protection according to the hypoxic air venting standards (VdS, 2007; BSI, 2011) was conducted. This revealed severe deficiencies for the proposed test method resulting in oxygen concentrations on the unsafe side, indicating that the test method is inappropriate.

For sensitive areas in multifunctional buildings the protection option that hypoxic air-venting provides is a good alternative to traditional protection system if the oxygen concentration is lowered to below the inerting point of possible fuels. If a higher oxygen concentration is used there is a risk for larger damage due to increased production of e.g. soot and corrosive gases. This increased production, however, needs to be considered together with the fact that the mass loss rate decreases with a decrease in oxygen concentration (Paper II). Further as shown by Drysdale (2011) the flammability limits are widened with an increase in temperature. In electrical appliances rooms it is not uncommon with higher temperature as well as an energetic discharge locally increasing the temperature to very high levels. This needs to be

accounted for if the system is used in such an application. In addition, in multifunctional buildings, there are indications of poor maintenance of fire protection systems (Paper I). Fire compartmentations that are not tight could render the hypoxic air system ineffective if oxygen is leaking into the room. Furthermore, the maintenance issues enforce the need for reliable measurement to ascertain even oxygen levels within a room. In addition if taking antagonistic events into account arson is one of the more common events. Arson may be conducted by the use of an accelerant, i.e. flammable liquids, that burns even at very low oxygen concentrations and this needs to be accounted for if considering antagonistic exposures. Hence a lower oxygen concentration than the inerting point of the fuel normally present may be needed. Another issue with antagonistic exposures is the potential to impair active systems or to damage passive systems. Impairment of the device providing the reduced oxygen concentration, as part of an antagonistic event may be possible or if an explosion occurs the compartmentation to the protected area may be rendered ineffective resulting in leakage of oxygen into the protected area.

The literature review has shown the advantages and challenges with using hypoxic air venting as fire protection. This information is beneficial for potential users of such a system in order to be able to understand benefits and limitations and how it can be used, hence providing the opportunity to make informed decisions. In addition, gaps in knowledge and further research needs have been identified which are beneficial for the scientific community in order to further develop the hypoxic air venting method which in turn benefits the end-user.

6 The need for further research

In chapter 4 research areas and questions were formulated. The answers to these questions would aid the application of the evaluation method presented in chapter 3. Two of the research questions in chapter 4 were addressed in chapter 5, these were research questions SL 3 regarding quantification of fire growth rates and SA 1 regarding hypoxic air venting as fire protection. During the research regarding quantification of fire growth rates and the use of hypoxic air venting as fire protection additional research needs for these areas were identified. In this chapter, suggestions for further research and next possible steps are given, for the questions and areas identified in chapter 4 as well as for areas identified during the research presented in chapter 5

6.1 Safety levels

In section 4.1 three research questions were formulated, SL 1, SL 2 and SL 3.

- SL 1. How conservative is the chosen fire scenario?
- SL 2. How does antagonistic scenarios affect the safety level?
- SL 3. What percentile does the chosen fire growth rate represent and how is it affected by arson?

In general they address how to determine the severity of the analyzed scenario and how antagonistic attacks would affect the scenario and the resulting safety level.

In order to provide better and more certain information regarding research question SL 3 there has been identified a need for: further testing (section 6.1.1) and reducing uncertainties (section 6.1.2). With respect to research question SL 1 a need to quantify the maximum heat release rate of the fire scenario has been identified (section 6.1.3).

In general to provide more information regarding research question SL 2 there is a need to further investigate and quantify other antagonistic events in the same manner as was done for fire growth rates. Hence an inventory of likely antagonistic events is suggested together with providing additional guidelines on how to determine the severity of such scenarios.

6.1.1 The need for testing

The effect of including arson fires have been shown in Paper III and it was shown that there is a considerably higher fire growth rate if arson is included. The quantification method addresses the arson fire by assigning different α -values to different starting objects where one of the starting objects is a flammable liquid. Once the flammable liquid used has been burnt off it has ignited secondary items. For example pouring flammable liquid onto a sofa and igniting it burns off the flammable liquid and then the sofa continues to burn. The resulting fire growth rate in such a scenario is quite unknown, i.e. once the flammable liquid has been burnt off, what is the growth rate of the sofa? During the development of the quantification method information was sought regarding this matter, only a few publications were found. Janssens et al (2012) used 59-118 ml of flammable liquid to ignite furniture showing no change in fire growth rate compared to when using a gas burner. There has also been some testing conducted on carpets and other flooring material, see e.g. Putorti et al (2001) and Ma et al (2004). However these do not really describe the issue with igniting objects with a more complex geometry. Richards (2008) used a Molotov cocktail to try to ignite a wooden stair resulting in no significant burning, however the media was not porous, such as a sofa would be. Krüger et al (2013) used approximately 1 l of flammable liquids in a room, showing a fire growth rate of approximately 0,07 kW/s² and when no flammable liquids were used showing a growth rate of approximately 0,01 kW/s². This shows that there is a potential for far much higher fire growth rates when looking at fires ignited with flammable liquids. Hence there is a need for research addressing how the fire growth rate, of the combustible ignited with flammable liquid, is affected by e.g. the amount and type of the liquid and the secondary item to be ignited. It is suggested to test single burning items with ignition by different amounts and types of flammable liquids (especially amounts common during arson fires) also varying ignition locations in furniture calorimeter apparatus to investigate the effect of the size and type of the ignition source. It would also be beneficial to investigate how the effect on fire growth rate can be quantified, e.g. by a heat transfer model, heat of vaporization and amount of fuel. Ma et al (2004) e.g. showed that the energy balance dominated the burning rate of flammable liquids on porous media (carpets) but also showed that capillary forces play a role. Before conducting testing an extended literature review on the subject is recommended.

6.1.2 Reducing uncertainties

As pointed out in Paper III there are uncertainties regarding choosing deterministic fire growth rates for first objects ignited. It would therefore be desirable to treat those

uncertainties by describing them by the mean of a statistical distribution for the fire growth rate for different first objects ignited, i.e. single burning items. A first step would be to collect fire growth rates in the available literature for different objects. For some objects there may already be enough data to arrive at a reliable distribution, e.g. there has been a lot of testing on sofas. For those objects where not enough data can be obtained additional testing is suggested. To further improve the accuracy of the quantification method improvements in the statistics would be helpful. The main issue would be to reduce the categories unknown and other. To do this, development of the way of collecting data is needed, e.g. by development of the form used when collecting data. Such development must start by identifying important parameters needed to be able to quantify the data and transform it into useful information.

6.1.3 Maximum heat release rate

Another important parameter describing the fire severity of a scenario is the maximum heat release rate reached during a fire. To get another step further in quantifying the fire scenario, probability distributions for the maximum heat release rate for building fire is needed. This is a more complicated task than making estimations of the growth rate due to the fact that experimental data cannot be used in the same manner. There are ways to describe the maximum heat release rate, e.g. by assuming that the fire reaches flashover and becomes ventilation controlled and by assuming a certain amount of openings calculate the heat release rate based on the available air, see e.g. Karlsson and Quintiere (2000). This approach is certainly valid in small rooms, but in large open spaces where a flashover is unlikely the approach is more questionable. Furthermore such an approach ignores fires that for some reason get extinguished or do not become under-ventilated. May it be due to manual fire fighting, that it did not spread from the starting object, or some other reason, but such an approach excludes the probability part. A first step towards obtaining such information would again be to develop the way statistical data is collected; it would e.g. be helpful to include the degree of fire damage/spread in a more quantitative way. However the desired parameters to collect need to be further investigated.

6.2 Sensitive areas

In section 4.2 three research questions were formulated, SA 1, SA 2 and SA 3.

- SA 1. What are the advantages and challenges with hypoxic air venting as fire protection?
- SA 2. At what levels of fire exposure are critical components damaged to the extent that they lose their functional performance?
- SA 3. What is the sustained damage to different equipment in sensitive areas with different types of protection systems?

SA 1 was in large answered in section 5.2. However when conducting that research further needs for research were identified, these are presented below.

For research questions SA 2 and SA 3 a first step would be to conduct an extended literature review to determine available experimental data on failure criteria for electrical components, as has been done for cables in e.g. Andersson and Persson (2001) and Andersson and van Hees (2000). After such a review, testing is recommended to fill gaps in knowledge. Once critical levels have been determined the effect of different protection systems can be analyzed.

Hypoxic air venting as fire protection

The need for further research on hypoxic air venting as fire protection is described in detail in Paper II. In this section the research need is just briefly described and focus is devoted to describing how the research may be conducted and the benefits of such research.

Since an oxygen level that completely removes the risk of fire is often not achievable due to health aspects there is a need to investigate the effects should a fire occur and the likelihood that a fire occurs at reduced oxygen levels.

Burning behavior

The information is limited on the effect of configuration and orientation of fuel on the heat release rate (HRR), fire spread and ignition thresholds in reduced oxygen atmospheres. Further, more information is needed regarding production rates of corrosive, irritating and other gases. There is some information on generic material such as PMMA, PVC etc, however the information is limited on actual products, e.g. cables, electrical components etc. For this part of the research two types of testing is suggested. First Cone Calorimeter (CC)/Fire Propagation Apparatus (FPA) testing at different oxygen concentrations, different orientations and configurations of fuel measuring HRR, production of certain gases and recording fire spread with camera.

To investigate ignition thresholds it is suggested to try different ignition scenarios on different types of materials in a room where the atmosphere is controlled. Parameters that could be varied are spacing between materials, corner configurations, material, oxygen concentration, ignition source (fuel and energy) etc.

Further an attempt to describe the above effects based on physical material properties would be helpful to be able to estimate the effect on materials not tested.

Reliability

In order to further be able to perform risk analysis there is a need for information on reliability. A first step here would be to investigate already installed systems and determine how often the systems are out of order. Furthermore the components of a system could be investigated in order to be able to quantify potential failure modes and to estimate the associated probabilities.

Test methods

The test method presented in PAS 95:2011 (BSI, 2011) and VdS 3527en (VdS, 2007) has been found inadequate and there is a need for further development of the test method. The information that may be obtained from the research described above will help identify critical parameters that a test method needs to handle. Once the above research has been conducted one can take further steps towards a standardized test method that in a sufficient way tests the system. Such a test method would contribute to a more safe and uniform application of the system.

6.3 Fire protection

In section 4.3 three research questions were formulated, FP 1, FP 2 and FP 3.

- FP 1. To what extent do smoke and fire spread between protected and unprotected (e.g. sprinkler) rooms?
- FP 2. To what extent is the fire development limited when a sprinkler system cannot reach the seat of the fire?
- FP 3. How well does regular fire compartmentation resist smoke spread?

These research questions were not addressed in the thesis. As next step a literature review is recommended to determine the current research status for the three questions. Once this has been conducted gaps in knowledge can be filled through testing. Testing is most likely needed at larger scale.

6.4 Ignition scenarios

In section 4.4 two research questions were formulated, IS 1 and IS 2.

- IS 1. How is the fire development affected by the size/type of the ignition source?
- IS 2. How is the fire spread affected by a large ignition source when active systems been used to motivate removal/reduction of passive systems?

The effect of the size of the ignition source, i.e. research question IS 1 was discussed in section 6.1.1 “The need for testing” and suggested research steps are given in that section. When more knowledge has been obtained regarding the importance of the ignition source and how that affects the fire development, then relevant research steps can be determined in order to pursue this research question IS 2.

6.5 Domino effects

In section 4.5 three research questions were formulated, DE 1, DE 2 and DE 3.

- DE 1. What are possible domino effects in multifunctional buildings?
- DE 2. What are possible domino effects as a result of antagonistic attacks?
- DE 3. How can the evaluation method be complemented with further guidance on how to handle domino effects?

To address the above questions, an extended literature review is recommended to determine possible domino effects as a result of multifunctionality and antagonism. Once these have been determined it can be examined how the evaluation method can be complemented with further guidance. One possibility is to use guidance from the process industry, see e.g. Abdolhamidzadeh et al (2010), Gómez-Mares et al (2008), Khan and Abbasi (1998), Khan and Abbasi (2001a) and Khan and Abbasi (2001b) or critical infrastructure, see e.g. Zimmerman and Restrepo (2009), Little (2002) and Utne et al (2011).

7 Conclusions

This thesis focused on fire safety evaluation of multifunctional buildings with special emphasis on antagonistic attacks and protection of sensitive areas that has been found to be of special importance to the continuity of functions. Mainly three research questions were addressed:

- RQ 1:** What are the specific problem areas within multifunctional buildings when considering the multifunctional aspects as well as antagonistic attacks?
- RQ 2:** How could an evaluation method that identifies and analyzes fire related risks, including antagonistic threats, in multifunctional buildings be designed?
- RQ 3:** Are there specific research areas that need further investigation or research questions that need to be answered in order to support such an evaluation method?

Specific problem areas with respect to multifunctionality and antagonism were identified and presented in chapter 2, this answered RQ 1. Based on those problem areas an engineering method for selection and evaluation of fire related scenarios in multifunctional buildings considering antagonistic attacks was developed and presented in chapter 3. The evaluation method answers RQ 2.

The strength of the evaluation method is that it provides a systematic approach to evaluate new aspects of fire safety. New in that essence that focus is also devoted to ensuring continuity of functions and being able to handle antagonistic events in addition to the normal focus, life safety in case of accidental fires. The tools presented in Paper I, i.e. flowcharts and tables, are designed so that the engineer captures the essential aspects of multifunctional buildings and antagonistic attacks. Finally the evaluation method treats uncertainties in a recognized way, i.e. by scenario analyses and by choosing conservative values.

In chapter 4 research areas and questions that needed further investigation in order to support application of the evaluation method was identified, hence answering RQ 3. Two of the research areas were further addressed.

A method for quantifying fire growth rate was developed and application of the quantification method showed the effect of arson fires increasing the growth rate of a fire. Hypoxic air venting as fire protection in sensitive areas was also studied. The system is promising if the oxygen level can be maintained at sufficiently low levels but presents challenges if the oxygen level is so that fire can still occur.

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Appendix: Appended papers

- Paper I** Nilsson, M., Frantzich, H., & van Hees, P. (2013). Selection and Evaluation of Fire Related Scenarios in Multifunctional Buildings Considering Antagonistic Attacks. *Fire Science Reviews*, 2(3), pp. 1-20. doi: 10.1186/2193-0414-2-3.
- Paper II** Nilsson, M., & van Hees, P. (2013). Advantages and Challenges with Using Hypoxic Air Venting as Fire Protection. *Fire and Materials*. doi: 10.1002/fam.2197. (published on-line).
- Paper III** Nilsson, M., Johansson, N., & van Hees, P. (2014). A New Method for Quantifying Fire Growth Rates Using Statistical and Empirical Data – Applied to Determine the Effect of Arson. Accepted for publication in: *Proceedings of the 11th International Symposium on Fire Safety Science*.
- Paper IV** Nilsson, M., van Hees, P., Frantzich, H., & Andersson, B. (2012). Analysis of Fire Scenarios in Order to Ascertain an Acceptable Safety Level in Multi-Functional Buildings. In *Proceedings of the 9th International Conference on Performance-Based Codes and Fire Safety Design Methods*, Hong Kong, China, 20-22 June 2012, Society of Fire Protection Engineers, USA.

REVIEW

Open Access

Selection and evaluation of fire related scenarios in multifunctional buildings considering antagonistic attacks

Martin Nilsson*, Håkan Frantzich and Patrick van Hees

Abstract

Multifunctional buildings have become more common in the last years. At the same time the threat from antagonistic attacks has increased. This presents challenges for the fire safety systems in multifunctional buildings since continuity of functions, especially those considered to be of societal importance, need to be operational and at the same time antagonistic exposures may present more challenging fire scenarios. A method for selection and evaluation of fire related scenarios in multifunctional buildings, that also considers antagonistic attacks, has been developed. Based on literature review and interviews with stakeholders typical for a multifunctional building, specific problem areas that the developed method needed to take into account were identified. A first framework for development of fire scenarios, developed by the authors in previous work, was refined taking into account the identified problem areas resulting in the method described in this article. The method, still simple to use, provides guidance on how to determine assets needing protection, relevant protection objectives, exposures (both accidental and antagonistic), fire related scenarios and evaluation of scenarios. The method also takes into account the inherent probability of failure for active systems, security features, domino effects and damage to protection systems due to antagonistic attacks.

Keywords: Fire scenarios; Design fire; Performance-based design; Antagonism; Terrorism; Multifunctional building; Multipurpose building

Introduction

Multifunctional buildings, for terminology see Appendix, are characterized by the multiple social or commercial functions or occupancies located within a building or interconnected buildings. There is a trend when designing new buildings to locate many functions or occupancies within one building rather than designing several single purpose buildings as has been done previously. Almost every major city has one or more buildings that may be characterized as multifunctional, e.g. hosting theatres, a subway-station, a shopping center, restaurants, offices and/or hotels within the same building. These buildings are often open to the public hosting a variety of businesses and tenants as well as a large number of visitors. Often areas within these buildings host important societal functions such as; transport facilities, municipality offices etc. All

of these factors contribute to the overall complexity, vulnerability and potentially unacceptable consequences to society if an incident was to occur. An incident in such a building may result in significant consequences as a result of death, property damage and impaired functions that may be essential to societal and/or business operations.

During the last decades terrorism and physical attacks on buildings have continued to increase (Brown and Lowe 2003) adding to the overall complexity and vulnerability for multifunctional buildings. Nilsson et al. (2012) conclude that the likelihood of an antagonistic attack is in the same order of magnitude, for some buildings, as is deemed to be unacceptable by some recommendations, and antagonistic attacks can therefore not be ignored. Det Norske Veritas (Davidsson et al. 1997) for example has suggested risk criteria for individual risk between 10^{-5} and 10^{-7} and between 10^{-4} and 10^{-6} per year for $N = 1$ with a slope of -1 for societal risk and Stewart (2008) suggests that the

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probability for a terror attack on a US commercial building is between 10^{-6} and 10^{-7} . In addition, arson should also be considered as an antagonistic attack and is a relatively common event. Richards (2008) suggests that 15% of all fires in New Zealand are deliberately lit and for public buildings (retail shopping, cinemas etc.) this may be as high as 40%. Hall (2007) concluded that 6% of all fires in the US are intentional and Simonson (2007) states that at least 25% of all fires in Sweden are intentional. Some examples of antagonistic attacks that can be mentioned include; the subway arson fire in Korea 2003 (National Emergency Management Agency 2004), the underground explosion in the UK 2005 (Handley et al. 2009), the explosion in the World Trade Center 1993 (Isner and Klem 1993), the gas attack on the subway in Japan 1995 (Pangi 2002) and the bombings in Boston, USA, 2013 (Winter et al. 2013). Since multifunctional buildings host a large number of people, critical functions important to society and may be considered iconic buildings or historically significant etc. they are more likely to be selected as targets for antagonistic attacks. This is due to the fact that such an attack is likely to inflict significant emotional and/or economic damage as well as impairment to societally important functions (Brown and Lowe 2003). Further, antagonistic attacks have the potential to cause a long-term effect on society, beyond the physical damage and interruption of services. As an example, Rubin et al. (2007) concluded that the population had reduced their use of the public transportation system within the London area 8 months after the London bombings in 2005 by 19% and Handley et al. (2009) conclude that 45% of persons directly affected by the bombings reported disabling travel anxiety that had interfered with their everyday life. In addition when considering antagonistic attacks these can be considered catastrophic with a high potential of large fires. These large fires are perceived as less acceptable than ordinary fires (Wolski et al. 2000). Wolski et al. (2000) further state that the high-rise fire risk is perceived as catastrophic compared to for example the single-family home building fire. A high-rise fire can be compared to multifunctional buildings as they also are generally large and have a potential for catastrophic events. Wolski et al. (2000) discuss nine risk factors: volition; severity; effect manifestation; familiarity; controllability; benefit; necessity; exposure pattern and origin, that can be used to describe why people require a higher or lower safety level. Many of these factors point towards a required higher safety level in multifunctional buildings, especially if antagonistic exposure exists.

Traditional fire safety design, to obtain code compliance, focuses on life safety considering accidental fire events (Klason et al. 2011) and limited consideration is given to property protection and continuity of functions. Further scenarios incorporating antagonistic events are generally

not considered by the building code (Gilbert et al. 2003) and the traditional prescriptive design generally does not account for arson fires since it does not consider the actions of the individual lighting the fire (Richards 2008, Klason et al. 2011). Due to the fact that antagonistic events can be more severe and carefully planned there is a potential for larger consequences, especially if such attacks have not been taken into account at the design phase. Antagonistic attacks, as seen in the above examples, can differ widely and it may be hard to define such a scenario. However, in multifunctional buildings, there is also a potential that other protection objectives than simply life safety are present, e.g. continuity of functions and protection of property that is generally not considered by building codes.

The large number of multifunctional buildings, where not only life safety is of concern but also continuity of operations and functions, and the increased threat for antagonistic attacks create a demand for a method analyzing the fire safety level from a holistic view. Such a method needs to incorporate life safety with regards to accidental fires as well as other protection objectives (e.g. continuity of functions, property, cultural heritage) and the possibility of antagonistic events. Most building codes are reliant on prescriptive rules, however these rules are inflexible if not applied to a historically traditional building (Frantzich 1998). Multifunctional buildings are by definition not traditional buildings even though the number has increased, hence a holistic method needs to be performance-based since such a method defines protection objectives to be achieved (Frantzich 1998) and there is a possibility to consider a large variety of scenarios. Such a method includes the management of hazards more severe than usually assumed for life safety design, fire spread prevention etc. in the current building codes.

A holistic method, for selection and evaluation of fire related scenarios in multifunctional buildings considering antagonistic attacks, must incorporate a selection of fire related scenarios that need to be analyzed and evaluated. Due to the wide variety of possible antagonistic attacks the method also needs to incorporate a structure to be able to determine relevant antagonistic threats and how such scenarios may develop, i.e. initiating event, possible domino effects etc. Although antagonistic attacks might include a much greater scope than simply fire related attacks, the aim of this method is to evaluate fire related scenarios and will therefore not include antagonistic attacks such as gas attacks, cyber attacks etc., however some parts of the method may be applicable for exposures other than fire. The defined scenarios must then challenge the protection objectives and be chosen based on an analysis of possible exposures. Finally an evaluation procedure, as to whether the protection objectives are met or not, needs to be specified. In summary such a method must:

1. Define what facilities/functions/property/life safety etc. (hereon called assets) need to be protected.
2. State clearly protection objectives for these assets.
3. Evaluate what exposures or threats (including antagonistic exposures) may cause the protection objectives not to be met.
4. Incorporate a selection of scenarios based on protection objectives and exposures.
5. Evaluate whether the protection objectives are met or not for the scenarios.

Goal, purpose and working process

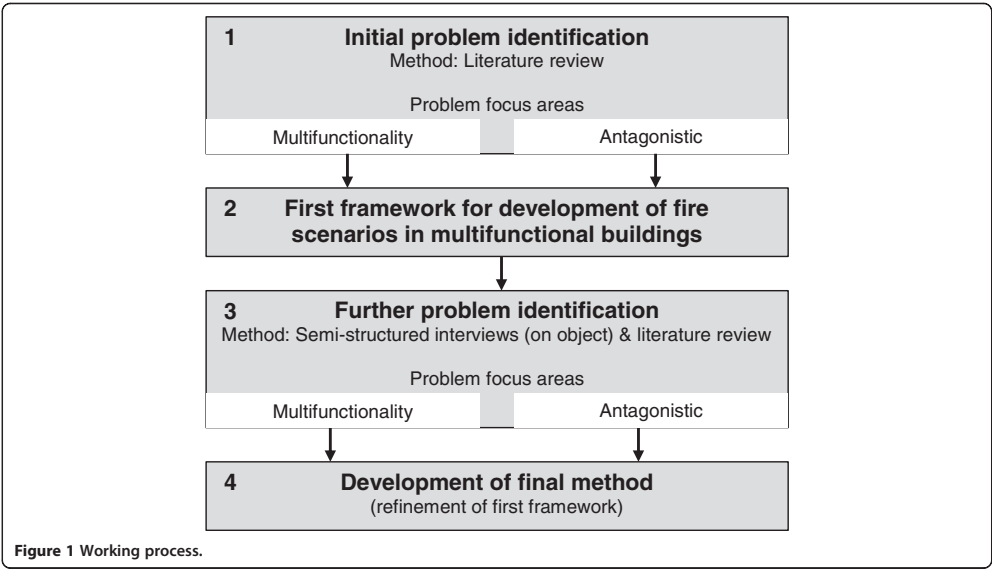
The goal is to present a method for selection and evaluation of fire related scenarios in existing multifunctional buildings that also considers fire related antagonistic attacks. The working process to develop such a method is presented in Figure 1. The method should identify assets, relevant protection objectives and exposures, including fire related antagonistic exposures. Further it should incorporate the selection and quantification of fire related scenarios that may pose a threat to the protection objectives not being met. Finally, the method then needs to evaluate whether the protection objectives are met or not for the selected scenarios. The purpose of the method is to support prevention of fire related accidents and consequence mitigation in case of fire related accidents in multifunctional buildings, incorporating a variety of relevant protection objectives as well as fire related antagonistic events. The main field of application for the method is for existing

buildings, however parts of the method may also be applicable for new designs.

To develop the method the work was divided into four steps, represented by the four boxes in Figure 1. Two steps (step 1 and 3) comprised problem identification to support development of the method and two steps (step 2 and 4) comprised development of the method itself.

The problem identification steps had two problem focus areas for multifunctional buildings. The first was problems associated with multifunctionality can include a large number of tenants, variety of different functions, different occupancies etc. The second problem area was associated with antagonistic events, e.g. larger initiating events, degree of planning etc.

In step 1 (part of problem identification), a literature review was conducted which resulted in a first framework for development of fire scenarios in multifunctional buildings, i.e. step 2 (part of development of the method). This first framework and the conclusions from the literature review are described in Nilsson et al. (2012), however the main conclusions regarding problem areas are summarized below. The main focus of the literature review was identification of problems connected to multifunctionality and antagonistic events that the method needs to consider. The literature review also comprised a review on performance-based fire design guidelines to give input on possible evaluation procedures for multifunctional buildings. Overall, the literature reviewed included the following: performance-based design guidelines; design fire guidelines;



papers regarding multifunctional/multipurpose buildings; design guidelines regarding antagonistic attacks; review of occurred antagonistic attacks and their implications.

In step 3 (part of problem identification), interviews with stakeholders in a selected multifunctional building were conducted. The selected building's main purpose was infrastructure (transport center) but the building also hosted a large variety of other businesses and functions. A total of nine interviews were conducted with different business owners, rescue services, the safety management team, etc. The interviews were semi-structured, which gave the benefit of ensuring flexibility in how and in what sequence questions are asked, for the interviewees to be able to develop their thoughts and for the interviewer to be able to ask follow-up questions so that unexpected themes could emerge (Mason 2004). The aim of the interviews was to identify additional problems with respect to multifunctionality and antagonistic events that the stakeholders in multifunctional buildings are dealing with. Further, an understanding of how different stakeholders are working with these additional problems as well as protection against antagonistic attacks and their view on such exposures was also sought. In addition questions were asked to support refinement of the first framework for development of fire scenarios presented in Nilsson et al. (2012). An interview guide was created based on the purpose with the interview. The full description and findings of the interviews can be found in Nilsson and van Hees (2012), however the main conclusions are summarized in the following section. Additionally, an extended literature review was conducted on information obtained and deemed relevant during the interview process.

The first framework developed in step 2 (part of development of the method) and presented in Nilsson et al. (2012) was to some extent based on the SFPE engineering guides (SFPE 2006, 2007), however with several modifications. Based on the information from the interviews and the extended literature review in step 3 (part of problem identification) a refinement of the first framework (developed in step 2 (part of development of the method)) was done in step 4 (part of development of the method). Step 4 (part of development of the method) resulted in the final method for selection and evaluation of fire related scenarios in multifunctional buildings considering antagonistic attacks. The method is presented in the following sections, however, first the results from step 1–3 are presented.

Problem identification to support development of method

Below are the results from the problem identification presented, starting with the literature review and then the interviews. Finally remarks and a summary are presented on aspects that need to be considered within the method.

Literature review

The literature review was conducted using Web of Science search engine for peer-reviewed papers. An extended search was also conducted to find appropriate standards, dissertations etc. The results are presented below.

Stakeholders

The nature of multifunctional buildings is to gather many different occupancies and businesses in one building. This results in the fact that there are many different functions provided and that there are many different stakeholders having interests in the building. One identified problem area in Nilsson et al. (2012) is that these stakeholders can have very different views on what needs to be protected resulting in a large variety of protection objectives or goals that needs to be accounted for. For some stakeholders fire safety might not be of primary concern while as others cannot accept an interruption to the functions they provide in case of fire. There might also be interdependencies causing problems further down the line warranting a higher safety level and the protection objectives might be considerably different from what the building code generally addresses (Nilsson et al. 2012).

Fire protection systems

Multifunctional buildings often incorporate a variety of different protection systems such as; active fire protection, e.g. sprinkler system, gaseous extinguishing systems and smoke evacuation, and passive fire protection; e.g. fire compartmentation and space separation. Building codes often focus on minimizing damage to third party by requiring fire protection systems such as physical separation or fire barriers between different occupancies within a multifunctional building and between different buildings. In reviewing previous real-life antagonistic attacks and their consequences it was noted that there is a tendency for protection systems to become impaired or not to function as expected during the course of an antagonistic event. This is especially true for antagonistic events involving explosions or highly energetic initiating events which may result in physical separation or fire barriers as well as the installed active protection being inadequate or damaged due to the initiating event. As an example the bombing of the World Trade Center (WTC), 1993, can be mentioned, where the fire alarm communication system (control center) was lost so that occupants did not get evacuation information, and masonry fire walls and fire doors were voided by the force of the explosion (Isner and Klem 1993). Normal and emergency electrical power was lost affecting sprinkler system as well as emergency lighting (Isner and Klem 1993) and the smoke management system was damaged (Quenemoen et al. 1996). The situation where a single failure (in this case electricity) is disabling several protection systems is often referred to as common-

cause failure (CCF) and will be discussed further in the following sections. Other examples, where protection systems have been lost are; the arson fire in Gothenburg where the fire started in an evacuation route impairing its function (Eksborg et al. 2001) and the attack on WTC, 2001, where the structural fire protection was damaged by the plane crash (Gutierrez et al. 2005). Other issues with antagonistic attacks may be that fire protection is bypassed, there is the potential for multiple fires to be ignited which the protection cannot handle or the severity of the fire is too challenging for the protection (Richards 2008). Thompson and Bank (2007) also points out the importance of attacks on fire suppression systems and attacks against evacuation routes. Since a successful outcome of a fire often is dependent upon the effectiveness of the protection systems, special consideration is needed when considering antagonistic attacks. The potential for domino effects where the initiating event escalates, e.g. an explosion followed by a fire where the protection system is affected during the event, is pointed out in Nilsson et al. (2012) and needs to be incorporated in the analysis. Not only do these examples indicate the importance of the protection systems but also supporting systems such as electricity, i.e. damaging support systems could impair the protection system. This is analogous to important functions as well in case they are dependent upon support systems.

In addition it may also be the case that the protection system is not effective in achieving the protection objective, e.g. if an electrical room is of critical importance and the room is protected by sprinklers. In this case soot, heat etc. may cause too much damage to some of the electrical components before the system activates, even though the fire is controlled and does not spread outside the room (Nilsson et al. 2012).

Fire size and location

If a fire is started as part of an antagonistic attack flammable liquids or explosives may be used and in this case the fire development could potentially be accelerated when compared to that of an accidental cause (Richards 2008). This will have an impact on both life safety and other protection objectives. Generally buildings are not designed for arson fires, which is supported by the consequences related to the fire in Gothenburg (Eksborg et al. 2001) as well as the subway fire in Korea (National Emergency Management Agency 2004) with a large number of fatalities. In terms of multifunctionality there may also be sensitive equipment, support systems or rooms of special importance where even a small fire could cause large damage. Such small fires are generally not considered due to their limited effect on life safety, however these fires might be of great importance in terms of continuity of businesses and/or functions (Nilsson et al. 2012).

Both in terms of continuity of functions as well as antagonistic attacks the location of the fire is of great importance, a well-informed attacker might know exactly where to place the attack to achieve the most damage. An accidental fire at an unfortunate location might cause large consequences in terms of interruption to a function. The location of the fire therefore needs to be considered in the light of what is supposed to be protected (Nilsson et al. 2012). Unusual locations, i.e. fire locations not normally analyzed, might therefore need to be considered, for example; in sensitive areas or external facades which is a common starting area for arson fires (Klason et al. 2010).

Security and the aggressor

When reviewing design guidelines for protection against terror attacks and antagonist attacks such as Brown and Lowe (2003), it becomes clear that one of the main protection features against antagonistic attacks are security measures. Security includes surveillance, site perimeter protection, access control etc. and could help in limiting the exposure. If a building has a parking garage, vehicles that could carry potential hazards e.g. large amount of explosives, may have easy access to the building causing increased potential exposure, on the other hand if there is no parking garage the exposure may be limited to what one can carry. Analysis of the security system is therefore necessary.

Brown and Lowe (2003) suggest an evaluation of the aggressor and they state that terrorism attacks are likely to be conducted because the aggressors seek e.g. publicity for their cause, monetary gain or political gain through their actions. Richards (2008) lists the reasons for arson as vandalism, excitement, revenge, crime concealment, profit and extremist beliefs. Brown and Lowe (2003) point out the significance of understanding who the people are that want to cause harm, their means and resources. All this information provides input to be able to determine what the relevant antagonistic scenarios are that could occur.

Interviews

The conclusions and results from the interviews are given in full in Nilsson and van Hees (2012) and are, therefore only, summarized below. The interviews focused on questions related to the first framework for the method, i.e. "Assets worth to preserve" (called assets further on), "Protection objectives", "Exposure analysis" and "Fire scenarios", for further information see Nilsson et al. (2012). When conducting the interviews and visiting the specific building it became clear that to be able to do an analysis of such a complex building, the method needs to be simple enough so that the user is able to identify scenarios to be analyzed during a site visit.

Assets and protection objectives

The interviewees were of the opinion that the highest priority in terms of fire safety should be given to life safety and the second most important to protect was functions deemed societally important, in this case infrastructural functions within the building. Within the building of concern there were many other functions, but the main focus of the interviewees was aimed towards the core functions of the building, in this case infrastructure functions (transport center). Therefore the determination of building core functions needs to be part of the method, which is also pointed out by Brown and Lowe (2003). In order to facilitate continuity of such functions a variety of support systems are needed, examples given were electricity, control rooms, telecommunications, physical infrastructure etc. An example was given where a fire damaged a cable used for telecommunications, and caused interruption to municipality functions. Another area that the interviewees focused on was areas or functions needed to be able to handle an ongoing incident, such as dispatch centrals etc.

During the interviews it became clear that stakeholders who took part in the interviews did not have a clear opinion about protection objectives. The protection objectives were of the form “no one is supposed to get hurt”, “we do not allow any interruption to our services” etc. Additionally, during the interviews the stakeholders raised questions showing that they started to consider these issues more seriously and realized that protection objectives need to be firm and measureable. Further, they had a sense for possible make-up in case there was to be loss of a function but the procedures and potential for make-up was not formalized.

Exposures

The interviewees associated areas with high occupant density to be weak points of the building, they also considered areas where there are large amounts of combustible or flammable materials together with areas where vehicles have access and where the fire intensity can be large to be of importance. Another exposure that was brought up by the interviewees was areas in which people (i.e. the general population) have easy access and can prepare an antagonistic attack without anyone noticing, i.e. where the security was considered to be poor.

Management and multi-tenant issues

Most interviewees stated that their main protective measures against fire and antagonistic attacks are the emergency management plans and action plans put in place in case of an accident. These plans do not generally consider how to address the fire itself but rather how to evacuate the premises or how to act upon seeing a suspicious bag that may contain explosives or how to coordinate efforts with the fire rescue service. Not all the interviewees had their

own plans and none of the interviewees were aware of what plans their neighbor had, i.e. there is no holistic view from the building management. Management and action plans will of course have an effect on the scenario and the method needs to be flexible enough to account for that.

A problem that some interviewees raised was that the tenants within the building had a very different view on what level of fire safety should be achieved and none of the tenants had made an assessment on how other businesses within the building may be exposing their own business.

Fire protection systems

During the interviews there were indications that the landlord was not fully aware of how the fire protection systems within the building was supposed to work, e.g. whether there was a programmed delay from detection to sounding the evacuation alarm. There were also indications that the sprinkler system was not maintained properly. Further the tenants were not aware of the limitations of the protection systems, in terms of storage heights etc., which may result in storage configurations or occupancies exceeding the design limits of the suppression systems. This again reinforces the need to analyze a scenario in which active fire protection systems fail. Further, in one fire case, the fire compartmentation did not fulfill its task and extensive smoke spread occurred, hence the method not only should consider active fire protection systems, but, needs to evaluate deficiencies in, and the reliability of, passive protection systems as well.

Rescue service

During the interviews with the rescue service they stated that there is often too high an expectation on what the rescue service can achieve. As examples of such expectations were given the ability to control and handle technical systems as well as the belief that the rescue service can fight a fire with higher heat release rate than they actually are able to. Another issue that they raised was that their access routes often collide with evacuation routes, making it harder for them to undertake a rescue operation.

Antagonism

When the interviewees were asked what kind of antagonistic threats they could imagine happening, the general opinion was that this is highly dependent upon what the aggressor wants to achieve and the aggressor's imagination, indicating the need for aggressor evaluation. One interesting antagonistic exposure that was raised was the fact that there was an action plan in place stating that if a vehicle receives a bomb threat, and there are limited means to evacuate the vehicle at its current location, the vehicle should be brought into the multifunctional building for evacuation. This action plan results in the fact that the

exposure, i.e. the potential bomb, is actually brought into the building.

Discussion and summary of the problem identification

In the following section, remarks and thoughts are discussed on some areas identified in the literature review and during the interviews. The issues raised during the interviews are dependent upon the interviewees and the choice of building. The results from the interviews, however, have been generalized to be applicable to multifunctional buildings in general. The interviews in combination with the literature review helped to make sure that important issues are identified and that the risk of excluding important issues is minimized. In the next section a summary of identified problems is given.

Discussion regarding the problem identification

The large number of stakeholders within a multifunctional building present challenges as discussed above, e.g. many different protection objectives and goals for the fire safety, the stakeholders do not "know" each other etc. Even though not explicitly identified within the literature review or interviews it is probable that the stakeholders will have different financial prerequisites influencing their goals with regards to fire safety and their ability to achieve those goals. Further, different stakeholders will also have different exposures from antagonistic threats; some will be more exposed than others. Even though an antagonistic exposure may not exist against an important function there might still be risk of exposure due to the fact that a neighbor could potentially be exposed. The number of stakeholders presents challenges as identified above and the method needs to be able to handle these challenges and work despite these difficulties.

The number of fire protection systems within a multifunctional building can be large due to the required flexibility of the building, e.g. large open spaces, varying occupancies, etc. If these systems are integrated with each other, say dependent upon electricity or smoke detector activation there is a risk of common-cause failure (CCF), i.e. a single fault disabling several protection systems (Lundin 2005). This is an aspect that needs to be covered in the method. However, there may be systems that are considered not to be integrated with each other, e.g. if redundancy is provided for electricity by emergency power to minimize the probability of CCF. Emergency electrical power had been provided in the WTC to minimize the risk of a CCF, however the initiating event impaired both the normal and emergency power systems (Isner and Klem 1993). This illustrates that there is still a probability for CCF's since there is dependency upon electricity even though redundancy was provided to minimize the probability of a CCF. This illustrates the potential for increased probability of a CCF when the initiating event is more

severe and widespread, in the described case for instance, a bomb. This implies that systems considered not to be integrated may need to be considered as integrated depending on the scenario.

The need for evaluation of an aggressor when considering antagonistic attacks was pointed out both in the literature review and during the interviews. Such an evaluation should be conducted as part of the analysis, however it is clear that a continuous evaluation and external environment monitoring will be necessary during the life time of the building due to changing circumstances.

The development process during the interviews, e.g. stakeholders realizing that protection objectives need to be firm and measurable, indicates the need for the stakeholders to be part of an evaluation process. Just by performing an evaluation, the fire safety level will increase due to raised awareness. The large number of stakeholders in a multifunctional building means that it is important to determine which stakeholders should be present in order to make the evaluation process effective.

The interviewees divided the weak points into two main categories, areas with high occupant density and areas with high fire severity or high probability of fire occurring. In the first framework these can be divided into two separate issues, a large amount of people is an asset while as fire severity or risk of fire is an exposure. The exposure needs to be considered in the light of the asset, there is no point in analyzing a fire if it is not exposing the asset. Therefore the initial assumption, in the first framework, that the analysis should have its starting point in the asset is still valid. Further the issue with neighbors becoming exposure risks needs to be covered in the exposure analysis and the method needs to make sure that this is considered, as the interviews indicated that this is not the case today.

In general the interviewees deemed electrical appliances rooms, telecommunication rooms, computer rooms etc. important for continuity of functions. These areas are very sensitive to fire damage, especially smoke and there is a need to investigate efficient protection options for these areas. This might include clean agent extinguishing systems (FM Global 2010), hypoxic air-venting systems (BSI 2011, VdS 2007, Nilsson and van Hees 2013) and the like.

The uncertainties in what the rescue service can achieve in the case of an accident indicates that the efforts made by the fire rescue service should not be taken into account when evaluating or designing a multifunctional building, at least not in Sweden with the resources the fire rescue service has there. However the fire rescue service may be able to help with management, communication, coordination etc. during an incident. This however requires planning and that the fire rescue service is included in the emergency management plans for the facility.

Summary of specific problems the method needs to consider

In Table 1 below the identified problems that need to be accounted for in the method are summarized. It should be noted that these problems are in addition to or of greater importance than when evaluating or designing a building not considering antagonistic attacks or multifunctionality such as when using general strategies as described in guidelines from SFPE (2006, 2007).

Method for selection and evaluation of fire related scenarios

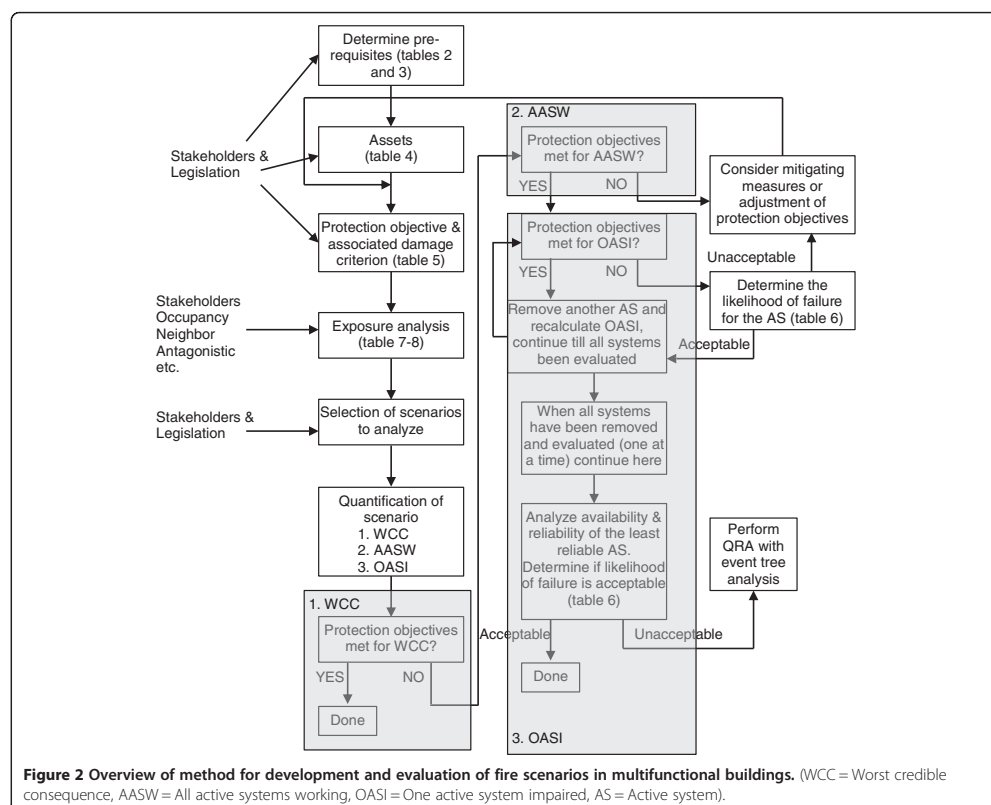
The overall method for selection and evaluation of fire related scenarios is shown in Figure 2. Due to the fact that the main purpose of the method is to evaluate existing buildings and that there is often limited time available to get access to the building, stakeholders etc. the method needs to be fairly easy and straightforward. In practice, during a site visit, there is a need to be able to identify how a scenario may develop, i.e. qualitatively describe the scenario, and later in the process quantify that scenario. Given the possible amount of scenarios

and the many different ways these can develop it would not be feasible to identify all possible scenario developments during a site visit. Therefore it was chosen to base the method upon scenario analysis choosing a worst-credible case for every scenario to be analyzed. A scenario chosen this way will also cover a range of other possible scenario developments due to the fact that such a scenario is more challenging than the majority of other possible scenarios.

With scenario analysis uncertainties are handled by choosing 'the worst possible conditions that could reasonably be expected' (Paté-Cornell 1996), i.e. choosing conservative values, which is what Paté-Cornell (1996) refers to as Level 2 when treating uncertainties. Level 2 implies that uncertainties for different parameters, such as heat release rate etc., are handled by choosing values that are judged to be on the conservative side, i.e. based on the current knowledge more severe values are thought to be unlikely. The benefit with using scenario analysis is that it is a simple approach and it is transparent, it is known what the scenarios are that have been designed and accounted for. The method outlined in this paper is therefore primarily based upon scenario analysis

Table 1 Problems to consider in the method

Aspect that needs to be considered/addressed in the method	M = Multifunctional A = Antagonistic
Flexibility so that a large variety of protection objectives can be addressed	M
Large number of stakeholders	M
Stakeholders with a high exposure to antagonistic attacks (exposing less exposed stakeholders)	A
The initiating event might impair both passive and active fire safety features	A
Common-cause failure due to large number of protection systems and increased probability for common-cause failure due to larger initiating event.	A/M
A lot of different functions provided, however not all are of main concern and the most important ones need to be determined	M
The fire severity, fire development or growth rate might be higher than what is usually designed for (including what protection systems are designed for)	A/M
Support systems that are important for functions and fire safety features	A/M
Domino effects (e.g. fire following explosion)	A
Location of fire (critical locations, e.g. sensitive areas, smaller fires where fire protection do not achieve the protection objective)	A/M
Security features (surveillance, access control, easy access areas etc.)	A
How to determine relevant antagonistic attacks (both large scale and small as arson)	A
First priority should be life safety then the core function of the building	A/M
Core functions of the building and relevant stakeholders need to be determined	A/M
Areas or functions needed to handle an ongoing event need to be analyzed	A/M
Guidance on firm and measurable protection objectives	M
Flexibility to take into account emergency management plans and action plans	M
Higher tendency for failure of protection system due to maintenance issues	M
Passive protection might be inadequate due to maintenance problems	M
External exposures such as a bomb threatened vehicle brought into the building for evacuation	A
Method needs to be simple enough to identify and determine scenarios to be analyzed during a site visit	-



(treatment of uncertainties on Level 2 according to Paté-Cornell (1996)) and the first analyses in the method are conducted with scenario analysis.

One disadvantage with treating uncertainties by choosing conservative values is the matter of not knowing how conservative the chosen values are, i.e. the uncertainties are not quantified and the risk is unknown (Paté-Cornell 1996). Therefore treating uncertainties this way presents shortcomings in the risk management phase when the risks cannot be reduced enough at low costs and when under budget restraints (Paté-Cornell 1996). Since the risk is not quantified there is no way to determine cost effective mitigating measures or to prioritize what scenarios to address. Due to these reasons there is a possibility that the first scenario analyses, i.e. the level 2 analyses, do not give satisfactory results, i.e. it cannot be concluded that the situation is acceptable. If this is the case the method will recommend that a Quantitative Risk Assessment (QRA) be performed. QRA corresponds to what Paté-Cornell (1996) classifies as Level 4 regarding

the treating of uncertainties. The reasoning behind this approach is that it is ineffective, unpractical and time consuming to perform a full QRA if it is not warranted and sufficient information can be obtained using simpler methods.

Determine prerequisites

The first step in the evaluation process is to determine the prerequisites for the evaluation. In order to determine what is supposed to be analyzed, it is important to determine the core functions of the building so that the efforts and resources are allocated for evaluating the fire safety according to the level of importance of these functions. If for example the core functions of the building are infrastructure and municipality functions and there are large number of visitors, the efforts should be directed towards maintaining those functions and ensuring life safety in case of fire. Less important functions in the building such as smaller shops, restaurants etc. should not be given the same attention since it does not fall within the core functions of

the building. However these businesses need to be considered as potential exposures to the core functions. Once the core functions have been determined, relevant stakeholders associated with these functions can also be determined. There may also be other indirect stakeholders that have a vested interest in the building's safety, such as authorities, that need to take part in the evaluation. Tables 2 and 3 can be used for guidance on finding core functions and relevant stakeholders. The stakeholders are of great importance for the further evaluation since they need to provide a lot of information on how the functions of the building are provided. The possible stakeholders are mainly obtained from Brown and Lowe (2003) and SFPE (2006) but have been divided into primary and indirect stakeholders. The indirect stakeholders might have information giving value to the analysis, e.g. the police with regards to recent antagonistic threats in the area or the fire brigade giving input on how they may intervene in case of fire.

When determining the prerequisites for the evaluation, building and occupant characteristics must also be determined (Nilsson et al. 2012). The characteristics of the occupants within the building as well as the buildings functional, geometric and operational characteristics will be the basis for developing the fire related scenarios. Examples of these factors include, but are not limited to, spatial connection and/or separation between fire compartments, the flow of people at the time of building use, the evacuation routes, issues with regards to the variety of business types and hours, the management form and responsibilities among different tenants, emergency action plan and evacuation guidance depending on tenants and floors, mutual communication between each tenant and the emergency operation center etc. Other issues that may affect the evaluation include, but are not limited to, property location, utilities, applicable regulations etc.

Assets

The next step in the method for developing fire scenarios is to determine the assets that need to be protected. An asset is a resource requiring protection (Brown and Lowe 2003) and can be humans, functions, property etc. In order to be

Table 2 Examples of core functions

Core functions	Present?
Infrastructure	
Societal functions	
Production	
Health care	
Education	
Financial	
Office	
Other	

Table 3 Examples of stakeholders

Stakeholders	
Primary	Indirect
Building owners	National Intelligence Service
Business owners	Municipality
Tenants	Regulators
Facility Staff	Police
Occupants	Insurer
Designers	Fire Brigade
Risk Managers	Neighbors
Other	Other

able to determine the relevant assets, input is needed from the stakeholders (determined in the previous step). During the interviews it was found that the discussion itself is a useful way of determining assets and such a discussion could be a helpful tool in an evaluation process. The relevant assets need to be determined based upon the core functions of the building so that the evaluation is focused based on the level of importance. For the purpose of this method assets have been divided into four main categories: life safety; property; environmental and functions, based upon the work in Nilsson et al. (2012). To provide guidance in finding relevant assets, Table 4 may be used.

The assets life safety, property and environment are generally fairly straightforward as opposed to what the functions might be. Providing a main function, such as train transport, might be highly dependent upon other functions supporting the main function, e.g. electricity, tracks, telecommunications etc. These supporting functions or 'support systems', need to be determined. Brown and Lowe (2003) suggest a two-step method, the first step is to define and understand the main function of interest and then identify the building infrastructure. This way, vulnerabilities are identified and focus is put on what a building does, how this is achieved and how various threats may affect the building (Brown and Lowe 2003). By using this approach focus is given to the support systems that were deemed important during the interviews. Using the asset evaluation form in Table 5 guidance is given to find different support systems. Further, to address the importance of functions that is needed to handle an ongoing incident, these functions have been listed in Table 4. Such functions may be control rooms, communication centrals or actual protection systems. Due to the determined importance and proneness to loss of protection systems in some scenarios a form for evaluating active fire protection systems has been developed, this is found in Table 6, and the usage of this form is discussed further under the section Quantification of scenarios.

As noted in Nilsson et al. (2012) it should also be considered that the loss of property or environmental

Table 4 Examples of assets

Asset type	Asset	Present?
Life Safety		
	Visitors	
	Employees	
	Rescue Service	
	Other	
Property		
	Building	
	Equipment	
	Stocks and Supplies	
	Cultural heritage	
	Other	
Environmental		
	Ground	
	Air	
	Water	
	Other	
Functions		
	Functions needed to handle an ongoing accident	
	Train transport	
	Bus transport	
	Car transport	
	Ferry transport	
	Air transport	
	Municipality function	
	Office	
	Archive	
	Payment system	
	Data System	
	Hotel	
	Production	
	Health Care	
	Education	
	Financial system	
	Other societal important function	
	Other	

damages could result in the loss of a core function. Naturally if a building is lost it will be unavailable to provide its functions and authorities may forbid operation if functions needed to ensure environmental control, required by law, have been lost.

Protection objectives and associated damage criteria

Protection objectives need to be developed for the assets and will vary depending on the asset. Some protection objectives might be governed by legislation, e.g. life

safety and environmental. Most building codes have a life safety protection objective stating something like “*in case of fire, occupants should be able to leave the building in reasonable safety or the risk to occupants should be acceptably low*”, for examples refer to NFPA (2012), Swedish National Board of Housing, Building and Planning (2011a) and BSI (2001). However, this protection objective is quite vague, a more precise protection objective for life safety may be that no people should die in case of fire in the building. However such a protection objective may not be achievable in every scenario and it may be necessary to develop more sophisticated protection objectives such as acceptable number of injured people or fatalities depending on the severity of the scenario. Life safety protection objectives may also, for example, be expressed as acceptable individual and societal risk. In order to be able to assess whether the protection objective is achieved or not, damage criterion associated with the protection objective needs to be developed, i.e. at what measureable impact is the protection objective not met. Most building codes have a set of damage criteria associated with life safety, one example is visibility of not less than 10 m, for example refer to BSI (2004) and Swedish National Board of Housing, Building and Planning (2011b). The International Code Council (ICC) (2011) has established protection objectives in the form of different acceptable impacts where for example, acceptable structural damage has been qualitatively described, such as “*moderate structural damage, which is repairable*”. Such descriptions of protection objectives and associated damage criteria might be useful and the code is recommended for input and further guidance. However the damage criterion needs to be further quantified in these cases, than is done in the code, and in terms of ‘at what impact’ the protection objective is not met, e.g. at what pressure or force is the structure damaged. Depending on the scenario, the damage criterion may differ, e.g. in case of an explosion an acceptable level of elevated pressures may be needed.

Property damage objectives might be expressed as acceptable monetary value of loss or as an acceptable damage area and environmental objectives are typically defined in terms of contamination of a medium (Nilsson et al. 2012). Again a damage criterion need to be associated with the protection objective in order to determine at what exposure level from the fire is the protection objective not met.

The protection objectives for functions however, may be more difficult to determine. Loss of functions is often associated with interruption to services, e.g. a business or important societal function. As stated above support systems may be of great importance and important support systems may also need protection objectives and associated damage criteria in order to be able to ascertain the overall protection objective for the determined asset.

Table 5 Asset evaluation form with examples

Asset evaluation form		Support systems ^a				
Asset		Electricity		Heat	Cooling	Tele-comm.
		Switchgear/ transformer	Cables			
Data system		X	X			
Prot. Obj.	RTO 8 h	Max 4 h outage due to 4 h reboot	...			
Damage Criteria	200°C on critical cables, smoke in both server rooms	360°C on linings	...			
Construction & HVAC	3 h fire rated, separate vent sys, holes in wall	2 gypsum on metal studs, ventilation direct to outside	...			
Occupancy	Comp. equip, regular comb.	...				
Exposure	Electrical fault, hot work, targeted attack with flam liq	...				
Protection/ Security	Clean agent extinguishing sys., steel door, access control, back-up of data off site	...				
Possible Scenarios	Fire in comp. equip., fire in reg. comb., flam liq fire in both server rooms (Antagonistic)	...				

^aNot all possible support systems are listed, just examples, others might include but is not limited to, server room, computer room, control room, water, evacuation alarm, structural frame, ventilation, gas, sewer, personnel, customers etc.

There is a need for a structured method to find appropriate protection objectives and to identify the different support systems that are important. In order to facilitate this process the stakeholders need to be interviewed to gain information, also Table 5 can be used for guidance to help find critical support systems. A structured way of determining protection objectives for functions is again to focus on core functions and it is essential to determine how the facility fits into the "big picture", i.e. how critical the facility is to the organization's operation, after that protection objectives can be established (SFPE 2006). One suitable way of establishing the objectives is to conduct a business impact analysis (BIA), often done for IT systems (Bowen et al. 2006) and as recommended in NFPA 1600 "Standard on Disaster/Emergency Management and Business Continuity Programs" (NFPA 2013). A BIA identifies a system's critical resources, each resource is then further examined to determine how long functionality of

the resource could be withheld before an unacceptable impact is experienced (Bowen et al. 2006). The time identified is maximum allowable outage (MAO) and the balancing point between MAO and the cost for recovery establishes the Recovery Time Objective (RTO). This method can be applied to multifunctional buildings as well by establishing the impact on a function if loss occurs of a component or support system. Recovery strategies together with protection should then result in a downtime less than the RTO. It might also be beneficial to include loss of customers due to prolonged downtime in this analysis. Damage criteria depend on the support systems or resources required to maintain the functions and could include equipment, personnel etc. Business continuity plans and possible make-up at other locations can be incorporated into this analysis. To determine opportunities such as make-up and to establish business continuity plans, standards for business continuity planning and emergency management

Table 6 Active protection system evaluation with examples

Active protection system		Support systems ^a				
Type		Fuel/power	Water	Bells/ speakers	Piping/ Valves	Detector
Sprinkler system		X	X			X
Isolation (from event)	Separate building		...			
Exposure	Closing valve as part of scenario		...			
Function (adequacy)	Designed for the occupancy		...			
Human action	None needed, automatic	...				
Reliability/ Maintenance	Maintenance according to standard	...				
Evacuation alarm						
Isolation (from event)	...					

^aThere could be far more support systems than listed here, e.g. control panels, extinguishing agents, cooling, personnel etc.

such as NFPA 1600 (NFPA 2013) can be utilized. If there is make-up available at other locations this might allow for a longer RTO.

Virtually any protection objective can be chosen for any asset, hence the method fulfills the requirement of being able to address a large variety of protection objectives. Further this step also focuses on support systems and therefore also addresses the issue of identifying critical fire locations. In Table 5 examples are given of protection objectives as well as associated damage criteria.

Exposure analysis

The next step in the method is to determine the hazards/threats that could pose a risk that the protection objectives are not met for the specified assets and associated support systems. This is referred to as an exposure analysis, sometimes called hazard identification. A hazard is a condition or physical situation with a potential to cause harm (SFPE 2006). A physical hazard might be flammable liquids or combustibles, but if a hazard relates to a person or group it will normally be defined in terms of state of knowledge, attitude or belief that is characterized as human action within an event (Nilsson et al. 2012). Sometimes the physical hazard might be separated from the asset, e.g. by physical separation, fire compartmentation or by active fire protection systems etc. Therefore it is essential to evaluate how the asset is protected from any hazards. To facilitate this, the asset evaluation form can be used as a checklist, see Table 5. The checklist contains an evaluation of the construction, i.e. is it fire rated, are penetrations sealed etc. Further it contains an evaluation of the occupancy and the associated hazards that comes as a natural consequence of the occupancy, the protection and security features are also evaluated. Hence, the asset evaluation form addresses the identified issue with for example maintenance of fire separation not being adequate and other potential deficiencies in construction features as well as evaluation of security features mitigating the exposures.

Exposures are divided into two main types based on the work by Nilsson et al. (2012), accidental/natural exposures and antagonistic exposures. If the exposure is actually endangering the asset, needs to be determined based upon location of the asset in relation to the exposure, hence the construction features and physical separation in the asset evaluation form, Table 5, need to be considered. Based on the exposures identified according to the sections below possible, scenarios can be added to Table 5.

Accidental/natural exposures

Accidental/natural exposures are exposures causing an accidental fire, i.e. without intention. An example can be a fire in regular combustible material that was ignited by an electrical fault or through hot work operations, in

this case the exposures being the combustible material and the ignition source. Accidental/natural exposures that present an exposure to life safety are generally considered by the building code. For multifunctional buildings however, a larger focus on the functions is needed, which follows from the determined assets and their support systems (Nilsson et al. 2012). It is important not to overlook any exposures that may expose the assets (including their support systems), there may be what could generally be considered a small exposure, say a small fire in an electrical room, that may not generally be analyzed. However this smaller fire might cause the damage criterion for an asset or support system to be exceeded hence the protection objective may be exceeded. It is therefore important to consider the exposure in relation to the damage criterion and the protection objective, if these are reflecting a high proneness to fire damage these small exposures need to be considered as well. For accidental/natural exposures the method for hazard identification in the SFPE engineering guide has been adapted and a more detailed description can be found in that guide (SFPE 2006). Also Table 7 can be used for guidance in finding exposures. The accidental/natural exposures have also been divided into Internal and External exposures just to raise the awareness that there may be exposures further away from the building itself endangering the protection objectives, one example could be a fire at a neighbor, a gas explosion further away or a train on fire entering the building.

Antagonistic exposures

As determined by the literature review and the interviews the way an antagonistic attack may develop can vary considerably and the literature gives a broad list of possible attacks. Examples from Brown and Lowe (2003) and Thompson and Bank (2007) include, explosion, arson, fire as a secondary effect to blast, attacks on load-bearing members, bypassing fire protection, attacks against evacuation routes to slow down evacuation etc.

Additionally, with antagonistic attacks the possibility that the attack is targeted against something else needs to be considered, there may be tenants within the building having a more severe antagonistic threat against them than the core functions considered. One example was given during the interviews where the procedure was to transport a bomb-threatened vehicle (say train, ferry, airplane) into the multifunctional building in order to evacuate the vehicle. This due to the fact that provisions in the multifunctional building made evacuation quicker.

The exposure from antagonistic events is a combination of many factors. Brown and Lowe (2003) suggest an approach where the existence of a threat, the capability of the aggressor, history of attacks and intentions of the aggressor is evaluated in order to give guidance regarding

Table 7 Examples of accidental/natural exposures

Accidental/Natural exposure		
Internal		External
Heat sources	Fuel sources	Type
Smoking	Regular combustibles	Explosion
Hot Work	Flam liquids	External fire (facade)
Heating equipment	Plastics	Fire at neighbor
Cooking appliances	Room linings	Vehicle fire
Tools	Concealed comb spaces	Other
Machinery	Proximity to heat source	
Motors	State of fuel (solid/gas/liq)	
Hot surfaces	Gases	
Static electricity	Vehicle	
Other	Other	

the exposure. Nilsson et al. (2012) suggested adding threats and security to this as well and the approach given in Nilsson et al. (2012) is chosen in this method for evaluating the exposure from antagonistic threats. In order to be able to determine the existence and history of an exposure, input from different stakeholders is needed. Tenants and owners may know if they have experienced attacks before and the police or fire department may have information on vandalism in the area etc. The intentions to conduct an antagonistic attack will give one piece of information on how the attack may be conducted. Adding the factor of security will give guidance on the magnitude of the scenario as well, e.g. if a car cannot enter the building the amount of explosives or accelerants that can be brought into the building may be limited and the exposure less severe. Table 8 presents steps to go through to determine antagonistic exposures. It should be noted that the table is not conclusive and the process is somewhat iterative; sometimes starting with the aggressor and its capabilities, sometimes with possible scenarios and then determine who has that capability.

It needs to be recognized that antagonistic attacks may be more severe and targeted as opposed to accidental/natural exposures. A well-informed attacker may know exactly where to strike to achieve the intention of the

attack, therefore focus need to be put on the assets when determining exposures. When considering the severity of an attack, explosives, flammable liquids etc. has the potential for a rapid development of a scenario with potential for domino effects such as a fire followed by an explosion. Security features, i.e. how much hazardous material can be transported into the area of interest, give some guidance on severity as do the evaluation of the aggressor's capability. However, there is a clear possibility for extreme events, i.e. events exceeding the design level event (Bukowski 2006), when considering antagonistic attacks. Brown and Lowe (2003), however, state that the more secure a building is and the better designed it is to resist an antagonistic threat, not only will the damage probably be less severe, but the building is also less likely to be picked as a target. The procedure described above and in Table 8 gives guidance on what possible exposures may be present. Whether the building should be designed to resist those exposures or not is up to the relevant stakeholders.

Selection of scenarios to analyze and qualitative description

Based on the determined assets, the protection objectives and the exposure analysis, fire related scenarios challenging the protection objectives have been identified and listed in the asset evaluation form (Table 5). At this stage the scenarios have not been quantified but are rather described with qualitative characteristics such as initiating event, fire spread to secondary rooms, etc. An example would be "An explosion in the mail room, tearing down the fire wall and damaging sprinkler piping causing extensive fire spread to the adjacent computer room". In the qualitative description of the scenario it is important to list possible domino effects, such as a fire following an explosion or damage to fire walls resulting in larger damaged areas. The possibilities of domino effects need to be recognized at this early stage and later quantified during the quantification of the scenario to determine if such a scenario is possible and if it will develop as first described qualitatively. Further variation in time and room need to be considered, if e.g. life safety is

Table 8 Antagonistic exposures

Step	Examples of aspects to consider
Existence	Who is hostile to the assets, organization etc. and might they be present at the location?
Capability	What methods, material, means etc. do the aggressors have? Is the material available at the building or do they need to bring it?
History	What has the aggressors done in the past? Where have they done it? Is there any history of such events in the area?
Intention	What do the aggressor hope to achieve? (vandalism, political, excitement etc.)
Threats	Explosion (e.g. by stationary vehicle, moving vehicle, mail, supply, thrown, placed, personnel), arson (e.g. via direct contact or remotely via projectile), attacks on electrical supply, fire protection systems (e.g. by-passing, damaged by initiating event, attacks on evacuation routs and stairs) etc.
Security	Surveillance, access limitation, site perimeter, lighting, security personnel etc.

of concern there may be large variations in occupant density depending on time of the day and location within the building. The same may also be true for other protection objectives, e.g. interruption to transportation facilities may have greater consequences during rush hours. From the previous steps the identified number of scenarios are likely to be unmanageable and the scenarios need to be merged into clusters (SFPE 2006). From each cluster one or more scenarios are chosen for further quantification in order to represent the other scenarios within the cluster in terms of challenging the stated protection objectives. Another input on the choice of scenarios that should be further analyzed and quantified can be given by listing the scenarios and determine how many assets each scenario threatens. Scenarios that pose a threat to several assets may be more critical to analyze.

Quantification of scenarios

The scenarios chosen for further analysis, in the previous step, need to be fully quantified, e.g. heat release rate (HRR), soot production etc. need to be specified. The process is described in Figure 3 below and is based on the method presented in Staffansson (2010) and further details on how to quantify e.g. HRR can be found in this literature. However factors affecting the scenario need to be defined and should at least include building, occupants and fire characteristics (SFPE 2007). In large these factors have already been determined while using the asset evaluation form presented in Table 5. Occupant characteristics may not have been determined, however if life safety is to be evaluated this needs to be done.

The quantification of fire scenarios, and determination if the protection objectives are met or not, is done in three steps. The three steps are illustrated in Figure 3 and the complexity of the analysis increases with each step, if it is necessary to continue to the next step. The idea is to do an initial screening on whether a detailed analysis is needed or not and still to some extent include the probability of failure of active fire protection systems as this has been identified as important when considering antagonistic threats. Further, the consequences can be determined for the specific scenario. The three steps are scenario based and treat uncertainties on Level 2 according to Paté-Cornell (1996), i.e. by choosing conservative values. If the design cannot be deemed to be acceptable after these three steps a QRA is recommended. QRA is outside the scope of this article and therefore not discussed further.

Scenarios incorporating antagonistic events have a potential to be more severe, this has been discussed above, e.g. flammable liquids present the potential of a fast developing fire (Richards 2008) and of course an explosion can create a significant damage. As discussed in the Literature review section there is a potential that

fire protection systems, both active (sprinkler, self closing doors etc.) and passive (fire barriers, physical separation etc.) are inadequate or damaged if the initiating event is severe, e.g. an explosion. To handle this within the method a question is always asked whether the passive/active fire protection is still operational after the initiating event, see Figure 3. These factors need to be included in the evaluation and should have its starting point in the assets as well as the exposure analysis and be qualitatively described in the previous step. In this step the basis of quantifying this scenario need to be developed, e.g. what kind of flammable liquid, amount etc., i.e. input needed in order to calculate the scenario.

Worst credible consequence (WCC)

The worst credible consequence (WCC) scenario is the first step in evaluating a scenario. It considers the scenario when all active fire protection systems are impaired. Active fire protection systems can be active fire suppression systems such as sprinklers, evacuation alarm, self closing doors activated by smoke detection etc. This scenario has similarities with maximum foreseeable loss or estimated maximum loss within the insurance industry. However, it should be pointed out that different insurance companies have different definitions, some assumes that fire walls are not breached and others require a special fire wall or physical separation if it should be assumed to limit the fire damage. The benefit of analyzing this scenario is that it provides information to whether active fire protection systems are needed to meet the protection objectives. If the protection objectives are met without any active fire protection system there is no need to conduct any further analysis of the scenario. Further, if protection objectives are met, there is no need to analyze impairment of the fire protection systems due to any reason (as part of antagonistic attack or common failures), hence there is no need to analyze the availability and reliability of the systems.

Depending on the initiating event impairment of passive fire protection may also occur, especially when considering antagonistic attacks, e.g. fire walls may be damaged, structural fire protection may be damaged or evacuation routes may be blocked as recognized in the literature review. This is considered in the second box in Figure 3.

All active systems working (AASW)

The next step in the method is to evaluate the scenario with all active fire protection systems operational, i.e. the active systems are available at the time when the initiating event occurs and continue to operate during the fire scenario, if the system is not physically damaged by the initiating event. For a system to be available during the scenario means e.g. that for a sprinkler system the pump is in automatic and all appropriate valves are opened etc. However, the initiating event might still cause

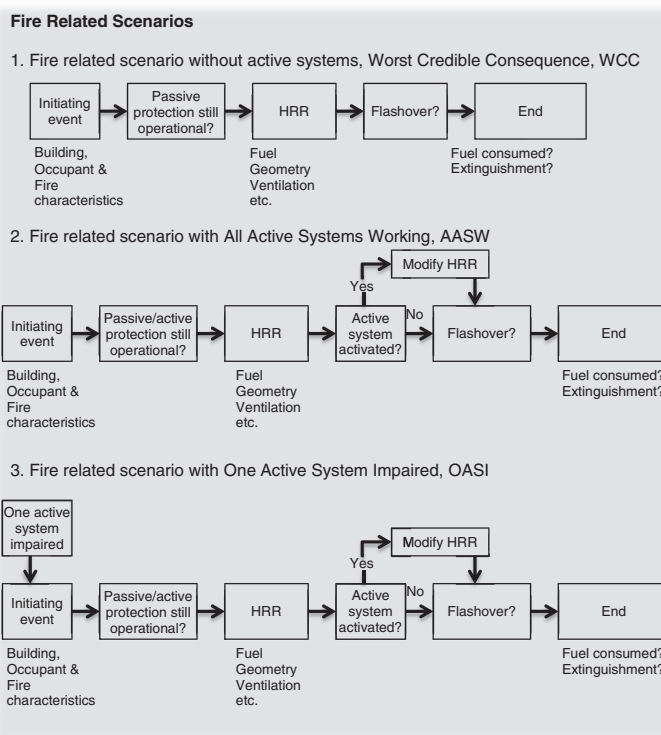


Figure 3 Fire related scenario development.

the active protection system to fail, one example would be an explosion tearing down a wall bringing sprinkler pipes down rendering the system ineffective (Nilsson et al. 2012), this is what is checked in the second box in Figure 3. Another example is that the systems are bypassed as a part of an antagonistic attack or a wall is damaged to a room protected with hypoxic-airventing as is suitable for some areas in multifunctional buildings, e.g. electrical rooms (Nilsson and van Hees 2013). Such considerations are all addressed in the second box in Figure 3.

If the fire safety systems are not impaired due to the initiating event, there is still the question whether the system effectively will control or protect against the event. How different active systems affect the fire development in a building with an occupancy it is designed for and with a general fire initiation can be found in the literature (Nystedt 2011, Madrzykowski and Vettori 1992, Evans 1993, Swedish National Board of Housing, Building and Planning 2011b). However the effectiveness needs to be determined against the stated protection

objectives and the anticipated fire hazard the system was designed for. If the fire hazard for some reason is higher than what was designed for, e.g. if multiple fires are started as part of an antagonistic event (Richards 2008) or if the protection objective concerns e.g. contamination, then the suppression system might be ineffective (Nilsson et al. 2012). A fire in a computer room for example may be adequately controlled by a sprinkler system to not spread further within the building but the protection objective for functional performance of the computer system may be exceeded due to smoke or water damage.

During the interviews a need was identified for flexibility to include how action plans, emergency management plans, fire rescue service etc. affect the scenario. As pointed out by Lundin (2001) the effect of human interaction during an event is very hard to predict and model, therefore caution need to be applied. However there is a flexibility to include any damage mitigating actions into the method. This can be applied for example, either by modifying the design fire if there are

appropriate means for manual fire fighting or including effects of the emergency management plans on evacuation behavior due to assistance from personnel.

If the protection objectives are not met when all active systems are working mitigating measures or adjustment of the protection objectives are needed. This is due to the fact that the protection objectives are not met in the most beneficial circumstances for the scenario, and will therefore never be met unless something is changed. One could come to the conclusion that other mitigating measures are needed, the protection objective was set to high or the scenario considered was too severe, whatever the cause the process needs to be reevaluated with a change in some of these factors.

One active system impaired (OASI)

If the protection objectives are met for the scenario when all active systems are working, there is still a need to analyze the robustness of the fire safety, i.e. how dependent is the fulfillment of the protection objectives upon one single fire safety system. The need for robustness of the fire safety, i.e. to not be fully dependent upon one system in order to achieve the protection objectives for a scenario, has been recognized by e.g. Lundin (2005) the Swedish (Swedish National Board of Housing, Building and Planning 2011b) and the New Zealand (Department of Building and Housing 2012) building code as well as in design fire scenario 8 in NFPA 101 (NFPA 2012).

In Figure 3 the process for developing the scenario with one active system impaired is described. The scenario starts with one active system being impaired, e.g. the sprinkler system is not considered to affect the scenario. In this case the active system is assumed to be impaired before the initiating event occurs (the first box of Figure 3) due to some general failure mode of the active system. A general failure mode could e.g. be that the pump has been inadvertently turned off, a valve is closed by accident or the batteries for starting the engine are empty. This is assumed in order to account for the inherent probability of failure of active fire protection systems. However, there is still the question of whether the initiating event damages and impairs any other (excluding the already assumed impaired system) active or passive fire protection system and this is addressed in the third box of Figure 3.

In the third box of Figure 3 a check is done as to whether the other active systems and passive systems are still operational and that they have not been damaged or disabled as part of the scenario. As an example, in the first box the sprinkler system is assumed to be impaired due to empty starting batteries. An initiating event occurs which is an antagonistic attack including an explosion, in the third box a check is done and it is concluded that the explosion damaged the control panel for the evacuation alarm. Hence the scenario now includes two impaired

active systems, the sprinkler system due to empty batteries and the evacuation alarm that was damaged by the initiating explosion. The difference from the AASW scenario is that the inherent failure probability of active systems is accounted for in this scenario by assuming impairment to the sprinkler system before and during the scenario.

If the protection objective is met for the scenario the process is repeated but with another active system impaired in the first box in Figure 3, e.g. the smoke management system (only one active system is assumed to be impaired due to inherent failure modes at each scenario, i.e. in the second case for the example above the sprinkler system is assumed to be working again). This is then repeated so that all active systems have been impaired once in the first box in Figure 3.

If the protection objective is not met for any of the scenarios, with one active system impaired, one needs to determine whether the likelihood of failure for the system is acceptable or not. If the likelihood of failure is acceptable, then continued evaluation is conducted testing with other active systems impaired. If the likelihood of failure is unacceptable then mitigating measures, change of scenario or altering protection objective needs to be considered (the same that is done when protection objectives are not met for AASW, see above). Generally, there is an acceptable probability of failure for an active system and a higher consequence is probably acceptable in this case meaning that it may be acceptable that the first stated protection objective is not met and a larger damage is accepted when an active system fails.

When all active systems have been assumed to be impaired in the first box in Figure 3 and all these variations of the scenario have been evaluated the availability and reliability of the least reliable active system need to be analyzed. The likelihood of failure for that system needs to be determined and if the probability of failure for the least reliable active system can be accepted, the situation is acceptable, since this is the highest probability for failure. If the determined probability is too high the situation may be unacceptable, however this is unknown since the protection objective is either met with the system failing or the probability was earlier determined to be acceptable. Hence failure of another system at the same time as the first system is needed in order for the situation to be unacceptable. At this stage the evaluation process is starting to become more complex and it is recommended to perform a full QRA.

An availability and reliability analysis of active protection systems is needed to assess the likelihood of failure of the system. Availability refers to if the system is in operational mode when the fire starts (compare to the first box in Figure 3), e.g. the system is unavailable if it has inadvertently been left out of service after maintenance (SEPE 2007). The system reliability on the other hand considers that

Table 9 Attributes considered

Attribute	Applicability to evaluation of active protection systems
Function	This is to determine if the protection is designed according to the relevant hazard and if it will perform as designed
Human action/performance	If human action is needed in order for the system to work there is an uncertainty added due to human error.
Complexity	A complex fire protection system increases the probability of error, e.g. if many support systems are needed for the system to perform as intended, (detector activating, fan for smoke exhaust, inlet air needed at the same time). Another issue adding to the complexity is the probability of common cause failures, e.g. if power is lost then the sprinkler system as well as the evacuation alarm is lost. This is addressed in Table 6 by identifying common support systems for different protection systems.
Reliability	This is the probability that the system will fulfill its purpose on demand. This is connected to both the function (whether it is properly designed) and issues like maintenance. Evaluation of e.g. maintenance needs to be done and a starting point should be to fulfill relevant standards on maintenance for the considered system.
Vulnerability	This attribute describes the conditions for the survival of the system when exposed to internal and external stress. This is linked to how the system is isolated from the actual event, is it in a separate building etc.

the system does not always perform as designed or intended, e.g. if a component is failing during operation or if the fire hazard for some reason is greater than the design of the system, say an antagonistic attack. Another issue is whether the system is affected by the initiating event or not, as asked in Figure 3, this has mainly to do with if the system is isolated from the event, e.g. a separate pump house for the sprinkler pumps and risers presents a fairly isolated system compared to a sprinkler room within the building the system is protecting. In order to facilitate evaluation of an active system for the purpose of this method Table 6 has been developed.

The categories in Table 6 have been developed based on the discussion by Lundin (2005) regarding attributes for defining fire safety. For the purpose of the evaluation of active systems the relevant attributes are: function; human action/performance; complexity; reliability; and vulnerability, these are described in Table 9. The attributes are discussed in detail in Lundin (2005) and are based on the work done by Meister (1991).

By using Table 6 and addressing the attributes an assessment can be made of the availability and reliability of fire safety systems and help in determining likelihood of failure in order to assess if the likelihood is acceptable or not.

Once the last box in Figure 2 has been evaluated the analysis for a scenario is either finished or it has been determined that a QRA is needed for the scenario. The process is then repeated for all scenarios chosen in the step "Selection of scenarios to analyze". Once this has been completed the analysis of the building is done.

Future work

The method is still in the developing phase and the method has not been fully tested in practice yet. This is a weakness and the next step is to apply the method on an actual building to test and determine its strengths and weaknesses. One identified focus area to be evaluated when applying the method is how well domino effects are captured within the method or if refinement is needed in

this aspect. Such effects might include multiple events such as a coordinated attack with for example a fire and an explosion at different locations but as part of the same attack.

Conclusion

An engineering method for selection and evaluation of fire related scenarios in multifunctional buildings, considering antagonistic attacks, has been developed. The method is based on identified (through literature review and interviews) important aspects and problems, specific for antagonistic threats and multifunctional buildings. The specific identified problems that are taken into account are summarized in Table 1.

The strength of the method is that there is now a process available for a systematic evaluation considering new aspects of fire safety. Further the method is based on sound principles and there is a clear connection to both fire safety engineering in the normal (accidental) case and principles for protection against antagonistic events. The method is also compatible with standards on emergency management and business continuity planning and can e.g. be used in the risk assessment phase of such standards such as NFPA 1600 (NFPA 2013). Finally the method treats uncertainties for the scenarios in a scientifically recognized way, i.e. by choosing conservative values according to the level 2 approach.

**Appendix
Terminology**

Active fire protection systems, AS: Fire protection system that needs to activate as a response to fire, e.g. sprinkler system, evacuation alarm, self closing doors activated by smoke detector etc.

Antagonistic attack: Manmade attack, against a specific target to which the aggressor bear hostility, with the intention to cause harm as a consequence of the attack, e.g. terrorist attack such as an explosion or arson fire.

Security: Security is protection aimed towards limiting access such as perimeter fencing, CCTV, watch service, locking etc.

Multifunctional building: One or several connected buildings hosting several functions (e.g. societal) or occupancies (e.g. office, restaurant) where the facility and its functions is one integrated whole. The definition also includes underground facilities.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

MN carried out the problem identification (i.e. the literature review and the interviews), developed the method for selection and evaluation of fire related scenarios, drafted and completed the manuscript. HF suggested improvements to the method, helped drafting and critically revising the manuscript. PVH provided input during the development of the method and critically reviewed the manuscript. All authors read and approved the final manuscript.

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Paper II

Advantages and challenges with using hypoxic air venting as fire protection

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ABSTRACT

The use of hypoxic air venting system as fire protection is increasing and is sometimes used to replace traditional extinguishing systems. An oxygen level of 15% is generally used because a lower concentration could pose serious health risks. On the request of the Swedish Radiation Safety Authority, a literature review was conducted to determine advantages and challenges with the system and further research needs. The main advantages with a reduced oxygen environment are the reduced probability of ignition and lowered heat release rate. However, at 15% oxygen level, risk for fire still exists, and the system cannot be seen as an alternative to extinguishing systems. Reduced oxygen environment also results in higher production rates of soot and smoke, and there is limited knowledge regarding the effect of fuel configuration and fire behavior of products. In addition, a first evaluation of the test method specified in the hypoxic air venting standards was carried out through testing. The testing showed that the particleboard passed the test criteria at normal atmosphere even though it is commonly known that a particleboard burns in normal air. It is concluded that the test method has deficiencies, and there is clearly a need for development of the test method to guarantee safety levels. © 2013 The Authors. *Fire and Materials* published by John Wiley & Sons, Ltd.

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KEY WORDS: hypoxic air venting; reduced oxygen; burning behavior; ignition; heat release rate; limiting oxygen concentration

1. INTRODUCTION

Over the last years, the use of hypoxic air venting systems has increased and been proposed as an alternative to traditional extinguishment systems. Hypoxic air systems have been introduced, for example, in storage rooms of museums, computer rooms, and warehouses [1], where even a small fire could cause large damage before the fire is extinguished. The systems are now being considered in other industries as well, for example, the system is planned to be installed in electrical appliance rooms in one of the Swedish nuclear power plants. Further, in multifunctional buildings, electrical appliance rooms and computer rooms have been found to be essential to societal important functions [2,3]. These occupancies are very sensitive to fire and products of combustion, and the main purpose of hypoxic air venting is to prevent ignition by a permanent reduced oxygen environment, hence, potentially offering a suitable protection option. The level of protection, however, is dependent on the oxygen level, which in reality has to be balanced against the possible negative health effects of working or being present in a reduced oxygen atmosphere without personal

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protective equipment [4]. Usually, a design oxygen concentration level of around 15% is used [1,4,5]; hence, the achieved oxygen level is generally higher than the limiting oxygen concentration, for example, refer to Xin and Khan [6], and therefore, a potential for fire occurring and developing still exists.

2. PURPOSE, GOAL, AND METHOD

On request of the Swedish Radiation Safety Authority, a literature review was conducted. The purpose of the literature review was to determine the current state of the art regarding hypoxic air venting as fire protection and to increase the knowledge about using the system as fire protection in electrical appliance rooms. The goal was to present advantages and disadvantages with the system and to identify areas where further research is needed. A number of specific questions were formulated to achieve the purpose and goal of the literature review:

- How is the risk for fire affected by a reduction of the oxygen concentration to 15% ,and how is the potential for ignition affected by a reduction in oxygen concentration?
- How is the fire development (heat release rate (HRR), soot production, and flame speed) affected by a reduction in oxygen level?
- How does a reduced oxygen environment affect a smoldering fire?
- What are the advantages and disadvantages with different test methods, and how well do they account for different configurations of fuel?
- How is the information on reliability and effectiveness of a hypoxic air venting system? Especially considering uneven oxygen levels, experiences from fires, and the need for redundant systems.
- What are the health risks associated with a reduced oxygen environment?
- Are there any specific considerations (temperature, combustible material, functionality of equipment, etc.) needed with respect to the occupancy, that is, electrical appliance rooms?

For the literature review, two scientific databases were used, Web of Science and Google Scholar. Searches were made with the keywords 'fire', 'burning behavior' in combination with 'hypoxic air', 'reduced oxygen', 'hypoxic', and 'hypoxia'. The searches in the two scientific databases yielded 27 articles considered to be relevant to obtain the purpose and goal of the literature review, that is, focusing on hypoxic air venting systems for fire protection. Many of the articles that came up in the searches discussed medical aspects of hypoxic air. Because of the limited amount of relevant peer-reviewed articles, the search engine 'Google search' was used to find more articles on the subject. Through these searches and through the reference lists in the articles, a base with relevant literature was established through which the questions could be answered. In addition, standardization web pages were used to find any standards for hypoxic air venting systems. The relevant literature has been cited in the reference list of this paper.

In addition to the literature review, the test method, specified in hypoxic air standards [5,7], to determine the required oxygen level in a protected space was evaluated through testing. This testing was performed in a normal atmosphere, and the material used was a regular particleboard. The purpose of the testing was to determine if the test method results in an adequate safety level based upon the known fact that regular particleboard burns in normal atmosphere.

3. RESULTS AND DISCUSSION

The results are presented and discussed in the succeeding texts; each subsection addresses the questions previously mentioned. The last question in the aforementioned bullet list is, however, discussed under Section 4.

3.1. The risk for fire at 15% oxygen concentration and the potential for ignition

According to PAS 95:2011 [7] and VdS 3527en [5], different oxygen concentrations should be used depending on the material subject to burning (refer to Section 3.4 for description of the tests). In

Table I, different values of oxygen concentrations, below which burning cannot take place in the test application, is shown. It can be seen that the values differ quite widely; this is dependent upon the test procedure. The limiting oxygen concentration was obtained by Xin and Khan [8] in the Fire Propagation Apparatus (FPA) with an external heat flux of 30 kW/m^2 for solid fuels and with no external heat flux for the liquids. In the table, values for the oxygen index obtained according to ASTM 2863/ISO 4589-2, and values from NFPA 69 [9] are given. It should be noted that NFPA 69 covers explosion prevention systems; hence, values for solids are obtained for dusts resulting in low values, which are not appropriate for the hypoxic air application.

When staff occupies the protected area occasionally or normally, the used oxygen concentration is generally 15–16%, which is referred to as preventive mode [1]. The 15% oxygen concentration was also the preferred concentration in the electrical appliances rooms in the Swedish nuclear power plants. When comparing this concentration to the concentrations in Table I, it can be seen that according to the VdS standard, a 15% oxygen concentration can generally be used to protect an area with plastic materials as the combustible load, which is applicable to electrical appliances rooms. However, the values provided by Xin and Khan [8] shows significantly lower concentrations because of the applied external heat flux, which is not present in the test method in VdS 3527en. Xin and Khan [8] showed that the oxygen concentration needed to extinguish a fire is highly dependent upon the external radiation level; however, below a certain oxygen level, extinguishment will occur even with an infinite external radiation. Delichatsios [10] also showed that with an external heat flux plywood can be ignited at 15% oxygen concentration, at 13% ignition was not possible. An external heat flux could be obtained, for example, if an arson fire is expected where flammable liquids are used as an ignition source or if materials are reradiating towards each other as in the parallel panel test [8]. The test method, specific for hypoxic air venting systems, to determine the required oxygen concentration for protection with hypoxic air venting is described in VdS 3527en [5] and Pas 95:2011 [7]. This test method challenges the material more than the oxygen index according to ASTM 2863/ISO 4589-2, but there is still a risk for fire if the ignition source is more challenging than the one used in the test method. Stating that a 15% oxygen concentration fully protects against fire in plastic materials is therefore not completely true, it is only under those conditions used during the test where the 15% was obtained that fire is prevented. Polyvinyl chloride (PVC), for example, needs 44.9% oxygen to burn on the basis of the ASTM 2863/ISO 4589-2 test, and there are several examples where PVC has burnt in normal air. The oxygen index method is therefore questionable for purposes other than ranking materials, and the obtained result is, for example, dependent upon the material, sample type, and ignition procedure. Another example is the parallel panel test where PMMA is extinguished first at 14.7% oxygen concentration with no external radiation present [8].

The ignition energy, needed to ignite dusts, as a function of oxygen concentration has been studied by, for example, Schwenzfeuer *et al.* [12] and Ackroyd *et al.* [13]. The results show that the ignition energy needed increases with a reduction in oxygen level; measurements have been made with oxygen concentrations as low as 6% [13]. A schematic is shown in Figure 1, which also shows two

Table I. Oxygen concentrations below which burning cannot occur in the test.

Substance	VdS ignition threshold (vol%) (design concentration vol%) [5]	Limiting oxygen concentration (vol%) [8]	Oxygen index ASTM 2863/ISO 4589-2 (vol%) [11]	NFPA 69 (vol%) [9]
Methanol	11.0 (10.0)	11.64	—	10
Ethanol	12.8 (11.8)	12.40	—	10.5
PMMA	15.9 (14.9)	10.48	17.8	
Polyethylene	HD: 16.0 (15.0) LD: 15.9 (14.9)	LD: 11.39	HD: 16.9	h.p.: 10
Corrugated Board	15.0 (14.0)	12.86	—	—
Polyvinyl chloride	16.9 (15.9)	—	44.9	—

HD, high density; LD, low density

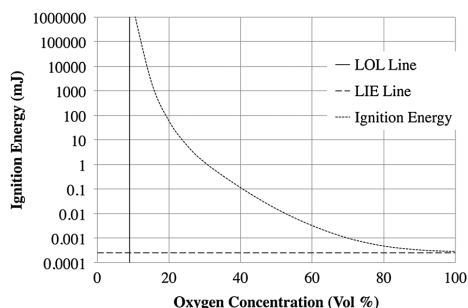


Figure 1. Schematic of relationship between oxygen concentration and MIE, reproduced from Schwenzfeuer *et al.* [12].

asymptotes [12]. One asymptote, lowest ignition energy (LIE) line, represents the energy below which no ignition is possible even in 100% oxygen. The other asymptote, lower oxygen limit (LOL) line, represents the oxygen concentration below which no ignition is possible even with an unrealistic high ignition source. The same trends have been shown for gases (see e.g., Blanc *et al.* [14] and Glor [15]). Because the ignition energy needed increases with a reduction in oxygen concentration, the probability for fire occurring is lowered with a reduction in oxygen concentration; it can be compared with removing some of the ignition sources. Little information has been found on the minimum ignition energy needed to ignite solid materials in reduced oxygen atmosphere, but the same trend is expected for solids; however, such values would be beneficial for risk assessment purposes.

Babrauskas [16] discussed the oxygen concentration's effect on ignition times. He stated that there are studies that show a dependence upon oxygen concentration where a decrease in oxygen concentration leads to an increased ignition time [16]. However, the reported tests were either performed with fuels where an oxidizer was mixed in the fuel or autoignition was tested [16]. Babrauskas also reported results from the tests in Mullholland *et al.* [17] (PMMA, ABS, PE, and Douglas Fir); with external radiant heat flux and piloted ignition, it is shown that the oxygen concentration had no bearing on the time to ignition down to a 14% oxygen level [16]. Delichatsios [10] in his experiments with wood concluded that a reduced oxygen atmosphere does not affect the time to ignition as long as the fuel mass flux is nearly independent of oxygen concentration and suggests that ignition times are weakly dependent upon reduced oxygen concentrations, that is, when the irradiance level is low (larger dependence upon oxygen concentration was shown for an irradiance of 50 kW/m² in Delichatsios tests) [10]. Hsieh and Beeson [18] also showed that for flame retardant epoxy composites and two out of three tested phenolic composites, the time to ignition is relatively constant between 30% and 18% oxygen concentration, but for phenolic graphite, the time to ignition increases with a decrease in oxygen. Chiti *et al.* [19] reported that the ignition times are increased with a decrease in oxygen concentration. This is consistent with Mikkola [20] who reported an increase in ignition time of about 25% for a variety of solid fuels. However, Mikkola [20] used an external radiation level of 50 kW/m², the same level at which Delichatsios [10] also saw a weak dependence. It appears that the time to ignition could be increased with a reduction in oxygen, and this seem to be dependent upon fuel and external radiation level; however, the results are not completely conclusive.

In electrical appliances rooms, there is a potential for higher temperature than ordinary temperature, especially in electrical cabinets. In addition, extremely high temperatures can arise if a high-energy electrical discharge because of an electrical fault occurs. The flammability limits are affected by temperature and is extended with an increase in temperature as shown in Figure 2 [21]. This means that the oxygen limit is reduced when the temperature increases [22]. Such a situation could move the fuel into the flammable limit even with a lower than normal oxygen concentration.

In conclusion, a reduction of the oxygen level to 15% does not achieve conditions where a fire cannot occur or is extinguished. However, it reduces the probability of a fire occurring by increasing

HYPOXIC AIR VENTING AS FIRE PROTECTION

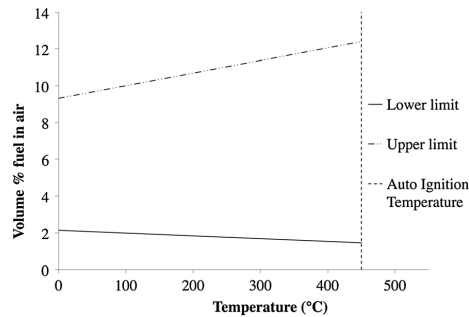


Figure 2. Effect of temperature on flammability limits for propane, reproduced from Drysdale [21].

the ignition energy needed, and there are also indications of increased ignition times. To fully protect against a fire, the oxygen level needs to be lowered even more, to the inerting point of the fuel also known as the limit line [22]. As a comparison, the FM Global Data Sheet on clean agent extinguishing systems recommends a 12–14% design concentration for typical electrical equipment where no ordinary combustibles are present [23]. In addition, different test methods provide different oxygen concentrations at which burning cannot take place for the same material, and these materials are only generic (PVC, PE, etc.) and not for specific components. The test method in hypoxic air venting standards [5,7] appear to obtain concentrations where burning is still possible under certain conditions. The effect of a rise in temperature on flammability limits also needs to be accounted for.

3.2. The oxygen concentration's effect on fire development

If the oxygen concentration is higher than the inerting point, a risk for fire still exists. If a fire occurs in a reduced oxygen atmosphere, the fire will become ventilation controlled or smolder. Under such conditions, for example, more soot, carbon monoxide, and other hydrocarbons will be produced [24]; the effect is illustrated in Figure 3. The increased production of these products could increase the damage to sensitive components, the need for clean up, and some products also have a negative effect on life safety. However, the knowledge on production of other gases such as corrosive and irritating is limited. Tewarson *et al.* [25], however, showed that there is an increase in other gases than soot, CO, CO₂, and hydrocarbons when the oxygen concentration decreases, examples are HCHO and HCN.

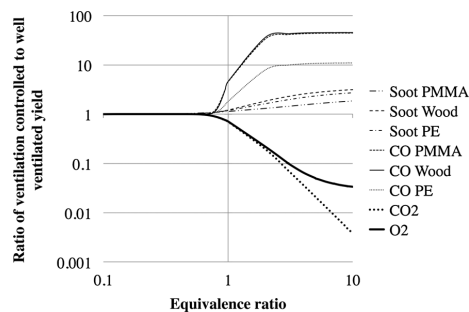


Figure 3. Effect of underventilation on yields for carbon monoxide, carbon dioxide, oxygen, and soot based on correlations by Tewarson [24].

Xin and Khan [8] conducted one parallel panel test in the FPA using PMMA with 21% oxygen concentration until the HRR reached steady state (after that, the oxygen concentration was reduced to obtain extinction). Xin and Khan [8] also conducted one parallel panel test using PMMA and a constant oxygen concentration of 15%. When comparing the graphs, that is, the slope of the HRR curve, from the two tests, it can be concluded that the test with 15% oxygen concentration had a lower fire growth rate than the test with 21% oxygen concentration. This indicates that a decrease in oxygen concentration results in a decrease in fire growth rate for the two tested oxygen levels. Rasbash and Langford [26] showed the same trend where the flame speed for wood in a vertical configuration is reduced from 2.75 to 1.82 cm/s when the oxygen concentration is reduced from 21% to 13.7%. Loh [27] studied flame spread of PMMA and filter paper in concurrent flow and concluded that the flame spread was reduced with a decrease in oxygen concentration; oxygen concentrations from 100% to 18% were tested. From the graphs in Loh [27], it can be seen that the decrease in flame spread for PMMA is marginal when reducing the oxygen concentration from 21% to 18%; the thin filter paper was not tested below 21% oxygen concentration. Fernandez-Pello *et al.* [28] studied PMMA and thin paper sheets as well, but in opposed flow, he also concluded that the flame spread decreased with a decrease in oxygen concentration; oxygen concentrations from 100% down to 19% were used. Tewarson and Ogden [29] also showed a decrease in flame spread rate for PMMA with a decrease in oxygen; oxygen concentrations down to 16% were used. Carhart [30] provides a graph where he showed an increase in burning rate (m/s) with an increase in oxygen concentration for thin paper, but the study seems to be for elevated oxygen concentration only. Tewarson and Khan [31] showed an increase in flame propagation rate with an increase in oxygen concentrations; however, 21–45% oxygen concentration was used. Rasbash and Langford [26] also discussed that the effect on flame speed with oxygen reduction is greater for horizontal configurations. They attribute this to the mechanism of heat transfer, that is, for horizontal configurations, the radiation is dominant and where convective heat transfer is substantial, such as for vertical configurations, the effect of oxygen reduction is less prominent [26]. This is consistent with observations by Tewarson [32] that radiation to the fuel surface (horizontal configuration) decreases significantly with reduction in oxygen concentration.

A comparison of the results from the two parallel panel tests conducted by Xin and Khan [8] (also discussed previously) indicated that the peak HRR and the mass loss rate (MLR) decrease with reduced oxygen concentrations for the tested levels; Xin and Khan also pointed this out. In a horizontal test with PMMA with an external heat flux of 30 kW/m², Xin and Khan [8] showed a reduction in the HRR by 15–20% when the oxygen concentration is reduced from 21% to 15% compared at the same time into the test. However their horizontal experiment also showed that the peak chemical HRR remained the same but with a time delay [8]. Xin and Khan [8] also stated that the difference in fire growth rate is negligible for the horizontal test. Experiments with horizontal samples were also carried out by Marquis *et al.* [33] for PMMA with an external heat flux of 50 kW/m² in a modified cone calorimeter (CC) to examine the effect of the design of the controlled atmosphere CC (CACC). Marquis *et al.* [33] showed that there is approximately a 20% reduction in HRR per unit area, and also, the MLR is reduced when the oxygen concentration is decreased from 21% to 15%. They do not discuss fire growth, but by the slope of the HRR curve, it can be seen that the slope is about the same for oxygen concentrations of 21–12.5% [33]. Mikkola [20] showed a small decrease in HRR for horizontal samples for a variety of fuels with a 50 kW/m² external heat flux; the exception is PVC where the HRR was reduced by 60% when the oxygen concentration was reduced from 21% to 15%. Tewarson *et al.* [32] and Mullholland *et al.* [17] showed a decrease in MLR, Mullholland *et al.* [17] also showed a decrease in HRR (moderate for wood and greater for plastics) and that the effective heat of combustion was independent of oxygen concentration, that is, the HRR mirrored the MLR [16]. However, the experiments by Mullholland *et al.* [17] used a lowest oxygen concentration of between 13.7% and 12.4% (refer to Section 3.4 for further discussion). Yao *et al.* [34] conducted tests burning cardboard boxes with no external heat flux at high altitude (3650 m, corresponding to approximately 13.5% oxygen concentration (partial pressure) at sea level [35]) and at sea level (50 m). Similar to other references, Yao *et al.* [34] showed a decrease in HRR and MLR when the oxygen concentration is decreased (oxygen partial pressure). However, Yao *et al.* [34] showed that the heat of combustion is approximately 40% lower

at the higher altitude, which contradict the results by Mullholland *et al.* [17]. From the tests by Xin and Khan [8] (the two parallel panel tests previously discussed), the graphs indicate that the heat of combustion is independent of the oxygen concentration. The reason for the deviating results could be because of the total static pressure is lower at high altitudes and that Yao *et al.* [34] did not use external heat flux to pyrolyze the material, whereas oxygen concentration has been shown to affect the pyrolysis [36] (also, see discussion under smoldering combustion). It could also be because of the way of calculating the total HRR. However, the reason for the deviating results cannot be fully determined, and the affecting mechanism of low oxygen concentration on solid pyrolysis is complex and needs further research [34]. Peatross and Beyler [37] put forward a correlation where the MLR is dependent upon the oxygen concentration; this correlation agrees well with the test results for PMMA from Tewarson [32], and the reduction in MLR will also result in a reduction in HRR at moderately low oxygen concentrations. The mechanisms of heat transfer to the fuel surface reducing the MLR, HRR, and flame speed in a reduced oxygen atmosphere in the aforementioned applications is thought to be mainly two parameters. First, the flame temperature is decreased as an effect of the decrease in oxygen but also as an effect of the increased thermal capacity by nitrogen [38]. Second, because the combustion takes place further away from the fuel surface to encounter oxygen, the view factor is reduced as well. This was also observed, for example, during the experiments conducted by Marquis *et al.* [33] where combustion was observed further away from the fuel surface, and no change on MLR was observed. This is also consistent with the observation made by Tewarson and Steciak [39] where they show an increase in flame height with a decrease in oxygen concentration. The results by Xin and Khan [8] where the peak chemical HRR does not change with oxygen concentration for the horizontal configuration is deviating from the other results. It would be beneficial to investigate the reason for this deviation.

There appears to be a reduction in HRR when the oxygen concentration is reduced; however, it seems to be very dependent upon the fuel. The reduction in HRR would result in less radiation also between fuel packages, which would reduce fire spread between fuel packages. Further, there are indications that the flame spread decreases with a reduction in oxygen. Babrauskas [16] suggested that for lower oxygen concentrations, the dependence of flame spread rate becomes larger and approaches an asymptotic value upon which extinction occur. However, limited tests have been found at low oxygen concentrations, that is, ranging from 18% down to the point of extinction. All these effects would aid in limiting fire damage; however, there is an increased production of gases negative for smoke damage, and the information is limited for production of, for example, corrosive and irritating gases. Further, the underventilated fire could cause conditions where pyrolysis still occurs creating the risk for a backdraft or gas explosion; the probability for this event occurring is most likely low but has not been studied.

3.3. Smoldering combustion and oxygen concentration

Smoldering combustion may still occur even if flaming combustion is not possible, and materials might still smolder at reduced oxygen concentrations because less oxygen is required for a smoldering fire [35]. This process can produce combustible smoke, and if the smoke is ignited, a smoke gas explosion can occur. Berg and Lindgren [35] concluded that if the oxygen concentration is reduced to just a few percent smoldering heat will be significantly reduced. Chiti [4] concluded from his review of the literature that a reduction in oxygen concentration limits the smoldering spread and velocity, but the effect is not as relevant as in flaming fires. He also stated that hypoxic air would not be fire preventing under the circumstances where smoldering can still occur at very low oxygen concentrations [4]. Chaos *et al.* [36] studied pyrolysis of corrugated cardboard in inert and oxidative environments (under non-flaming conditions). They showed that under low incident heat flux (20 kW/m^2) an increase in oxygen concentration resulted in an increase in MLR, that is, pyrolysis rate, this was not evident for higher fluxes (60 and 100 kW/m^2) [36]. This indicates reaction of oxygen with char formed during pyrolysis [36]. The result is consistent with the conclusion made by Yao *et al.* [34] where they state that incomplete paper and cardboard pyrolysis is a result of the pyrolysis is suppressed by low oxygen concentration. Chaos *et al.* [36] also showed that the char oxidation HRR per unit area is reduced with a decrease in oxygen concentration, which is consistent

with Berg and Lindgrens previous statement. However, Chaos *et al.* also showed that the heat released from the char oxidation process is always lower than 15 kW/m^2 in their tests; hence, the contribution is low when considering high heat fluxes, which explains why an increase in MLR was not evident for higher heat fluxes [36]. However, effects on smoldering combustion at reduced oxygen concentrations is fairly uninvestigated, but it is clear that even at low oxygen concentrations, smoldering combustion can still occur.

3.4. Test methods and configuration of fuel

As discussed previously, at 15% oxygen concentration, most materials can still burn under certain circumstances, and it is clear that the, for protection, obtained oxygen concentration is dependent upon test procedure. A generalized test method to determine the required oxygen concentration to prevent fire therefore needs to cover a range of different possible initiating events and scenarios following to be able to state that the obtained oxygen level will prevent fire.

Because a hypoxic air venting system is designed to keep the whole atmosphere at a constant oxygen concentration, it is important that the testing procedures reproduce this condition; hence, it is important that burning takes place within such an atmosphere. Marquis *et al.* [33] investigated the design of the CACC where they varied the way of enclosing the sample and space in which burning takes place. One variation had no enclosure (the same setup as used by Mikkola [20]), one with a quartz chimney (similar to what Xin and Khan [8] used in the FPA) and one with a metal chimney [33]. Marquis *et al.* [33] did not perform tests with a full enclosure to the exhaust hood as Mullholland *et al.* [17] did. The tests by Marquis *et al.* [33] used horizontal samples of PMMA with an external heat flux of 50 kW/m^2 , and the oxygen concentrations used was 21%, 15%, 12.5%, and 10%. From the test results, it can be seen that the MLR is independent upon the design of the enclosure; however, the HRR varies depending on the design [33]. Just as Mullholland *et al.* [17] concluded, it can be seen from the tests performed by Marquis *et al.* [33] that the HRR mirrors the MLR with oxygen concentrations between 21% and 12.5% especially for the unenclosed configuration, when a chimney is used, the peak HRR is somewhat lower; however, given experimental uncertainties, this could not be proven. At 10% oxygen concentration, on the other hand, there is a statistical difference in measured effective heat of combustion and HRR. It is concluded that the design of CACC without direct connection to the exhaust hood and without a chimney seems to be inappropriate to study phenomena in the gas phase under low oxygen concentration [33]. In the tests for 10% oxygen concentration, a peak HRR of approximately 800 kW/m^2 is observed when the chimney is used. Without a chimney, the peak HRR is approximately 180 kW/m^2 , which is explained by dilution to below the lower flammability limit when no chimney is used [33]. The previous texts illustrates the importance of the design of the test apparatus and what conditions are actually tested. The design with a full enclosure to the exhaust hood, as used by Mullholland *et al.* [17], is appealing because there intuitively would be less of a risk for dilution with normal air, and the matter of deciding the length of the chimney so that all burning takes place within the chimney, as pointed out by Marquis *et al.* [33], disappears.

The test procedures specified in VdS 3527en [5] and PAS 95:2011 [7] have the advantage that the test is conducted in a room with reduced oxygen concentration, which is realistic to the real application of hypoxic air venting systems. As ignition source, an acetylene–oxygen torch is used and placed to the test sample for 180 s (also refer to Figure 5 for the test setup), if the sample keeps burning independently for a period of 60 s after the ignition source has been removed the test has failed, and a lower oxygen concentration is needed [5,7]. Use of acetylene as fuel for the ignition source is maybe not so common because of its specific combustion/flammability characteristics. There are small differences in the test procedures, PAS 95:2011 specifies that both a vertical and a horizontal sample should be tested [7], and VdS 3527en specifies that materials shall be tested as unfavorable as possible in terms of orientation [5]. In these proposed tests, there is no external radiation applied as in the CC or FPA tests, that is, the flame need to supply sufficient heat to assist the pyrolysis after the torch has been removed. External radiation in a fire scenario can occur if something else is burning in the room and radiates towards another fuel package, for example, if flammable liquids are used as ignition source. Although both VdS 3527en [5] and PAS 95:2011 [7] point out the

importance of testing both horizontal and vertical arrangements of the fuel, the standards do not consider the possible configuration between fuel packages. If the fuel packages are spaced close together but with flue spaces between them, such as in rack storage, the ignition at the bottom of such a flue with both surfaces burning would cause a radiation exchange between the surfaces. This can be compared with the parallel panel test performed by Xin and Khan [8] where no external radiation was applied, but sustained burning of PMMA was obtained at 14.7% oxygen concentration as compared to the ignition threshold according to VdS 3527en of 15.9% oxygen concentration [5]. Chiti [4] tested cribs made of wood with an acetylene–oxygen torch; however, he applied the torch only for 15 s on the wood cribs. The cribs were placed in a room similar to the one specified in hypoxic air standards [5,7] with a reduced oxygen concentration. At 16% oxygen concentration, there were small flames 2 min after the torch had been removed [4], and therefore, the test criteria in PAS 95:2011 or VdS 3527en would not have been fulfilled. As discussed previously, Rasbash and Langford [26] also showed sustained burning of wood at oxygen concentrations of 13.1%, without external radiation but with a configuration that favors radiation exchange between fuel packages. However, VdS 3527en specifies 17% oxygen concentration as ignition threshold for wood [5] on the basis of the test method in the standard. The reason for this discrepancy is probably because of the configuration of the fuel packages, which in the tests in VdS 3527en and PAS 95:2011 is not considered; hence, the potential for radiation exchange is ignored, and the obtained oxygen concentration in the standards appears to be nonconservative maybe overestimating the performance of the hypoxic air venting system. An even more common configuration might be that of a corner where also radiation exchange between surfaces can take place and more intensive air entrainment.

In addition, the thickness of the sample for testing is specified not to exceed 25 mm in VdS 3527en [5]. The thickness of the material has an impact on the time to ignition where an increased thickness increases the time to ignition. However, when increasing the external radiation, the time to ignition for different thicknesses approaches the same value, and the importance of the thickness of the material reduces when external radiation is applied [35]. Because the application of the torch for ignition in both PAS 95:2011 and VdS 3527en is of limited time, it cannot with certainty be stated that a thickness of 25 mm will not affect the result. If the material used in the real application is thinner than the one tested, the oxygen concentration might not prevent ignition. Application of external radiation will reduce the risk.

It needs to be recognized that if a scenario was to occur that presents a larger initiating event, both in terms of energy in the ignition source or exposure time, than was used in the test to obtain the oxygen concentration, there is a clear possibility that ignition followed by sustained burning could occur. Further, the tested configuration of the fuel packages and orientation of the fuel plays an important role; there are several examples of more challenging scenarios than the ones covered in both PAS 95:2011 and VdS 3527en. External radiation is excluded in the test methods proposed by the standards for hypoxic air venting; external radiation might be one way of challenging the test to cover different configurations of fuel and larger ignition sources. However, it needs to be pointed out that hypoxic air venting systems are not designed to extinguish fires, as is recognized in the standards [5,7], and therefore, the need for applying external radiation might not be entirely relevant. If external radiation is not applied, the configuration of the fuel becomes more important, and there appears to be a need for further development of the test methods for hypoxic air venting systems to cover this aspect and how large an initiating event needs to be.

3.5. Description and results from evaluation of the test method in PAS 95:2011 and VdS 3527en

Testing was performed according to the testing procedure in PAS 95:2011 [7] and VdS 3527en [5]. All tests were performed at normal atmosphere (21% oxygen concentration) to investigate the test conditions.

The flame length in all tests was approximately 0.3 m; it should be noted that it is hard to be exact when adjusting the flame length and the mixture between oxygen and acetylene, and there is no firm description of this in the test method (e.g., equivalence ratio to be used, gas flows, etc.). Mainly, a vertical orientation of the samples was used. All the tests specified in Table II had the sample in a vertical position. All sample sizes measured 0.2 m × 0.2 m, the thickness of the standard

Table II. Vertical tests performed.

Test	Flame (length is 0.3 m)	Distance from outlet to sample (m)	Material	Test criteria (P, passed; F, failed)	Comment
P1	Transition from orange to blue, slightly on orange side	0.2	Standard particleboard	P	No burn through, self-extinguish 13 s after flame removal
V2	Transition from orange to blue, slightly on orange side	0.1	Standard particleboard	P	No burn through, self-extinguish 20 s after flame removal
V4b	Transition from orange to blue, slightly on blue side	0.2	Standard particleboard	F	135 s burn through, no self-extinguishment
V4c	Transition from orange to blue, slightly on blue side	0.2	Standard particleboard	P	140 s burn through, self-extinguish 5 s after flame removal
V5	Transition from orange to blue, slightly on blue side	0.1	Standard particleboard	P	75 s burn through, self-extinguish 5 s after flame removal
V6	Transition from orange to blue, slightly on blue side	0.2	Low density particleboard	F	45 s burn through, no self-extinguishment
V9	Transition from orange to blue, slightly on blue side	0.2	Medium-density fibreboard	P	No burn through, self-extinguish 9 s after flame removal

HYPOXIC AIR VENTING AS FIRE PROTECTION

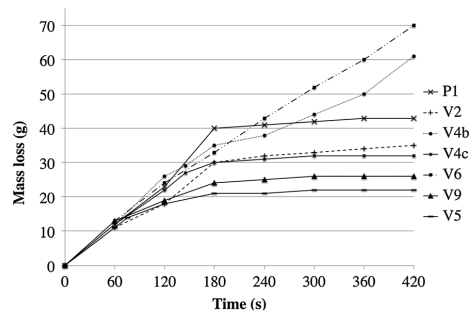


Figure 4. Total mass loss during the different tests.

particleboard was 10.5 mm with a density of 610 kg/m³, the low density particleboard 13.5 mm and 240 kg/m³, and the medium-density fibreboard board 18 mm and 600 kg/m³.

From the tests (refer to Table II), it can be seen that regular particleboard passes the test in many cases at normal atmosphere (21% oxygen concentration) (refer also to Figure 5 in the succeeding texts). This is remarkable because it is common knowledge that this type of material burns and contributes to fire spread in common applications and scenarios at normal atmosphere. Hence, it seems that the test method in PAS 95:2011 and VdS 3527en results in a protection level that might be on the unsafe side, and the test method does not differentiate protection performance sufficiently.

In test V4b, the test did not meet the test criterion, that is, sustained burning was still observed 60 s after the ignition source was removed; this was due to the position of the flame on the test sample. The position was so far down in the corner of the sample that once the flame burned through the sample the edges of the sample caught fire and continued burning during the test. However, the test standards are not clear on exactly where to position the flame, and the results illustrates the importance of flame position. Further, the description of the test procedures and criteria is on approximately one page in VdS 3527en [5] and on approximately two pages in PAS 95:2011 [7]; hence, it is fairly unspecified, and there is limited guidance given presenting the potential for varying interpretations and test procedures between labs. The lack of guidance on gas flows, equivalence ratio, imprecise, etc. can be given as examples.

In test V4c and V5 where burn through occurs and the sample passes the test criteria, it can be seen that the mass loss in principle stops shortly after burn through has occurred see Figure 4. This was observed in the tests as well where the material was virtually not burning after burn through. Oxy-fuel flames in an impinging jet-like configuration are designed to apply heat very locally [40] and at the same time with a very high heat transfer rate [41]. The main heat transfer mechanism for these flame jets is

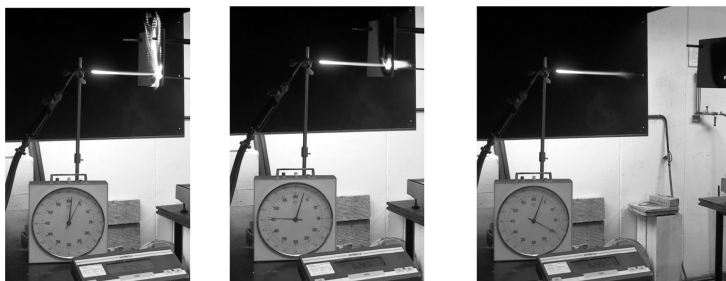


Figure 5. Particleboard tested according to the test method specified in PAS 95:2011 and VdS 3527en at normal atmosphere (21% oxygen).

forced convection, and when the flames are operated with an increased amount of oxygen, a higher flame temperature and burning velocity are achieved, hence, increasing the convective heat transfer [41]. The maximum laminar burning velocity at stoichiometric conditions for an acetylene-air flame is 175 cm/s and for an acetylene-oxygen flame is 1120 cm/s [42]. This velocity can be compared with, for example, methane air at stoichiometric conditions, which has a maximum laminar burning velocity of 40 cm/s, or propane air with 41 cm/s or propane oxygen with 360 cm/s [42]. Wang *et al.* [43] measured the convective heat flux of the Bunsen flame used in the UL94 test concluding that the initial convective heat flux approached 100 kW/m^2 with a convective heat transfer coefficient of around $54.3 \text{ W/m}^2/\text{K}$. The UL94 test uses a premixed methane flame [43]; hence, the heat transfer from the oxygen acetylene torch used in tests showed in Table II has the potential to be even larger because of the higher burning velocity of acetylene oxygen. The high local heat transfer rate to the sample causes pyrolysis of the sample in the tests at a high rate, at the same time the flame has a high speed and momentum; this is thought to be the main reason for the burn through occurring. In addition, the high speed causes other pyrolysis gases to be transported away from the sample causing stretching and blowout of the flames. This is thought to be the reason why burning almost stops after burn through has occurred. An observation that enforces this is that in some test, continued burning was observed on the backside of the sample where the velocity of the acetylene-oxygen flame has a limited impact. On the basis of the previous statements, it is believed that an oxygen acetylene torch is unsuitable as an ignition source in this application because of its high burning velocity (compared with any regular ignition source) causing blowout of flames that could otherwise occur on the sample and causing burn through. Further, the flame presents almost no radiation further enforcing that heat is applied only very locally resulting in an optimistic evaluation of the safety level. It appears that a flame with a lower burning velocity, not as local application, and a sootier flame causing more radiation would be a more appropriate and realistic ignition source.

3.6. Operational functionality and reliability

In general, hypoxic air can be created either by supplying nitrogen to a protected space (e.g., nitrogen generator) or by removing oxygen by an air splitting unit with distribution through the regular ventilation system [1,4]. According to Chiti [4], around 500 installations are known today. Because the number of installations are few, there is limited knowledge regarding the reliability of the system, and no incident has been found where the effectiveness of the system has been challenged. There is a need for more information regarding the reliability and effectiveness of the system, that is, how often is the system unavailable because of impairment, and how well does it work in actual applications if put to the test. If a high protection level is warranted, as in the nuclear industry, it might be necessary to provide redundancy, both for the hypoxic air venting system itself and/or a back-up extinguishing system should a fire occur. Both VdS 3527en [5] and PAS 95:2011 [7] put forward the possible need for redundancy. Berg and Lindgren [35] concluded that because there still is a possibility of a fire occurring if the oxygen level is not reduced to the inerting point there is in general a need for a highly sensitive detection system, manual fire fighting equipment and emergency management procedures.

Jensen *et al.* [1] put forward the challenge of ensuring an even oxygen level, especially if a nitrogen feed system is used for complex geometries. A special case of this could be where there are a lot of concealed spaces present or, for example, enclosed electrical cabinets. Both VdS 3527en [5] and PAS 95:2011 [7] state that the oxygen level should be monitored, but there is little guidance on placement of where measuring points to ensure even oxygen levels and states that it needs to be determined on a case-by-case basis. Another aspect regarding the obtained oxygen level is leakage areas. The leakage area affects the required size of the nitrogen feed [4]; hence, if leakages increases over time, the size might not be sufficient anymore.

However, a hypoxic air system benefits from always being in place and does not need to activate like a regular extinguishing system, reducing the risk of failure to activate. When the system is impaired because of, for example, maintenance measures to limit the risks are needed, as with any other fire protection system.

3.7. Health aspects

Health aspects with respect to a reduction in oxygen in the atmosphere are not the expertise of the authors, and the subject is just discussed briefly in terms of findings in the literature. Further information on the topic can be found in the literature [7,35,44–47].

Table III summarizes different symptoms at different oxygen concentrations; it should be mentioned that depending on the reference, the symptoms at different oxygen concentrations varies a little. However, the most important parameters are the oxygen concentration and duration of exposure but also disease, physical fitness, age, and sex are important parameters [35]. Küpper *et al.* [46] stated that an acute but limited exposure down to 13% oxygen concentration does not cause a health risk if the persons are healthy; hence, this could be interpreted as a limit. Further, they pointed out that employees in a reduced oxygen atmosphere for fire prevention purposes can leave the room immediately if they do not feel well [46]. Bartscher *et al.* [45] stated that people without severe illnesses, a health risk is unlikely at greater than 14.5% oxygen concentration. However, they pointed out that there are large interindividual variations of response to hypoxia to be expected, especially in persons with preexisting diseases and that physical activity may increase the risk to get sick [45]. Angerer and Nowak [44] stated that oxygen reduced to 15% and 13% in normobaric atmospheres is equivalent to 2 700 and 3 850 m altitude, respectively. At these altitudes, persons respond within minutes to hours with increased ventilation rates, increased heart rate, etc. [44]. However, acute mountain sickness occurs frequently at these oxygen partial pressures, but the full syndrome is rare if the exposure is limited to 6 h [44]. Further, they state that at these concentrations mood, cognitive and psychomotor functions may be mildly impaired and that persons suffering from cardiac, pulmonary, or hematological diseases should consult a specialist [44]. Their conclusion is that working in environments with oxygen concentrations down to 13% does not impose a health hazard provided that precautions are observed, comprising medical exams and limited exposure time [44]. Angerer *et al.* [44], however, also pointed out that the evidence is limited particularly with respect to workers performing strenuous tasks or having various diseases.

Berg and Lindgren [35] suggested some possible consequences if fire occurs, for example, they discuss synergic effects, for example, the additional production of CO and low oxygen concentration; however, the effect is hard to determine. PAS 95:2011 [7] points out work environment considerations such as signage and low oxygen alarm. In conclusion, there need to be procedures to ensure people working in reduced oxygen atmospheres are healthy, that a risk assessment is conducted and that, the possibility of human errors because of work in reduced oxygen atmosphere with reduced cognitive performance as a result is considered among other aspects.

4. FURTHER DISCUSSION AND CONCLUSIONS

In general, a reduction of the oxygen concentration to 15% does not eliminate the possibility of a fire occurring, and at this oxygen level, a hypoxic air venting system cannot be seen as a substitute for an extinguishing system. If it should be seen as a substitute, the oxygen concentration needs to be lowered

Table III. Symptoms and exposure times at different oxygen concentrations, reproduced from Chiti [4].

Oxygen at sea level (vol%)	Symptoms	Maximum exposure time
20.9–17	No observed effects	—
17–15	Effects on night vision	—
15–13	Increased breathing and heart rate	—
13–11	Physical and intellectual performance impaired, fatigue, and headache	1 h
11–10	Giddiness and disorientation	20 min
10–8	Unconsciousness and torpor	2 min
5–0	Convulsion, apnea, cardiac standstill, and death	No exposure

even further, and if this is feasible, the system would present a good protection option for electrical appliances rooms and sensitive equipment rooms in multifunctional buildings. Those low oxygen concentrations are often not possible because of health aspects; however, there are benefits with the system even at a 15% oxygen concentration, but there are also challenges and disadvantages; these are summarized in the succeeding texts.

The test method specified in PAS 95:2011 [7] and VdS 3527en [5] seem to be inappropriate, and the oxygen levels obtained through this test method appears to result in an insufficient protection level. This is particularly enforced by the fact that regular particleboard passes the test criteria in normal air.

4.1. *Advantages*

- Lowered probability for ignition and possible increased ignition times. Mikkola [20], for example showed an increase in ignition time of roughly 25% when the oxygen concentration was decreased from 21% to 15% oxygen; however, it differs between materials, and there are other references showing other results. Also, see discussion in the section regarding risk for fire at 15% oxygen concentration.
- Heat release rate is decreased (magnitudes of around 15% decrease in HRR have been shown when reducing the oxygen concentration from 21% to 15%; however, it is also shown to be very material dependent). There are also indications of reduced flame spread/speed; this will also reduce the fire spread between fuel packages. The reduction in flame spread is also supported by the indications of increased ignition times; increased ignition times correlates to a decrease in flame spread.
- The reduced oxygen atmosphere is always operational and activation because of fire is not needed.

4.2. *Challenges/disadvantages*

- The magnitude of the aforementioned advantages seem to be very dependent upon the material present, and the information available is mainly for generic materials; it might be necessary to conduct tests of the specific materials supposed to be present within a protected area. It is not uncommon that components consist of composite materials, and not all materials show the same beneficial effects.
- The configuration of the fuel is of great importance, orientation and distance to other fuel packages presenting the possibility of radiation could increase the risk for ignition and fire spread.
- The production of soot, smoke, and corrosive gases increases, if a fire was to occur creating a potential for larger damage to sensitive equipment. However, this needs to be balanced against the possible decrease in MLR.
- The information on reliability is uncertain, and there might still be a need for redundant systems (to create the reduced oxygen atmosphere, detection, and extinguishing system).
- Better guidance on how to ascertain even oxygen levels, especially with complex geometries.
- Health risks need to be managed considering exposure times, medical exams, strenuous work, increased risk for human error, technical provisions, and information among others.

4.3. *Special considerations for electrical appliances rooms*

In electrical appliances rooms, the primary default could heat the environment; further, there is a possibility for high energetic discharges because of an electrical fault causing high temperatures locally. Elevated temperatures widen the flammability limits, and this needs to be considered when installing a hypoxic air venting system in an electrical appliances room because it will affect the required oxygen level. Further, special attention is needed both for electrical rooms and for computer rooms with respect to the possibility of an increase in production of smoke and corrosive gases if fire occurs. In addition, where a high reliability and redundancy is warranted, such as in the nuclear industry, a reduction of the oxygen concentration to 15% has been shown to be a borderline case where a risk for fire still exists, and there is a possibility that additional fire protection systems are needed to limit the risks. Further, the effects of a reduction in oxygen concentrations are material dependent, and the introduction of a new material in such rooms or transient fire load needs to be controlled.

4.4. *Main concerns regarding the testing method in PAS 95:2011 and VdS 3527en*

One of the main concerns regarding the testing method in PAS 95:2011 and VdS 3527en is that the ignition source is unsuitable. The oxygen acetylene torch has too high burning velocity and results in a very local heat transfer causing burn through of the material and blowout of any diffusion flames on the sample. Further, the flame presents virtually no radiation, and it appears that a sootier flame with a lower burning velocity and not as locally applied would be a more challenging, appropriate, and realistic ignition source. Also, the ignition source is poorly defined, and in general, the test procedure and criteria are imprecise and poorly specified. This could result in a large variety of testing results between individual tests and between test labs.

In addition to the previous statements, the test method does not take fuel configuration and reradiation between fuel packages into account resulting in optimistic oxygen concentrations overestimating the performance of a hypoxic air venting system. There is no external radiation applied; hence, the robustness in the test method is questionable. Applying external radiation would result in less uncertainty regarding the achieved oxygen concentrations because it would account for scenarios such as arson and radiation exchange between fuel packages.

The aforementioned issues are believed to contribute to the result raising the highest concern: regular particleboard, known to burn and contribute to fire spread, passes the test criteria in normal air (21% oxygen concentration). This indicates that the test procedure is inappropriate.

5. FURTHER RESEARCH

On the basis of the literature review, at least four research areas have been identified. These consist of burning behavior, information needed to support risk analysis, burning behavior of more complex materials, and testing methods.

Concerning burning behavior, information is limited on the effect of configuration and orientation of fuel on HRR, fire spread, and ignition thresholds in reduced oxygen atmospheres. Especially most test results found in the review have been for horizontal samples, and there is a special need to determine the effect on HRR for vertical fuel configurations at reduced oxygen concentrations. Furthermore, the production rates of corrosive, irritating, and other gases at reduced oxygen concentrations and choice of the most effective test method to determine this needs to be investigated. There is also little information on the oxygen concentration's effect on smoldering combustion and the affecting mechanism of low oxygen concentration on solid pyrolysis. Finally, flame spread at oxygen concentrations less than 18% (most test results found in the performed literature review were for oxygen concentrations between 100% and 18%), also considering different orientation of the fuel and the impact of external heat flux, needs more attention.

Because hypoxic air venting systems are used in the nuclear power industry, there is a clear need to be able to perform risk analysis. To be able to perform such analyses, information on reliability and monitoring is essential. Therefore, the probability of different failure modes for the system to support risk assessment and studies of effectiveness of the system in a real scale is needed. To be able to compare the ignition energy available in a protected room with the ignition energy required to start a fire in a reduced oxygen atmosphere, studies of ignition energy needed for different materials at different oxygen concentrations is necessary. A research area related to ignition energies is also the effect on ignition time with a reduction in oxygen concentration. Ignition time studies to cover both piloted and spontaneous ignition would be useful. Last, to improve the reliability of hypoxic air venting systems, critical points for monitoring of oxygen levels to ascertain an even concentration and how these measuring points could be determined needs to be investigated.

Information on ignition properties for generic materials (such as PVC and PMMA) is available. However, ignition properties for less generic materials and products, such as composite materials and products consisting of different materials, for example, cables and electrical components, needs further investigation at different oxygen concentrations, temperatures and selection of the most effective test method to determine this is needed. HRR for less generic materials and products at

different oxygen concentrations, temperatures and selection of the most effective test method to determine this is also needed.

The concerns raised previously regarding the test method in PAS 95:2011 and VdS 3527en calls for validation and further development of this test method. Possibly, changes are needed of the fuel and ignition source and modifications to account for fuel configurations, material thickness and possible radiation are needed.

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Paper III

A New Method for Quantifying Fire Growth Rates Using Statistical and Empirical Data – Applied to Determine the Effect of Arson

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ABSTRACT

When designing fire safety of buildings the fire growth rate is an important parameter, in large affecting the overall fire safety level within the building. Generally, a deterministic fire growth rate is used raising the question whether the resulting design arrives at a reasonable level of safety. A method was developed to obtain distributions of fire growth rates in specific building types. The new method uses data from two sources: fire statistics, and fire growth rates on single objects obtained by calorimetry experiments. In addition, the method was demonstrated by a case study investigating whether the overall fire growth rate is faster for commercial buildings if arson fires are included than if they are not. The results show that there is a considerably higher fire growth rate when arson fires are accounted for, e.g. designing for a fast fire growth rate of 0.047 kW/s^2 covers 97% of accidental fires (arson excluded) but only 91% of all fires (arson included). The results indicate that there is a need to account for arson fires when designing buildings when the probability of arson is high. The developed method provides means to account for arson in fire safety engineering, and to further quantify the achieved fire safety level.

KEYWORDS: fire growth, statistics, building code, design fire, fire safety engineering

INTRODUCTION

A common approach in fire safety engineering, and design of buildings, is to determine a design fire where the heat release rate (HRR) is described with an exponential fire growth rate for the pre-flashover phase [1]. This in turn forms the basis of the design. The exponential fire growth rate is often referred to as the α - t^2 fire curve, and it is described in textbooks and guidelines used for fire safety engineering, see Eq. 1.

$$\dot{Q} = \alpha \cdot t^2 \quad (1)$$

In Eq. 1, $\dot{Q}$ is the HRR (kW), α is the fire growth rate (kW/s^2) and t is the time (s). A faster burning fuel will generally have a higher α -value, i.e. a faster fire growth rate, and approximate α -values for a range of different objects (i.e. fuel packages) are available in the literature [1]. Due to limited resources, it is not possible to analyse more than a very limited amount of possible fire scenarios during the design phase of a building. The resulting fire safety level is dependent upon a large variety of parameters, e.g. maximum HRR, production of smoke and soot, fire growth rate etc. In the early stage of a fire, the fire growth rate is probably the most important parameter for life safety. Consequently, the resulting safety level is highly dependent upon the choice of the fire growth rate, which in turn determines the HRR, previously expressed to be the most important variable in fire hazards [2]. Lately some building codes have prescribed fire growth rates, for different occupancies, to be used in performance based design [3, 4]. In general, this choice of a deterministic fire growth rate for design is thought to represent the worst possible conditions that could “reasonably” occur, often called the worst-credible case. This can be compared to treating uncertainties on level 2 according to Paté-Cornell [5], on level 2 uncertainties are treated by choosing conservative values. However deciding on what value of fire growth rate to be used for design is often problematic and, as Paté-Cornell [5] points out, there is always the question of how conservative the chosen value actually is. Since the uncertainties, or the risks, are not quantified, the worst-credible case approach presents shortcomings in the risk management phase since it does not allow for meaningful comparisons of risks and therefore priorities between mitigating measures are difficult [5].

A faster fire growth rate can be associated with a shorter available safe egress time (ASET) causing the required safe egress time (RSET) to be longer than ASET, hence endangering people [6]. In addition to the increased threat to life safety a faster fire growth rate could result in less time for the fire service to

intervene, which could affect life safety as well as property damage. A faster growing fire than designed for could also result in impairment of fire protection systems. As an example, a sprinkler system might not be able to control the fire if the fire is too large upon activation, smoke management system might be overwhelmed causing large property damage and a negative effect on life safety. Therefore, it is desirable to find the actual distribution of fire growth rates for different types of buildings, in order to quantify how conservative the chosen fire growth rate actually is. Furthermore, with a distribution of the fire growth rate the design can be made towards a well-defined target, e.g. the building should be designed to be able to handle 98% of all possible fires.

Most buildings codes have a focus on life safety in case of accidental fires, i.e. fires that starts by accident, or rather; there is no explicit approach to deal with antagonistic threats such as arson. This is of course reasonable if there is no significant difference between the fire growth rate of only accidental fires and all fires (including arson). Arson is a common cause of fires according to statistics from several countries, e.g. in Sweden and UK arson accounts for 10-15% and 15-20% respectively of all fires in buildings [7, 8]. However, the extent of arson also varies with the type of occupancy and in Sweden, for example, arson accounts for 8% of fires in residential buildings and for more than 40% of fires in school buildings. In many cases arson accounts for a large part of all fires, and it might be important to give special attention to these fires in fire safety design of buildings.

Typical arson fire scenarios in schools have been identified in a previous study [9] but there was no detailed analysis conducted whether these scenarios had a faster fire growth rate than accidental fires. Holborn et al [10] used the Real Fire Library, a database consisting of data collected by the London Fire Brigade investigators, to among other things find lognormal distributions for fire growth rates for use in probabilistic fire risk assessments. According to Holborn et al (see table 1) a fire with an alpha-value of 0.047 kW/s^2 will cover 95% of all fires in public buildings and 89% of all fires in retail (including arson fires). Nystedt [11] has also tried to quantify distributions of the fire growth rate in retail buildings with the conclusion that the 92nd percentile corresponds to a fire growth rate of 0.047 kW/s^2 . However, no study of how the fire cause (e.g. arson) affects the fire growth rate was conducted in the studies. Furthermore, Holborn's [10] data is limited to buildings in London and conditions there might not apply to other countries because of differences in construction, regulations, culture etc. Nystedt's [11] data used fire growth rates for upholstered furniture [12]; hence the results only apply to furniture while the combustibles in e.g. a retail store can be different. Anger and Frantzich [13] also tried obtaining a fire growth rate distribution by conducting an inventory of combustible material in 15 retail stores. The data, however, was limited and only resulted in a discrete distribution.

Table 1. Parameters for lognormal distributions and percentile values according to Holborn et al [10].

	μ_α	σ_α	$E(\alpha)$ (kW/s^2)	α_{95} (kW/s^2)	$\alpha_{99.5}$ (kW/s^2)	Percentile for α = 0.047 kW/s^2
Holborn (public buildings, N=10)	-6.2	1.9	0.012	0.0463	0.2711	95%
Holborn (retail, N=37)	-5.4	1.9	0.0275	0.1031	0.6046	89%

The fire growth rate is one of the most important parameters in fire safety engineering affecting the fire safety level of a building. Often a deterministic fire growth rate is chosen for design and there is no quantification of the severity of the chosen value, hence resulting in an unknown safety level. Furthermore the effect of more severe fire scenarios such as arson might need to be accounted for if they affect the overall fire growth rate. The aim of this paper is to develop a method to obtain distributions of fire growth rates in specific building types with the ability to differentiate between different fire causes, hence enabling quantification of the severity of the chosen fire growth rate. Furthermore, the aim is to use the method to investigate whether the overall fire growth rate is faster for commercial buildings (buildings containing retail e.g. shopping centres) if arson fires are included than if they are not. Since the fire growth rate impacts the overall safety level in the building it is believed that arson fires need special attention in building design. Especially in multifunctional and public buildings, like shopping malls, where the occupant density can be high, important societal functions can be gathered and the probability of arson fires occurring could be fairly high [14].

METHOD AND CASE STUDY FOR COMMERCIAL BUILDINGS

To assess the effect of different fire causes on the fire growth rate it is necessary to develop a new method that has its origin in fire statistics that differentiate between fire causes. This was not possible with the previous mentioned studies [10, 11, 13] as the results are presented. In Sweden, the Swedish Civil Contingencies Agency (MSB) has gathered statistics from all rescue service operations since 1996 [8]. More than 150,000 incidents where the rescue service has responded to a fire in a building are included in this extensive database. The statistics can be used to make analyses of a range of different parameters. However, the database does not hold any information on fire growth or fire size at certain time points, as the data used by Holborn et al [10] did. Consequently, the MSB statistics alone cannot be used to determine distributions of the fire growth rates in Swedish buildings. Therefore, the new method needs to include other sources of data.

Firstly, the statistics from MSB were examined in order to determine the possible ways of using the data to obtain distributions for the fire growth rates. It was concluded that the statistics from MSB needed to be complemented with experimental data on fire growth rates for single burning objects. The principle of the method is shown in Fig. 1. In certain building types there are a number of recorded fires with recorded first objects ignited. By determining the fire growth rates for all recorded first objects ignited and grouping the fires where the fire growth rate falls in a certain interval a histogram is obtained. The histogram essentially is a discrete distribution to which a continuous distribution can be fitted. The practical working procedure in Fig. 1 is starting from the right and works further to the left. Each object ignited has been assigned a fire growth rate and each fire has a first object ignited and therefore the fire growth rates have a frequency creating the distribution for the building type.

For some of the objects it was difficult to determine a fire growth rate due to imprecise labeling of first objects ignited in the statistical data. The imprecise labels were “other”, “unknown”, “furnishing and decorations”, “other furnishing and decorations”. In order to obtain more representative fire growth rates for these labels, the room type was used to be able to pinpoint likely fire growth rates, i.e. an “unknown” fire in a kitchen will likely be different from an “unknown” fire in a sales area. The values for “furnishing and decorations” and “other furnishing and decorations” were chosen based on the room type and what type of combustibles that are expected to be present in the room type. The objects “other” and “unknown” on the other hand were given a fire growth rate that is a weighted average value for each room type, i.e. when the object is unknown it is assumed to have a fire growth rate that is distributed according to the other objects in that room type. This is considered to give a better estimate than if an overall average of fire growth rate in the building was used. Also see Appendix A for further information.

These procedures constitute the method itself and then a case study was done for Swedish commercial buildings to find the distributions for all fires (including arson) and accidental fires (excluding arson).

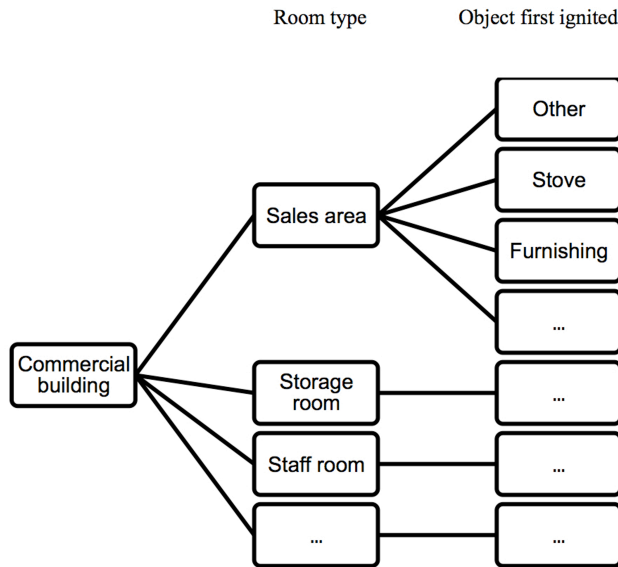


Fig. 1. The fires are categorized with respect to room type and object first ignited.

Fire statistics

The statistics used in this paper originates from the Swedish IDA database, provided by MSB [8] during twelve years (2000-2011). IDA is national and freely available database where all rescue service response is recorded. All rescue services in Sweden reports to this database. To be able to compare and identify differences between arson and accidental fires two cases have been studied (see table 2).

Table 2. Numbers and type of fires.

Case	Number of fires
All fires	2965
All fires except arson	2365

Approximately 95% of the fires in each case have been categorized with respect to the room of fire origin. An example of this categorization is presented in table 3.

Table 3. The eight most common room types of fire origin in commercial buildings.

Room of fire origin	Number of fires	Share of total
Sales area	846	0.28
Kitchen	382	0.12
Other	349	0.11
Outside building	222	0.07
Storage	165	0.05
Outside	128	0.04
Staff area	103	0.03
Loading dock	72	0.02

The categories “Outside” and “Outside building” represents the same type of fire origin, the reason for the two different labels is that the form that the rescue service fills in has been changed sometime during the data collection period. This means that the total share of fires outside building is 0.11.

The fires in each room of fire origin have then been categorized with respect to the object first ignited. An example of this categorization is presented in table 4.

Table 4. The eight most common objects first ignited in the sales area in commercial buildings.

Object first ignited	Number of fires	Share of sales area fires	Share of total
Other	171	0.20	0.06
Outside building	24	0.03	0.01
Other electrical installations	86	0.10	0.03
Stove	16	0.02	0.01
Unknown	75	0.09	0.02
Fluorescent batten	97	0.11	0.03
Furnishing	59	0.07	0.02
Paper/cardboard	16	0.02	0.01

A fire growth rate is assigned to each one of the objects first ignited and it can be weighted with its share of total fires.

Fire growth rate

A review of literature and experimental test reports have been conducted in order to find fire growth rates for the objects categorized in the statistics, also see Appendix A. The fire growth rate will depend on the material, size and configuration of the object, but the statistics do not reveal much in regard to this. This creates uncertainties when assigning deterministic alpha-values to each object. It would of course be desirable if a statistical distribution for the fire growth rate for each category could be created based on experimental data. However, a vast amount of experiments and data is needed in order to create such distributions and for most objects only a few data points are available. The alpha-values assigned to the objects in this study are mean values based on available literature and published experimental test reports. The entire list of alpha-values used in this study is available in Appendix A.

To obtain the distributions the assigned fire growth rates were divided into intervals of 0.003 kW/s^2 from $0-0.192 \text{ kW/s}^2$. In each interval the mean value of the fire growth rate was assigned to the interval and the frequency of each fire growth rate was plotted in a histogram. To the histogram a lognormal distribution was fitted using MATLAB [24].

The expected value, $E(x)$, of a lognormal distribution is given by Eq. 2.

$$E(x) = \exp\left(\mu + \frac{\sigma^2}{2}\right) \quad (2)$$

Where μ is the mean and σ is the standard deviation. The X^{th} percentile of a lognormal distribution provides a single parameter measure of the largest value that will occur in $X\%$ of the cases and is given by Eq. 3.

$$x_{x^{\text{th}}} = \exp(\mu + A\sigma) \quad (3)$$

where A is a constant depending on what percentile is sought and can be found in tables for normal distributions. For the 95^{th} percentile $A=1.645$ and for the 99.5^{th} percentile $A=2.575$.

RESULTS FOR COMMERCIAL BUILDINGS

Table 5 shows the estimated lognormal distributions of the fire growth rate for commercial buildings in Sweden based on the statistical data and estimation of fire growth rates as described in the method section above. The distributions are divided into accidental fires where arson fires have not been included and into all fires where arson fires have been included into the statistical data.

Table 5. Parameters for lognormal distributions and percentile values

	μ_a (Std. Err.)	σ_a (Std. Err.)	$E(a)$ (kW/s ²)	a_{95} (kW/s ²)	$a_{99.5}$ (kW/s ²)	Percentile for a = 0.047 kW/s ²
Accidental fires (arson excl.)	-5.091 (0.023130)	1.100 (0.0163611)	0.011	0.038	0.105	97%
All fires (arson incl.)	-4.727 (0.024032)	1.246 (0.0169978)	0.019	0.069	0.219	91%

Figures 2 and 3 show the probability density function (PDF) and the cumulative distribution function (CDF) for the accidental fires and all fires respectively. The histograms shown in the figures display data sets using a probability histogram, i.e. the height of each rectangle is the fraction of data points that lie in the bin divided by the width of the bin [25]. This makes the sum of the areas equal to one.

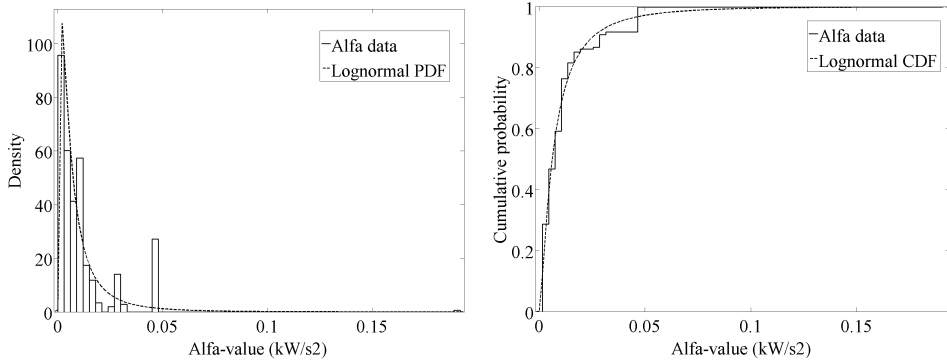


Fig. 2. Accidental fires (arson excluded), to the left: histogram and PDF for estimated lognormal distribution, to the right: CDF for the estimated lognormal distribution.

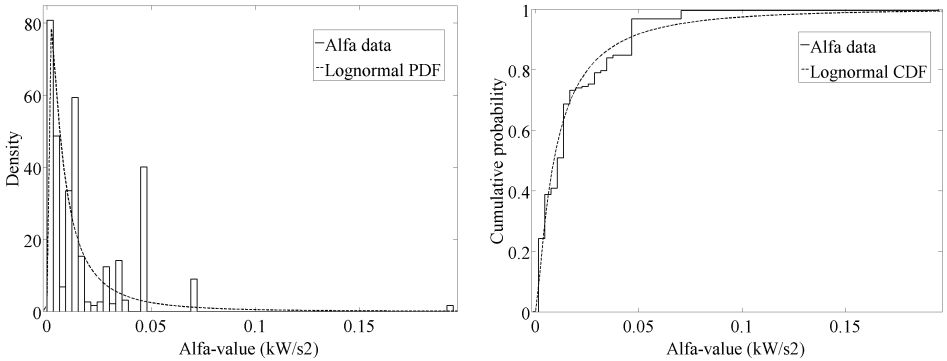


Fig. 3. All fires (arson included), to the left: histogram and PDF for estimated lognormal distribution, to the right: CDF for the estimated lognormal distribution.

The fitted curves show a difference between fire growth rates depending on whether arson is accounted for or not. If arson is not accounted for the expected value of the fire growth rate is 0.0113 kW/s² and if arson is accounted for the expected value is 0.0192 kW/s², i.e. a 70% higher fire growth rate when arson is accounted for. There is an even bigger difference when considering the tail of the distribution, for the 95th percentile the fire growth rate is 83% higher and for the 99.5th percentile the fire growth rate is 110% higher. It is concluded that considering arson increases the expected alpha-value as well as the tail of the distribution. In addition the distribution for the fire growth rates when considering arson has a higher

standard deviation than when not considering arson, indicating that the uncertainties in the values are larger. Also it is shown in table 5 that if a fast [15] fire growth rate with an alpha-value of 0.047 kW/s^2 is used for design, 97% of all accidental fires are covered while as only 91% of all fires (including arson) is covered. In the figures above, there is a high density in the histograms around a fast fire growth rate of 0.047 kW/s^2 , this is due to the discretization of determined alpha-values, also see the discussion section.

DISCUSSION

The approach where a fire growth rate is assigned to describe the HRR of a fire according to Eq. 1 is commonly used within fire safety engineering during design of buildings. Due to limited resources it is not possible to analyze more than a very limited amount of possible fire scenarios during the design phase of a building. Nevertheless, there is a need to evaluate a wide variety of objectives such as the ability to achieve protection objectives and life safety. In order to do such evaluations estimations of parameters like fire growth rate, fire location, maximum HRR, smoke production rate etc. is needed. In general a deterministic fire growth rate according to the worst credible case is often used. However, this type of deterministic analysis presents shortcomings, as discussed above and as concluded by Paté-Cornell [5], in the risk management phase since the fire risk is not quantified. The new method, presented in this paper, to develop a distribution of fire growth rates, presents one piece of the puzzle to further quantify the risk and estimate how conservative the chosen fire growth rate actually is for a specific building. Furthermore since the fire growth rate and the HRR are very important for life safety, i.e. using a non-representative fire growth rate results in other parameters such as smoke and gas production, radiation etc. being affected as well, the impact of the fire growth rate is therefore decisive. The new method is beneficial for practicing fire safety engineers, business owners, authorities etc., since the design fire can be quantified in terms of probability and therefore a concise design criterion can be stipulated, e.g. 95% of all fires should be covered by the design.

As shown in the study for commercial buildings there is a considerable difference in fire growth rates at the higher percentile values if arson is included into the data, e.g. the 95th percentile value including arson is 0.069 kW/s^2 and if arson is not included it is 0.038 kW/s^2 . Both the Swedish and the New Zealand building codes have stipulated fire growth rates for the pre-flashover fire and for the considered commercial buildings both countries have chosen a fast fire growth rate of 0.047 kW/s^2 [3, 4]. According to the results for commercial buildings a fire growth rate of 0.047 kW/s^2 incorporates 97% of the accidental fire growth rates (excluding arson) and 91% if arson is included. If designing for the fire growth rate stipulated by these codes [3, 4] the estimation of the fire growth rates, shown in table 5, results in 9% of all fires being expected to actually grow faster than the design value (when arson is included). If the building type considered has a large percentage of arson fires there is clearly a need to take this into account during the design phase due to the relatively large difference in anticipated fire growth rates. In most cases a faster fire growth rate would result in a shorter time to reach tenability conditions. If the building in question's fire protection is optimized and designed for a specific fire growth rate, e.g. a growth rate stipulated by code, an actual fire having a faster fire growth rate, than designed for, would result in people getting exposed to untenable conditions during evacuation. However, to our opinion most buildings are not that optimized and it should also be noted that the tenability conditions, as stipulated by building codes, are not lethal conditions, i.e. there are a variety of safety margins built into the code. But excluding arson during design will decrease the safety margin and expose people to a higher risk than if arson was accounted for during design. Faster fire growth rates will of course affect other protection objectives as well, e.g. protection of functions in multifunctional buildings, where the location and size of the fire is of great importance [14]. The design fire growth rate will have an impact on the overall fire safety level, both life safety as well as other protection objectives such as property, functions and businesses. Furthermore there is a clear trend, shown in Fig. 2 and 3, that accounting for arson fires results in a higher fire growth rate. Hence it is important to take arson into account if a large percentage of the expected fires are likely to be arson fires.

The presented method combines two different data sources, data regarding fire growth rates for specific objects and statistical data of occurred fires. There are uncertainties connected to both data types. For the fire growth rates there are problems with finding values for different starting objects, there might not be any data at all available and experiments are needed or gross estimations have to be made. Furthermore there are also problems with the very broad categories used in the statistics, e.g. if the first ignited object is a sofa and an alpha-value is needed for the category sofa, there can be a large variation of growth rates

between different tests and sofas, see e.g. Fig. 4. One way to handle this would be to describe every first ignited object's fire growth rate with a distribution. However, the available data is fairly limited for most objects and it would be very difficult to do and at the same time new uncertainties would be introduced. A problem with the case study for commercial buildings is the large number of "unknown" and "other" first objects ignited. For these objects a weighted average value has been used which creates an uncertainty. The weighted average value is probably not the accurate alpha-value for these categories and if e.g. more arson fires are present in these groups the alpha-value would be higher than estimated in the study. This is attributed to shortcomings in the statistics and improving the statistics would reduce this uncertainty. When using this method for retrieving alpha-values for building design purpose it is therefore recommended to conduct a sensitivity analysis of the effect of these "unknown" and "other" first objects ignited. It is believed that there is a tendency to categorize arson fires as unknown in a higher degree than other fires due to categorizing the fire as arson may have legal implications. If this is the case the effect on the result of the case study would be that the fire growth rate including arson is underestimated.

Another problem with alpha-values is whether the fire really is well described by an $\alpha-t^2$ fire. If looking at the HRR curves in Fig. 4 there is the matter to decide on what is the alpha-value for each single object. In addition the $\alpha-t^2$ fire might not at all describe the actual HRR, this is especially evident for sofa Y5.4/15 in Fig. 4. However it should be pointed out that exactly describing how a fire develops in reality is not the same as designing a building. As long as the design fire covers the worst credible fire, the design fire is probably acceptable to design for, as it covers most other fires. In Fig. 4 the design fire probably covers most of the sofa fires in the figure. Another issue with determining fire growth rates for starting objects is that the values are most often taken from furniture calorimeter tests, hence they are free burning and the room effects on the fire development is ignored [1]. For small rooms, in relation to the HRR, this can be of importance since the radiation from the smoke layer might increase the mass loss rate hence accelerate the fire. However this effect is assumed to be quite small in the early stage of the fire for the buildings studied where most areas are large open spaces reducing this effect.

As the fire spreads to additional objects within the room the total fire growth rate in the compartment might increase. This means that using one single alpha-value in a design could be non-conservative if it could be expected that the fire spreads to other objects than the first object ignited. The fire growth rate, after the fire starts to spread to other objects, will depend on several parameters like: distribution of combustibles, type of combustibles, compartment layout, compartment height etc. Thus, the presented distribution in this paper gives an estimate of the distribution of the initial fire. Within the statistics the first object ignited is sometimes a small item with a low growth rate, e.g. a light bulb. The low growth rate is believed to be valid due to the fact that in order to be able to determine the actual ignition source to be the light bulb the damage by the fire would be rather small indicating a low growth rate. However, the same method could be used to arrive at a distribution of the fire growth rate for a longer time period if data on room growth rates are used instead of single objects.

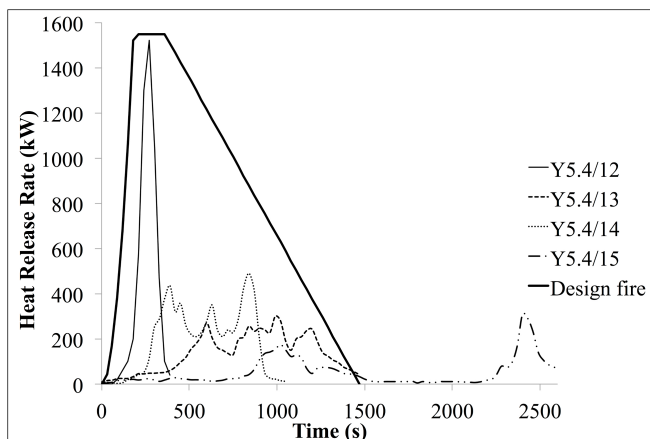


Fig. 4. HRR curves for different sofas reproduced from Särqvist [16] and a suggested possible design fire.

When comparing the histograms to the estimated distributions and the fitted PDF:s, see Fig. 2 and 3, it is shown that there are deviations between the distributions and the data for the alpha-values. This is especially evident at 0.047 kW/s^2 and 0.07 kW/s^2 . One explanation for this deviation is that discrete intervals and estimations have been made for each first ignited object. These estimations have then been used for all fires where the first ignited object is the same, resulting in the fact that there are a large number of “observations” at specific values. In reality the distribution is more continuous which would result in lower densities at e.g. 0.047 kW/s^2 making the fitted log-normal distribution more accurate. Also the adherence to the standard alpha-values, see e.g. [15], results in the fact that a large number of “observations” is shown at these specific values. If a distribution was used for the fire growth rates of the first objects ignited the distribution of the overall fire growth rate would have been more continuous, however such data is not available.

Another difficulty with the fire growth rates for the arson fires is that the effect on the growth rate when igniting other combustibles using an accelerant is not studied well. Richards [17] e.g. studied the HRR from a Molotov cocktail, however the ignition of secondary items was not studied well. Janssens et al [18] studied the effect of ignition of furniture with an accelerant, however only a small amount of flammable liquid was used, 59-118 ml, and the conclusion was that ignition with the large gas burner resulted in the same HRR considering uncertainties. The amount of flammable liquid used in the study by Janssens et al [18] is not considered to cover arson fires since a larger amount of flammable liquid is expected, around 1 L. Krüger et al [19] used approximately 1 L of flammable liquids resulting in a fire growth rate of approximately 0.07 kW/s^2 , the same fire growth rate as Holborn et al [10] used. In this study 0.07 kW/s^2 has been used since it is judged reasonable considering the time frame and amount of flammable liquids, also see Appendix A. However, there are considerable uncertainties and there is a need for further research within this area.

There are also uncertainties associated with the fire statistics, which is used as the second data source. Several countries presents fire statistics yearly and in many cases it is possible to distinguish the distribution of objects first ignited in different occupancies. In this paper Swedish fire statistics are used which means that the distribution of fire growth rates presented is primarily valid for Sweden. It is mandatory for all rescue services in Sweden to fill in a special form after every emergency turn-out. Data from these forms are collected and compiled by the Swedish Civil Contingencies Agency in a public database, which holds information on more than 160,000 fires in buildings. Even though there is a lot of data it still has its limitations. Firstly, the data is collected with a special form consisting mainly of tick boxes with different alternatives, this means that there is a control of the type of data that is collected and it can lead to interesting facts not being collected. Secondly, there might be some inconsistency in the filling of the forms since they are filled in by a variety of people within the rescue service organisation. Finally, the categories unknown cause and unknown first object ignited are often very large which will hold some hidden statistics that can be important. This is an uncertainty and in this paper the unknown cause and first object ignited has been assumed to have a fire growth rate distributed according to the known first objects ignited. However, this does not affect the method itself.

As can be seen in Fig. 2 and 3 the distribution for fire growth rates follows a log-normal distribution fairly well which is supported by other studies, see e.g. [10]. When taking into account arson fires in the distribution both the expected value and the percentile values increases. There are considerable differences when studying higher percentile values due to the tail of the distribution and that the standard deviation is larger for the distribution with arson fires. In the statistical data approximately 20% of the fires are reported as arson and this large percentage is of course affecting the result. In buildings where arson fires are less common the difference would probably not be as large, however this is dependent upon the type of arson fire. In the data the main reason for arriving at high alpha-values is the flammable liquid fires, which constitutes approximately 10% of all arson fires, i.e. approximately 2% of all fires. This affects the estimated growth rates of the fires that are unknown as well, which is a reasonable assumption due to the fact that there statistically should be some arson fires that are unknown. Another factor is that the arson fires often are started in areas where the growth rate is assumed to be high, e.g. approximately 25% of the arson fires are external fire where a “fast” growth rate is assumed.

The lognormal distribution is intuitive for the fire growth rate and this was also concluded by Holborn et al [10]. The study has been carried out for Swedish commercial buildings. The difference between countries is mainly expected to be due to the fire statistics, here the largest difference between countries are expected.

When comparing the results shown in table 5 with another similar study made by Holborn et al [10] they show similar results, see results from [10] in table 1. It should be noted that the values presented by Holborn et al are based on a small number of observations, however every observation is more detailed since a fire investigator attended every observed fire [10]. Therefore, it is not surprising that the standard deviation is larger for the values given by Holborn et al [10]. Further it is unknown whether arson fires are included or not and it is difficult to determine what category (public building or retail) that corresponds to the Swedish commercial building. However, it can be seen that the values are pretty similar and the values obtained in this paper is somewhere in between Holborn's public and retail values for most part. Also the values obtained with the new method are similar to the values presented by both Nystedt [11] and Anger and Frantzich [13] supporting its validity.

CONCLUSIONS

A new method for determining a distribution of fire growth rates for different buildings have been developed and is based on fire growth rates for first objects ignited and fire statistics regarding what kind of first objects are ignited. The method fills a gap in the current methods in determining fire growth rates since it provides a way to quantify the severity of the chosen fire growth rate, e.g. the 95th percentile fire growth rate. It has been shown that, if arson is included when determining the distribution, a considerably higher fire growth rate is obtained, especially for the tail of the distribution. If the probability for arson fires is considerable for the specific building (considering statistics for the area, building type etc.), a higher fire growth rate is expected and this might need to be taken into account during design since it affects the overall fire safety level of the building.

There are uncertainties connected with the obtained values for the commercial buildings, however the method itself produces values that are supported by the literature and improvements in statistics (e.g. reducing the amount of unknown first objects ignited) and values of fire growth rates will make the method even more usable. Furthermore the method provides a mean to quantify the fire risk and associated uncertainties in a better way than with just a prescribed fire growth rate to be used for design.

In order to limit the uncertainties more research is needed regarding the effect on the fire growth rate on ignition of secondary objects ignited with flammable liquids. Further, improving the statistics by reducing categories such as "unknown" and "other" would make the results even more reliable and there is a need for development of the way of recording data from the rescue service operations.

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APPENDIX A – FIRE GROWTH RATES

Table A1 below shows the chosen fire growth rates for the object first ignited that were common for all room types. The values are based on literature review and judgment by the authors. Based on gathered data in the literature review a fire growth rate was chosen for every single object. The values were chosen to represent the expected value for each object.

Table A1. Assigned alpha-values for first objects in all room types.

Object first ignited	α (kW/s ²)	References as basis for choice of α
Exterior fire	0.047	[9, 15, 16]
Other electrical installations	0.009	[10]
Stove	0.0029	[10, 20]
Fluorescent lamp	0.005	[10]
Paper/carton	0.002	[16, 21]
Fan/HVAC	0.0009	-
Trash in container	0.015	[16, 21]
Flammable liquid ^a	0.07	[10, 19]
Heating equipment	0.0009	-
Refrigerator	0.0029	[20]
Switchgear room	0.0009	[22]
Light bulb	0.005	[10]
Machine	0.0009	-
Car	0.017	[16, 23]
Transformer	0.0009	[22]

^aThis value was chosen for all flammable liquid fires except them in large storage areas where 0.19 kW/s² was chosen due to the expected fire growth rate in rack storage ignited with flammable liquids.

Exterior fires can vary considerably as discussed in [9] and they are often arson fires. However, due to the statistics it is assumed that when an exterior fire is indicated there was no flammable liquid used since flammable liquids is a separate category. This removes the high end of the growth rates for exterior fires and common first objects ignited are assumed to be idle pallets, trash, vehicle etc. Based on the references in the table a growth rate of 0.047 kW/s² was chosen.

Paper and carton is a fairly undefined category, the above value is based upon paper in waste baskets from [16] and trash bags from [21]. Trash in container was chosen based on the same references, however plastic commodities was included as well, hence the higher fire growth rate.

For switchgear rooms a recommended value from [22] has been used. This is also considered to represent transformer rooms since most transformers in these public buildings are dry-type transformers in Sweden. Other electrical installations have a wider spectrum and the value has been chosen according to [10]. Further the heating equipment is most often public district heating with limited amount of combustible material in technical areas, hence heating equipment was given a value in the same order as electrical rooms. In typical HVAC rooms the amount of combustible material is limited and considered equivalent to electrical rooms. Machine is also a quite undefined object and it was chosen equivalent to electrical equipment due to the fact that most expected machines in this type of occupancies are of electrical type. It should also be noted that the object machine was only the first object ignited in approximately 1% of the observed fires, hence the impact of the chosen value is limited.

Flammable liquids have a very fast fire growth rate. The use of flammable liquids in an arson fire is often of the type where the arsonist brings flammable liquids to start a fire. Hence the amount of flammable liquids is generally limited and in this study assumed to be around 1 L in average. When pouring out flammable liquid on other combustibles it is expected that the flammable liquid will burn off fairly quickly, but also increase the fire growth rate of the ignited object. Hence a fire growth rate that is faster than regular combustibles but slower than just flammable liquids is reasonable considering the studied time frame. The value presented by [10] is used which is also supported by the test performed by Krüger et al [19] showing a similar fire growth rate for a room where the fire was started with approximately 1 L of flammable liquids in the different tests.

The chosen value for car is a mean value of the fire growth rates presented in [23] and [16].

Below in table A2 are the values for the objects label: “other”, “unknown”, “Furnishing and decorations” and “other furnishing and decorations” dependent on specific room types presented. The “other” and “unknown” categories have values that are weighted average values. For “furnishing and decorations” and “other furnishing and decorations” representative values have been chosen based upon the assumed type of combustibles present in the specific room type. The values were chosen to be according to the standard values for fire growth rates, see e.g. [15], either slow, medium, fast, ultra fast or in the middle between the categories were chosen.

Sales area for example was assumed to consist of clothing store, food store, electronic store, flower store and furniture store. Based on curves in [23] clothing store was assumed to have a growth rate of 0.049 kW/s^2 based on clothing fires, food store 0.03 kW/s^2 based on solid pile storage of FM class 3&4 material, electronic store 0.013 kW/s^2 based on a tv-set, 0.012 kW/s^2 for flower store based on judgment, 0.050 kW/s^2 for furniture store based on furniture data. The average value was calculated and found to be 0.031 kW/s^2 and the closest category, 0.030 kW/s^2 (between medium and fast), was chosen. The same procedure was followed for the other room types, except for the category “other”. For the column “other” and “unknown” with respect to the row sales area, the probability (observed fraction of fires) of ignition of each first object ignited was multiplied by the assigned alpha-value for that object. The sum of all those values represents the weighted average value for the categories “other” and “unknown”. In the obtained weighted average values the categories “other” and “unknown” was included as well, this means that it was an iterative process obtaining the values, which was done in Excel.

Table A2. Alpha-values for imprecise first objects for the different room types

Room type	Object first ignited		
	“Other” and “unknown” (weighted average value) (kW/s ²)		“Furnishing and decorations” and “other furnishing and decorations” (kW/s ²)
	Incl. arson	Excl. arson	
Sales area	0.0150	0.00860	0.0295
Kitchen	0.00399	0.00372	0.012
Other ^a	0.0150	0.0110	0.0150 (incl. arson) 0.0110 (excl. arson)
Outside the building	0.0346	0.0286	0.047
Large storage area	0.0333	0.0141	0.19
Outside	0.0364	0.0323	0.047
Staff area	0.00781	0.00609	0.012
Loading dock	0.0255	0.0202	0.047
Office	0.00883	0.00544	0.012
HVAC area	0.00281	0.00285	No observed fires
Electrical appliances room	0.00803	0.00787	No observed fires
Small storage room	0.0232	0.00878	0.047
Separate small building	0.0308	0.0241	0.047
Unknown	0.047	0.047	0.047
Basement	0.0208	0.0171	0.047
Production area	0.00950	0.00658	0.047
Switchgear room	0.0029	0.0029	No observed fires
Parking garage	0.00996	0.0104	0.012
Assembly hall	0.0142	0.0125	0.0295
Boiler room	0.00373	0.00113	No observed fires
Garbage chute	0.0176	0.0167	0.047
Staircase	0.0117	0.00722	0.012
Attic	0.0199	0.0181	0.047
Toilet	0.00466	Not enough observed fires	0.012
Workshop	0.0171	0.00772	0.012
Corridor	0.00904	Not enough observed fires	0.012

^aDue to the fact that the category other is very imprecise it was chosen to just use the average value for both categories (the columns “other and unknown” and “furnishing and decorations and other furnishing and decorations”).

Paper IV

Analysis of Fire Scenarios in Order to Ascertain an Acceptable Safety Level in Multi-Functional Buildings

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ABSTRACT

The construction of multifunctional buildings has increased over the last years as well as the threat level considering antagonistic events. This presents challenges for the fire safety in these types of buildings since the protection objectives needs to be more focused on the functions the buildings are providing. Further the antagonistic exposures might present more challenging fire scenarios. A structured method how to determine fire scenarios in order to ascertain an acceptable safety level in multifunctional buildings has been developed and is based on the SFPE Engineering guides *Fire Risk Assessment* and *Performance-Based Fire Protection*. The method provides guidance on how to determine assets worth to preserve, protection objectives, exposures and finally the fire scenarios for multifunctional buildings. Previous accidents and events are discussed and serve as a background to the additional considerations needed for multifunctional buildings (compared to general buildings) and related to antagonistic exposures when determining fire scenarios. This article is a part of the project SAFE Multibygg that focuses on a methodology to identify fire risks with respect to antagonistic attacks in multifunctional buildings and to define fire safety solutions.

INTRODUCTION

Over time buildings in different parts of the world have become more multifunctional. These buildings are characterized by the multiple functions within the facility. Frankfurt airport e.g. hosts air, bus and train traffic; Scandinavium in Gothenburg hosts event arena and restaurants. The buildings are often associated with a large number of visitors and functions are often important to society, contributing to the overall complexity, vulnerability and potentially unacceptable consequences to society should an accident occur. An accident in such a building can result in large consequences due to death, property damage and impaired functions essential to society or a business/operation.

In addition since these types of buildings quite often host large numbers of people and critical functions they are more likely to be selected targets for an antagonistic attack since the attack is likely to inflict significant emotional and/or economic damage [1]. There are a number of examples where attacks have occurred in such buildings, e.g. the subway fire in Korea 2003 [2], the riots in Denmark 2008 [3] and France 2005 [4] all involving arson fires, the underground explosion in the UK 2005 [5] and the gas attack on the subway in Japan 1995 [6].

Multifunctional buildings are often large and it is difficult for visitors to get an overview of the building. Visitors are generally unfamiliar with the environment and/or evacuation routes and there might also be a variety of people e.g. children and disabled. All of this complicates evacuation. The ability to safely evacuate a building is also dependent upon smoke and fire spread and the ability to maintain structural integrity throughout a fire. Therefore the ability of the structural frame to withstand the experienced impact and the complex way smoke may spread in multifunctional buildings will need to be considered in the light that the building at the same time needs to be safely evacuated.

Traditionally, building codes in many countries such as Sweden focuses on life safety [7] due to accidental fire events and limited consideration is given to property protection and continuity of functions. When including protection of functions as well as antagonistic threats the potential fire scenarios could be considerably different from those generally designed for. However, depending on the severity of an antagonistic attack, a building designed according to code might be adequately protected against such a fire, this depends on e.g. location and magnitude of the fire. Fire and smoke spread in complex buildings presents challenges since many different operations result in multiple protection systems that need to function together hence increasing probability of failure. Methods have been developed to analyze smoke spread within a building as an isolated problem [8] and at the same time fire safety design using different risk analysis methods have been developed [9]. However, the rapid development and complexity of these buildings, together with an increased threat and a large variety of possible scenarios create a demand for analyzing the safety level from a holistic perspective in order to determine if an acceptable safety level for both life and functions is achieved. It is therefore important that carefully chosen fire scenarios addressing the complexity are analyzed and there is a need for a structured method to develop scenarios.

DEVELOPMENT OF FIRE SCENARIOS FOR MULTIFUNCTIONAL BUILDINGS

The overall process to determine fire scenarios is illustrated in figure 1 and is a modification of the process given in the SFPE Engineering Guide *Fire Risk Assessment* [10].

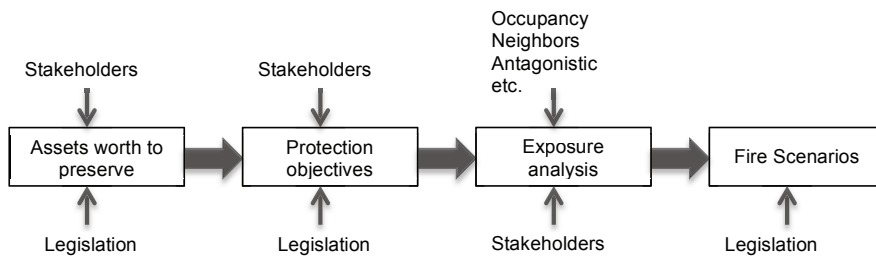


Figure 1. Overall process for development of fire scenarios in multifunctional buildings.

Due to the complexity of multifunctional buildings as described above performance-based design (PBD) for fire safety is necessary. The National Board of Housing, Building and Planning (Boverket) in Sweden has recognized this by demanding the fire safety be verified with PBD for buildings in large need of protection [11]. In many cases multifunctional buildings have this need due to high occupant density and a variety of functions. The need for PBD is governed by the complexity of the evacuation situation and the consequence in case of collapse [11]. This approach implies that the Swedish code mostly considers life safety and only to some degree property protection since it is only considering the worst credible property damage consequence of a fire event, i.e. collapse, this focus is also recognized by e.g. Klason et al [7]. The approach to mainly focus on life safety does not capture the entire complexity of safety in multifunctional buildings, not even from a societal perspective, since the loss of a building with important societal functions might cause unacceptable disturbances in the society. In addition these are more prone to antagonistic attacks than general buildings [1]. These types of events have generally not been considered by building codes [12] or other authorities and it might be necessary to consider these threats.

Assets Worth to Preserve

The first step in the process of determining fire scenarios is to determine what should be protected, i.e. assets worth to preserve. An asset is a resource of value requiring protection [1]

and this can be humans, facilities, the building itself, operations etc.. For the purpose of this method assets have been divided into five categories:

- | | |
|---------------------------------------|--|
| 1. Functions: | 2. Life safety |
| a. Functions important to society | 3. Property |
| b. Support systems (e.g. electricity) | 4. Environmental protection |
| c. Continuity of operations | 5. Safety and protection sys. (e.g. fire pump) |
| d. ... | |

The nature of multifunctional buildings is to host several functions, it might be a train station, restaurants and other public occupancies. However there might also be functions within such a building that are not readily visible, but a fire could result in loss of this function, which in turn could affect business or society. Examples of such functions are electrical systems, computer servers etc. where even a small fire could result in large consequences. Such fires are generally not considered by codes only focusing on safety of life, due to fire location.

People are naturally one of the assets worth to preserve. A fire by an accidental event such as an electrical fault or other “natural” cause should already have been part of traditional design. However if considering antagonistic threats such as arson or explosions the fire development might be considerably faster than that of a natural cause [13] and this might need to be considered.

Property includes the facility as well as its contents [10], it should also be noted that the loss of property might also cause interruption to important functions, as can environmental issues. A fire, due to contamination from smoke, water etc. might affect the environment, hence the authorities might forbid operation until environmental issues have been resolved.

The safety of the building is depending upon the protection systems provided within the building. If the systems fail in case of an accident the damages will most likely increase. When considering antagonistic attacks the integrity of protection systems become more important since the initiating event might impair the systems. An explosion damaging sprinkler pipes might render the system ineffective. During the bombing of the World Trade Center in 1993 the smoke management system and emergency lighting was damaged by the initiating event causing extensive smoke spread which aggravated evacuation [14].

Multifunctional buildings often have many different owners and businesses, hence many different functions might be important. In order to be able to determine the full scope of assets needing protection all stakeholders need to be involved during the design/evaluation of a building. Brown suggests a two-step method to ascertain that all assets are captured [1]. Step 1 is to define and understand the building's core functions and step 2 is to identify the building infrastructure. In this way, vulnerabilities are identified and focus is put on what a building does, how this is achieved and how various threats can affect the building [1]. The information needed to determine all assets needing protection might be comprehensive and so also the amount of people needed to provide input. It should be noted that the corporate of tenants, owners etc. should also be consulted if the interdependencies between functions demands it to get a full view of the exposure. The following stakeholders, obtained from [1] and [10], might need to be consulted (there might be more than the ones listed below):

- Building owner
- Tenants
- Facility staff
- Occupants
- Neighbors
- National Intelligence Service
- Municipality
- Regulators
- Police
- Designer
- Risk Manager
- Insurer
- Fire Brigade

Multifunctional buildings hosting functions important to society is of special interest since interruption to functions might have big implications on society's functionality. The Swedish Civil Contingencies Agency (MSB) has defined a function essential to society as having the following attribute: *loss or disturbance of the function would imply large risk or danger for life and health, the functionality of the society or its fundamental values* [15]. The agency lists some sectors where these functions might be present, e.g. energy supply, hospitals, transport and communication sector among others. From the broad examples of sectors it is implied that such functions could be located within many types of buildings. It is therefore not possible to list all types of buildings that need to be analyzed. If the building needs to be analyzed or not must be determined on a case-by-case basis.

Protection Objectives

Protection objectives need to be developed for the assets worth to preserve. The protection objectives will vary depending on the asset and some might be governed by legislation. Damage criteria for the asset need to be developed, and coupled to the protection objective, in order to quantify the exposure level causing the protection objective to be exceeded.

The protection objectives (e.g. no deaths) and associated damage criteria (e.g. loss of visibility) for life safety in case of fire is generally determined by legislation, see e.g. [11] and [16]. Depending on the scenario different protection objectives and damage criteria might be needed, e.g. in case of explosion an acceptable level of elevated pressures might be needed. Protection objectives may also be expressed as acceptable individual or societal risk.

Property damage objectives might be expressed as acceptable monetary value of loss or as an acceptable damage area. Environmental objectives are typically defined in terms of contamination of a medium [10]. Both damage to property and the environment might be associated with business interruption. However it is recommended that the cost of business interruption associated with a scenario is included when analyzing the function assets. This since property or the environment might not have been determined an asset worth to preserve.

The safety and protection systems are used to protect the assets from an event and naturally they need to be protected against the event. The protection objective for fire safety systems should be that there should be no damage to them due to an event requiring them.

Loss of functions is often associated with interruption to services, e.g. a business or important societal function. It is essential to determine how the facility fits into the "big picture", i.e. how critical the facility is to the organization's operation, after that protection objectives can be established [10]. One suitable way of establishing the objectives is to conduct a business impact analysis (BIA), often done for IT systems [17]. A BIA identifies a system's critical resources and each resource is then further examined to determine how long functionality of the resource could be withheld before an unacceptable impact is experienced [17]. The time identified is maximum allowable outage (MAO) and the balancing point between MAO and the cost for recovery establishes the Recovery Time Objective (RTO). This method can be applied to multifunctional buildings as well by establishing the impact on a function if loss occurs of a component. Recovery strategies together with protection should then result in a

downtime less than the RTO. It might also be beneficial to include loss of customers due to prolonged downtime in this analysis. Damage criteria depend on the support systems or resources required to maintain the functions and could include equipment, personnel etc.

Exposure Analysis

The next step is to determine what hazards/threats could pose a risk that protection objectives specified for the assets are not met, i.e. to conduct an exposure analysis. Sometimes called hazard identification [10], the purpose of the exposure analysis is to support the development of scenarios. SFPE [10] defines a hazard as a condition or physical situation with a potential to cause harm. A physical hazard might be flammable liquids or combustibles, but if a hazard relates to a person or group it will normally be defined in terms of state of knowledge, attitude or belief that is characterized as human action within an event. For the purpose of this paper exposures are divided into two types of exposures, *accidental or natural* and *antagonistic*.

Examples of accidental or natural exposures may be an occupancy containing combustibles that are ignited by an electrical fault or hot work. These hazards are generally considered within the design process of a building, but as stated above the main asset considered is most often life safety. For multifunctional buildings a larger focus is needed on functions provided, which follows from the determined assets. For the accidental or natural exposures the method for hazard identification in the SFPE Engineering Guide *Fire Risk Assessment* has been adapted and a more detailed description can be found in [10]. When considering multifunctional buildings it is essential not to overlook any hazards/exposures to the determined assets. Some assets might be very sensitive to fire and even exposures generally thought to be minor might cause large consequences in terms of property damage or interruption to the function, e.g. equipment in a computer server room upon which all business rely.

Antagonistic attacks have become more apparent during the last years. The attack on WTC and the London bombings are events with large consequences. In December 2010 there was an unsuccessful suicide bomb attack in Stockholm Sweden. If the bomb would have exploded in the nearby shopping mall and caused a fire the consequences would however been much larger. All these examples are large-scale attacks that might be hard to protect against but there are also other antagonistic exposures of smaller scale, such as arson fires, but with large consequences. Examples are the Gothenburg fire 1998 where 63 persons died [18] another is the subway fire in Korea 2003 where 192 persons died [2], both these events started with antagonistic attacks, namely arson fires. An important factor here is to determine if all possible exposures, even the worst cases, should be included in design.

What should be designed for and what is an acceptable level of risk is a difficult question. However, Det Norske Veritas has suggested risk criteria for individual risk between 10^{-5} and 10^{-7} and between 10^{-4} and 10^{-6} per year for $N=1$ for societal risk [19]. Stewart suggests that the probability for a terror attack on a US commercial building is between 10^{-6} and 10^{-7} [20]. Since the acceptable criteria and determined frequencies are of the same order of magnitude antagonistic attacks might need to be taken into account. This conclusion is also based on the fact that multifunctional buildings might be more prone to experience an antagonistic attack. Another issue reinforcing the need to analyze antagonistic threats is the long-term effect of such an event on society. As an example Rubin et al concluded that the population reduced their use of public transportation system in the London area 8 months after the London bombings in 2005 by 19% [21] and Handley et al conclude that 45% of persons directly affected by the bombings reported disabling travel anxiety that had interfered with their

everyday life [5]. Further Thompson and Bank discuss that since the terrorist attacks of 2001 in the US the anxiety level and the perceived risk of occupants of buildings have increased and that the perceived risks are not necessarily limited to terrorist attacks but could also be e.g. catastrophic fires [22].

Richards suggests that around 15% of all fires in New Zealand are deliberately lit and in crowd buildings (retail shopping, cinemas etc.) the number is as high as 40% [13]. Hall concludes that 6% of all fires in structures in the US are intentional fires [23]. The statistics show that a large percentage of fires is intentional indicating that, at least where consequences might be large such as in multifunctional buildings, these events should be considered.

Brown and Lowe give a broad list of antagonistic threats that should be considered and the fire related threats are explosions and arson/incendiary fire [1]. Explosions are divided into subcategories: vehicle, mail, thrown or placed explosives and for arson/incendiary fires the extent of damage is depending upon the accelerant and quantity. Thompson and Bank suggest terrorism-related hazards for buildings and of importance to consider especially regarding fire are arson, fire as a secondary effect to a blast, attacks on load-bearing members, attacks on fire suppression systems and attacks against staircases, elevators etc. that slow down evacuation [22]. These become important for multifunctional building due to a large amount of people and the importance of support systems to the functions. A well-informed attacker might know exactly where to place a fire or how to bypass fire suppression systems. This indicates the interaction between safety and security, i.e. if a car cannot enter the building the amount of explosives or accelerants that can be brought into the building might be limited and the exposure less severe. The difference between the terms safety and security is not clear and there are a lot of different attempts for definitions, see e.g. [24, 25]. The meaning for the purpose of this paper is found in the beginning of the paper.

Table 1. *Key points for antagonistic exposure analysis, modified from [1].*

Step	Examples of things to consider
<i>Existence</i>	Who is hostile to the assets, organization etc. and might they be present at the location?
<i>Capability</i>	What methods, material, means etc. do the aggressors have? Is the material available at the building or do they need to bring it?
<i>History</i>	What has the aggressors done in the past? Where have they done it? Is there any history of such events in the area?
<i>Intention</i>	What do the aggressor hope to achieve? (vandalism, political, excitement etc.)
<i>Threats</i>	Explosion, arson, electrical supply, fire protection systems etc.
<i>Security</i>	Surveillance, access limitation, site perimeter, lighting, security personnel etc.

Brown and Lowe state that terrorism attacks are conducted because the aggressors seek publicity for their cause, monetary gain or political gain through their actions [1]. Richards lists reasons for arson as vandalism, excitement, revenge, crime concealment, profit and extremist beliefs [13]. To determine the exposure to a specific building input from different stakeholders are needed. Tenants and owners might know if they have experienced attacks before, the police or fire department may have information on vandalism in the area etc. Brown and Lowe state the significance of understanding who the people are that want to cause harm, their means and resources [1]. However, the matter of what incidents should be protected against is a difficult question, especially when considering low probability high consequence events such as a large-scale terrorist attack, i.e. extreme events. Extreme events for a building are any incidents that exceed the design level event and are therefore beyond the design objectives [26]. For antagonistic threats, extreme events are clearly possible. However, the more secure the building is and the better designed it is to resist an antagonistic

threat, not only will the damage probably be less severe but the building is also less likely to be picked as a target [1]. Table 1 presents steps to go through to determine antagonistic exposures and is based on the method by Brown and Lowe [1]. It should be noted that the process is somewhat iterative. Sometimes you might e.g. start with the aggressor and its capabilities, sometimes with possible scenarios and then determine who has that capability.

Fire Scenarios

Credible fire scenarios are developed based on the exposure analysis with the assets worth to preserve in mind so that the fire scenarios challenge the protection objectives, see figure 1. At this stage the description of the fire scenarios are still qualitative and the development of a fire scenario is described with qualitative characteristics, e.g. initial heat source, fire spread to secondary rooms etc. [10]. The amount of possible fire scenarios is probably unmanageable and the scenarios need to be merged into clusters [10]. From each cluster, design or trial fire scenarios are chosen, these should be representative for all the fires in the cluster in terms of challenging the protection objectives. The term design fire scenario is used when designing a new building and trial fire scenario is used when analyzing an existing building. Once the design/trial fire scenarios have been chosen they need further specification, e.g. heat release rate. The general approach for quantifying this scenario is given in figure 2. The process is based on the working method presented by Staffansson [27] and the SFPE Guide [28]. Factors affecting the scenario need to be defined and should at least include building, occupants and fire characteristics [28]. The characterization (determination of heat release rate, evacuation etc.) of the design/trial fire scenarios for a multifunctional building in general follows the regular process as described in e.g. [28, 10, 27]. The remainder of this section will discuss specifics for multifunctional buildings and considerations regarding antagonistic threats.

Importance of availability and reliability of fire safety systems

The first step of quantifying a design/trial fire scenario is to determine the worst credible consequence. For this purpose the scenario is evaluated assuming all active protection systems are impaired. This provides an indication to how important active fire protection systems are and if they are needed to meet the protection objectives. If active fire protection systems are needed to meet the objectives an availability and reliability analysis should be conducted [28] to ascertain functionality in case of fire. It might also be necessary to study failure of individual systems depending on the criticality of each system. All protection objectives should be evaluated and for property this event could be compared to what is often referred to as Estimated Maximum Loss (EML).

Impairment of fire safety systems due to the event

The initiating event has a large impact on the subsequent development of the fire scenario. Of special importance is if the initiating event is impairing passive or active fire systems and how that affects the scenario development. The airplanes crashing into the WTC immediately affected several fire compartments, damaged the fire protection of the steel structure and damaged sprinkler piping rendering the system ineffective. The explosion in WTC in 1993 caused a power failure damaging both primary and back-up sources leading to failure of smoke management and emergency lighting with a large amount of casualties as a result from the fire following [14]. The fire in Gothenburg 1998, where an arson fire was started in a stairway led to a fast developing fire, blocking one out of two emergency exits with 63 casualties [18]. In this case a failure of human protection system or human factor plays an important role but even an attacker can place the fire load in the evacuation route with similar consequences. Another issue associated with antagonistic threats is the degree of planning of an attack; it may include bypassing fire protection [13]. The examples are all associated with

antagonistic threats and when such a threat is identified in the exposure analysis special attention to the impairment of systems is needed. However even natural or accidental exposures might cause impairment to the systems, e.g. an explosion in a flammable liquid mixing room bringing down a fire rated wall or sprinkler main. If the protection systems are essential to meeting the protection objectives means to improve the availability and reliability and protection of the systems against the scenario (e.g. isolation of the fire pump, access control, redundancy) itself is necessary.

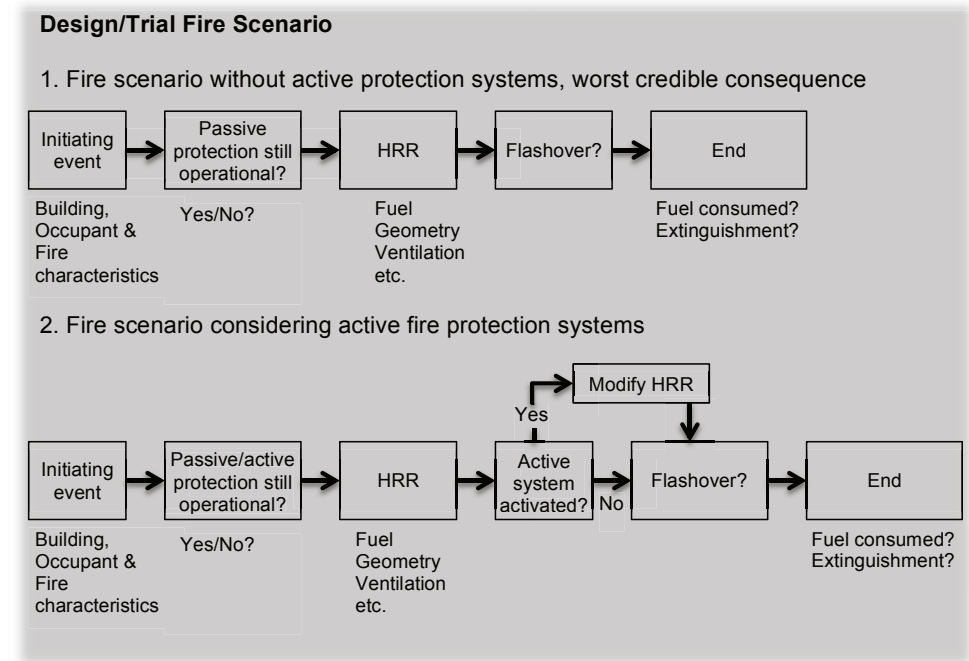


Figure 2. General process for development of fire scenario.

Effectiveness of fire suppression system

If the fire safety systems are not impaired due to the event, or for some other reason, there is still the question whether they effectively will control or protect against the event. How different active systems affect the fire development in a building with an occupancy it is designed for and with a general fire initiation can be found in e.g. [29, 30, 16, 31]. However the effectiveness needs to be determined against the stated protection objectives and the anticipated fire hazard the system was designed for. If the fire hazard for some reason is higher than what was designed for or if the protection objective concerns e.g. contamination, then the suppression system might be ineffective. A fire in an electrical room e.g. might be adequately controlled by a sprinkler system to not spread further within the building but the protection objective for functional performance of e.g. a computer system might be exceeded due to interruption for a prolonged time. One example where the fire protection system might be overwhelmed and rendered ineffective is the initiation of multiple fires, i.e. multiple fires started at different locations within the same building within a short time period [13]. Richards also discusses that multiple fires might block evacuation routes, overwhelm smoke management and sprinkler systems and might reduce the time to flashover [13].

One problem for multifunctional buildings is the many tenants and owners of the building, making it hard for every business to have knowledge about the fire safety systems installed and their capabilities. This might result in storage configuration or occupancy exceeding the design limits of the suppression systems. In addition there might be a high turnover of tenants and the occupancy might change considerably resulting in inadequate fire suppression systems. Another situation that might need to be considered is a fire involving flammable liquids. A fire deliberately lit in rack storage using accelerants might e.g. result in such a rapid fire growth that it overwhelms the suppression system. Another example might be the use of large amounts of flammable liquids causing a large burning area overtaxing the sprinkler system. This is of special importance when antagonistic exposures have been identified.

Fire size and location

In multifunctional buildings more protection objectives are needed to ascertain good protection for all assets worth to preserve including operation, property etc. than in general buildings. The fire location should reflect assets worth to preserve, protection objectives and exposure analysis. This means that fire locations that often are omitted due to small concerns for life safety might need consideration. A fire in a control room could e.g. be associated with lengthy interruption, even if the fire size is small and never spreads outside the room. Klason et al state that for school buildings, the code generally considers fires occurring inside a building and ignores external fires [32]. However, if an antagonistic exposure has been identified the likelihood of a fire occurring against e.g. the façade might be high, in New Zealand 8% of deliberately lit fires were started at the façade [13]. In a school in southern Sweden e.g. an incendiary fire started against the façade. No persons were injured but the fire impaired teaching functions, shopping facilities and a health care center [33]. When considering antagonistic threats security becomes important in order to limit the exposure. This goes not only for the site perimeter and external fires but also planned attacks with a specific target such as main components in a system, e.g. electrical or network distribution. Richards suggests e.g. that around 5% of deliberately lit fires in crowd buildings are started in support rooms [13].

In addition to the location, when considering antagonistic threats such as arson, the magnitude (growth rate, heat release rate etc.) of the fire might be larger than what usually designed for. In general buildings are not designed for incendiary fires [13] and the fire in the subway system in Korea [2] and the fire in Gothenburg [18] both enforces this. The fire in the subway system in Korea resulted in 192 casualties and this fire was started with only four liters of flammable liquids [2] as primary fire. Clearly the safety systems were not designed to handle fires like those and there may be many other reasons. Maybe the exposure was not foreseen, the code did not demand that such events should be designed for, the fire characteristics were poorly understood, routines were not followed etc. The Swedish building code today stipulates that a building hosting many people should be designed for a maximum heat release rate of 10 MW with a growth rate of 0.047 kW/s^2 [16]. If there is a sprinkler system that activates before the heat release rate reaches 5 MW the heat release rate is to be reduced and if above 5 MW the heat release rate is to be kept constant [16]. For antagonistic exposures these design fire curves might not be representative. Richards suggests e.g. that the peak heat release rate for a 1-liter Molotov cocktail is reached after around 12 s and the peak heat release rate is around 1 MW [13]. The growth rate could be compared to what is demanded for a crowd building in the Swedish code where 1 MW is reached after approximately 150 s. In addition the fire might be much larger when the sprinkler system activates later than what it was designed for. It is not easy to determine what scenarios are accounted for by the code since it depends on the fire development after the initiating event. If an antagonistic exposure

has been identified it is likely that there are more severe fire scenarios than what is usually designed for. In a design phase these more severe fire scenarios need to be designed for and in an evaluation stage these severe scenarios need to be considered.

Load bearing members

Fire design of load bearing members is often prescriptive in terms of an hourly rating according to a standard fire curve see e.g. [34]. Often structural elements will not be affected until the later stage of the fire. It is therefore necessary to analyze the full time scale of the fire including the possibility of a post-flashover development. The effect of a collapsing building due to fire was witnessed in the attack on the twin towers 2001 and some literature suggests that the experienced fire scenario would have caused collapse even if the impact load by the airplanes was neglected [35, 36]. Structures are generally designed for one accidental load at a time, see e.g. [37]. However, a fire following an explosion cannot be ruled out, see e.g. [14] regarding the bombing of the WTC 1993. When considering antagonistic exposures such as explosion one possible event following might be fire and as such maybe two accidental loads should be considered. This however needs further investigation.

CONCLUSIONS

A first framework for development of fire scenarios for multifunctional buildings has been presented and the following conclusions reached:

- There is a need for a structured method for development of fire scenarios for multifunctional buildings considering protection of functions as well as antagonistic exposures, otherwise an acceptable safety level cannot be ascertained.
- Buildings with multiple functions have more assets worth to preserve than regular buildings resulting in more protection objectives and different exposures. Therefore additional and different fire scenarios than what is usually designed for need to be evaluated. Often location and severity of the fire differs.
- To be able to capture all assets input from a large variety of stakeholders is essential.
- Antagonistic threats cannot be ignored for multifunctional buildings and the exposure generally results in more severe fire scenarios needing further analysis.
- Antagonistic events pose a higher probability for domino effects, e.g. first an explosion and then a fire following, and failure of active or passive protection system.
- The methods presented in the SFPE engineering guides [10, 28] appear to be suitable for evaluating multifunctional buildings. However this need further validation.

DEFINITIONS

Multifunctional building: One or several connected buildings hosting several functions or occupancies (e.g. office, restaurant) where the facility and its functions is one integrated whole. The definition also includes underground facilities.

Antagonistic attack: Manmade attack, against a specific target to which the aggressor bear hostility, with the intention to cause harm as a consequence of the attack, e.g. terrorist attack such as an explosion or arson fire.

Security: Security is protection aimed towards limiting access such as perimeter fencing, CCTV, watch service, locking etc.

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