Safety in Case of Fire - The Effect of Changing Regulations

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Safety in Case of Fire –
The Effect of Changing Regulations

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Doctoral thesis

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Abstract:

In this doctoral thesis some fundamental problems concerning society's ability to control the safety in buildings in the case of fire by issuing performance-based building regulations are identified and analysed. Fire protection documentation from forty-six projects was studied, together with a detailed analysis of the Swedish building regulations and an extensive risk analysis of a class of buildings. The results show that there is a lack of regulation and guidance on how to perform verification, which leads to arbitrary design decisions. It can be questioned whether the approach taken by many practitioners today is sufficient to fulfil the requirements laid out in the building regulations, that is society's demand for fire safety. Few tools are available to address these issues in a practical way. This thesis presents a procedure for verification and suggests general quality demands for verification as a means of addressing these issues.

To my dearly loved Jeanette.

Preface

A decade ago, the potentially dangerous fire safety designer was characterized as an engineer from the old school, who did his or her best to cope with complicated calculations and computational tools. Today, there is much evidence to suggest that the most serious mistakes are made by engineers who are highly qualified in the use of advanced computational tools, but who lack basic knowledge in design and building regulations. How can it be that the freedom to change traditional fire protection allowed by the new building regulations is treated so irresponsibly? This is especially remarkable given the fact that apart from Iceland, Sweden has the greatest number of graduate fire safety engineers per capita in the world.

The Swedish Board of Housing, Building and Planning (*Boverket)* is faced with a potentially extensive revision of building regulations in the near future, and will be forced to make an important decision. Will they pretend that the situation is acceptable and continue to fine-tune the existing regulations, or will they recognize the need for development and start to tackle the problems already identified in a systematic way, thus setting themselves a mammoth task?

It was courageous of *Boverket* to take the first step towards the introduction of performance-based building regulations in 1994. It is now time to take the next step.

Bitter sweet harmony!

Summary

The requirements concerning fire protection of construction works in the Swedish building regulation were reformulated a decade ago. Detailed demands on the technical design of buildings and their fire protection systems were replaced by requirements addressing the goals of fire protection, i.e. performance-based requirements. In order to satisfy these requirements, solutions recommended by the authorities may be used (prescriptive design), or the designer may choose to demonstrate compliance with the regulations through verification of other solutions (denoted analytic design or fire safety engineering design).

The main purpose of the work presented in this thesis was to investigate how these changes in building regulations have affected the ability of society to control fire safety in buildings. The following aims were defined:

- to identify and compile the problems facing society in ensuring safety in case of fire of construction works (buildings),
- to propose specific solutions to these problems, and
- to identify areas where further development is necessary.

A framework for risk control was used to create a general structure for the work. The framework consists of three different levels at which society can influence and control fire risks in buildings by issuing regulations. These levels are labelled: *safety output, safety procedures & safety case* and *direct risk control*. Regardless of the level used to control fire safety, problems and dilemmas will arise which must be dealt with. An important part of this work is therefore concerned with the identification of these problems. This includes studying the fire safety demands in the building regulation, how the requirements have been applied in a large number of building projects, and which methods were used in verification.

In order to evaluate the safety-related consequences of the problems identified, a particular class of buildings (assembly halls) was studied in detail, using a quantitative risk analysis method in combination with extensive sensitivity and uncertainty analyses. The results of this detailed study can be generalized to a considerable degree.

One dilemma identified is that no unambiguous acceptance criteria have been stated in the building regulations. In practice this means that analytic design must be verified by comparison with a solution accepted by the prescriptive rules and the level of risk inherent in this design to comply with the regulations. The next problem is then to determine the level of risk inherent or implicit in the design using the prescriptive rules. A substantial part of the thesis consists of a study of the variability and indeterminacy of risk levels resulting from using prescriptive design. An additional important problem is that it is stated in the building code that prescriptive design must not be used in certain types of buildings, despite the fact that there is no suitable alternative. No guidelines are given in the building regulations, or by *Boverket* (the Swedish National Board of Housing, Building and Planning), on how verification should be carried out following the use of the analytic design method in these buildings. This is extremely serious as fires in such buildings may lead to building fires with disastrous consequences.

Another problem is that a number of shortcomings were found in fire safety documentation of forty-six building projects. One of the most serious is that the models used to analyse and evaluate the risk are not appropriate for the purpose. One example of this is that the contribution to the risk from serious events is not included in the verification. Another example is the comparison of different fire protection measures where several attributes of great importance for safety, e.g. the potential to avert a catastrophe and the number of barriers making up the fire protection, are neglected. This means that verification does not guarantee that the requirements in the building regulations are met as anticipated. This is serious, as verification is one of the tools society relies on constituting the basis of the system used to ensure fire safety in buildings.

The conclusion drawn from the detailed study, in which risk analysis was used to study the level of risk resulting from the prescriptive design method, is that the method leads to great variation in risk level within a class of buildings. The actual risk is in some buildings estimated to be so high that its acceptability can be questioned. This high risk is the result of the design method *Boverket* is supposed to have control over, since the method is defined by their general recommendations in the building regulations. Furthermore, solutions in manuals, handbooks, guidelines and previously acceptable solutions not included in the prescriptive design method are being used without any kind of verification, which is contributing to a reduction in society's ability to control fire safety. As there is no form of regulated quality control of such common practice, and the level of safety afforded by a solution in a specific situation is not known, in practice the designers themselves decide what an acceptable level for compliance with the regulations is.

When performing verification in analytic design, it is necessary to evaluate all the scenarios making significant contributions to the risk in order to be able to determine whether the total risk has increased or decreased relative to that obtained with prescriptive design. If performance-based design is to be used properly, unambiguous criteria and procedures for verification that the regulations have been complied with must be defined.

Unfortunately it is concluded that the degree of arbitrariness in analytic design is so high that the variation in safety level can be greater than in prescriptive design, making it almost impossible for society to control fire safety. The problems reported in this work are so serious that if they are not dealt with they may in time lead to political consequences (e.g. questions raised in parliament and courts of public inquiry). The aftermath may very well severely limit the freedom of fire safety engineers to design building-specific solutions. Stricter regulation of the approaches used in analytic design is therefore suggested, whereby general demands are made on the quality of verification, as well as on the use of a systematic procedure.

Gross errors and extreme events cannot be dealt with using fire protection of construction works alone. Other kinds of protective measures must also be implemented, for example, systematic fire safety management, including organisation, instructions, drills and routines. An increase in the need for coordination between the design phase and the operational phase has been noted, and whether further procedures and routines are required to ensure this coordination should be investigated.

A procedure for verification and general demands on the quality of verification have been proposed in order to deal with several of the problems identified. The procedure means that the need for verification can be determined in a systematic way, and thus contribute to creating a clear structure and uniformity in verification.

The shortcomings revealed by this work indicate that the system of control in the construction process must be reviewed. A simple model has been presented to define a suitable level of design control in specific projects, but additional development of systematic approaches is necessary.

In the longer term, more basic research will be needed to develop design methods on which requirements in regulations can be placed, and which also ensure a sufficient level of safety. The continued development of prescriptive design is also required. A number of different strategies have been discussed, and the risk analysis method developed in this work can be used to analyse the safety-related consequences of changes in the prescriptive design method for classes of buildings. Such an analysis is necessary for the scientifically sound development of the prescriptive design method. The following changes in prescriptive design method have been used to exemplify how a reduction of the risk level and the variation of the risk level for a class of buildings (i.e. assembly halls) can be achieved. The analyses of these changes also serve as an example of the opportunities offered by the risk analysis method in the development of the prescriptive design method. The analysed changes are:

- limitation of the minimum ceiling height in assembly halls,
- restriction on the number of people in a building, or requirements to design for the maximum number of occupants of a building,
- demanding at least 3 exits from all assembly halls,
- 1 metre exit width is required per 100 people, instead of per 150 people, and
- required exit width is expressed as a function of the volume of assembly halls.

This thesis will hopefully inspire continued discussion and development in this important area and provide a step forward towards a more consistent and controllable fire safety design process.

Sammanfattning (summary in Swedish)

I de svenska byggreglerna ändrades kraven på brandskydd för drygt tio år sedan. Detaljerade krav på den tekniska utformningen av en byggnad och dess skyddssystem byttes mot funktionskrav, d.v.s. krav på brandskyddets målsättning. Följden har blivit att antingen myndigheternas rekommenderade lösningar kan användas för att uppfylla kraven (förenklad dimensionering), eller att det blir projektören som verifierar att kraven uppfyllts med hjälp av andra lösningar (analytisk dimensionering).

Ett huvudsyfte med den här avhandlingen är att utreda hur förändringen av byggreglerna har påverkat samhällets förutsättningar att kunna kontrollera brandsäkerheten i byggnader. Det sker utifrån följande tre målsättningar:

- att identifiera och sammanställa vilka problem samhället har när det gäller att kontrollera det byggnadstekniska brandskyddet,
- att föreslå konkreta lösningar på dessa problem, samt
- att peka på områden där fortsatt utveckling är nödvändig.

För att skapa en övergripande struktur i detta arbete har ett ramverk för riskkontroll använts. Ramverket består av tre olika nivåer. Samhället har möjlighet att påverka och kontrollera en verksamhet genom att utfärda olika typer av regler och föreskrifter. De tre nivåerna utgör tre olika kategorier av regler och benämns: *mål*, *tillvägagångssätt* och *tekniska lösningar*. Oavsett vilken kontrollnivå för säkerheten som används så uppkommer problem och dilemman som måste hanteras. En viktig del av föreliggande arbete har därför varit att identifiera problemen genom att först studera kraven på brandskydd i byggreglerna, sedan se hur kraven har tillämpats i ett stort antal projekt och att slutligen undersöka vilka tillvägagångssätt som används vid verifiering.

För att utvärdera de säkerhetsmässiga konsekvenserna av de problem som identifieras så detaljstuderades en viss klass av byggnader (en typ av samlingslokaler). Detta skedde med en kvantitativ riskanalysmetod, i kombination med omfattande känslighets- och osäkerhetsanalyser. Resultaten från detaljstudien går i hög utsträckning att generalisera.

Ett dilemma vid dimensionering är att det i byggreglerna inte har kunnat fastställas några entydiga acceptanskriterier för funktionskraven. Verifiering av att kraven uppfylls blir därigenom problematisk. I praktiken innebär det att den lösning som tas fram med analytisk dimensionering måste verifieras genom att jämföras med risknivån i förenklad dimensionering. Nästa problem blir hur denna risknivå skall bestämmas. Därför har förutsättningarna utretts för hur risknivån kan användas som underlag vid värdering av risk i samband med analytisk dimensionering. Tillvägagångssättet blir i vissa fall problematiskt, eftersom det anges i byggreglerna att förenklad dimensionering inte får användas för vissa typer av byggnader. Tyvärr saknas det en beskrivning av något lämpligt alternativt tillvägagångssätt. Avsaknaden av vägledning från *Boverkets* sida är påtaglig i många avseenden när det gäller analytisk dimensionering. Detta är allvarligt eftersom brand i flera typer av byggnader (t.ex. samlingslokaler) medföra mycket stor risk för personskada. God kontroll av säkerheten bör därför vara högt prioriterad.

Ytterligare ett problem har uppmärksammats vid en genomgång av fyrtiosex brandskyddsdokumentationer. De visar på en rad brister, där den allvarligaste består i att flera av de modeller som används för att analysera och värdera risk i samband med verifiering inte är ändamålsenliga. Ett exempel på detta är att det ökade riskbidraget från allvarliga händelser inte beaktas vid verifiering. Ett annat sådant exempel är att flera av de egenskaper som har stor betydelse för säkerheten negligeras vid jämförelser mellan olika brandskyddslösningar, t.ex. vilken katastrofpotential som finns och vilket antal barriärer som brandskyddet byggs upp av. Med dessa brister ger verifiering inte det kvitto på att kraven i byggreglerna är uppfyllda som det är tänkt. Detta är allvarligt på grund av att verifieringen är ett verktyg som samhället sätter stor tilltro till. Verifieringen utgör själva basen i det system som samhället använder för att kontrollera byggnaders brandsäkerhet.

Detaljstudien, där riskanalysen används för att studera risknivån till följd av förenklad dimensionering, leder till en slutsats, nämligen att den dimensioneringsmetoden leder till stor variation i säkerhetsnivå för en klass av byggnader. För vissa lokaler bedöms risknivån vara så hög att det kan ifrågasättas om det verkligen är acceptabelt, men detta i sin tur är ett resultat av den dimensioneringsmetodik genom allmänna råd, som *Boverket* skall ha kontroll över. Dessvärre bidrar handbokslösningar och tidigare accepterade lösningar till att samhället håller på att förlora den kontrollen. Lösningarna används utan någon som helst verifiering. Eftersom det inte sker någon kvalitetskontroll av handböckernas råd är det är ovisst vilken säkerhet lösningen medför i varje aktuellt fall. Det innebär i praktiken också att det blir projektörerna själva som avgör vad som är en acceptabel nivå för att uppfylla kraven och hur denna skall verifieras; en förskjutning av riskkontrollen som inte var avsikten när funktionskraven introducerades.

Vid analytisk dimensionering är graden av godtycklighet så stor att variationen i säkerhetsnivå kan vara större än vid förenklad dimensionering och dessutom näst intill omöjlig för samhället att kontrollera. De redovisade problemen är så pass allvarliga att de, om de inte hanteras, på sikt kan leda till politiska konsekvenser (t.ex. att frågor ställs i riksdagen och att haverikommissioner initieras), som i sin tur kan medföra begränsningar i projektörernas frihet att i framtiden utforma objektsspecifika lösningar. En hårdare reglering av tillvägagångssättet vid analytisk dimensionering föreslås därför, där det ställs både allmänna kvalitetskrav på verifiering och krav på ett systematiskt tillvägagångssätt. För att kunna verifiera om den totala risken har blivit högre eller lägre än vid förenklad dimensionering är det nödvändigt att med analytisk dimensionering värdera alla relevanta scenarier, för att se hur riskbidragen påverkar. Och för att analytisk dimensionering skall kunna tillämpas på ett riktigt sätt måste entydiga kriterier och tillvägagångssätt definieras för att verifiera att kraven i byggreglerna efterlevs.

Risken till följd av grova fel och extrema händelser, d.v.s. mycket allvarliga händelser, är inte lämpliga att hantera med enbart byggnadstekniskt brandskydd. I stället bör andra typer av åtgärder användas, t.ex. systematiskt brandskyddsarbete som är en typ av ledningssystem, där bl.a. organisation, utbildning, övning och rutiner ingår. Ett ökat behov av koordinering mellan projekteringsfasen och den operativa fasen (d.v.s. då byggnaden används) har uppmärksammats, och det bör undersökas om ytterligare procedurer och rutiner är nödvändiga för denna koordinering.

En procedur och allmänna kvalitetskrav för verifiering har här föreslagits, som kan användas för att hantera flera av de problem som har uppmärksammats. Proceduren medför att behovet av verifiering kan bestämmas på ett systematiskt sätt, och den bidrar till att skapa en klar struktur och enhetlighet vid verifiering.

De allvarliga brister som uppmärksammades när dokumentationerna över brandskydd gicks igenom hade inte heller identifierats i samband med byggherrens egenkontroll eller uppmärksammats av byggnadsnämnden vid projektering. Det tyder på att kontrollsystemet i byggprocessen behöver ses över. En enkel modell presenteras för att bestämma en lämplig nivå på dimensioneringskontrollen.

På längre sikt krävs mer grundläggande forskning för att i byggreglerna utveckla metoder som både är möjliga att ställa krav på och som samtidigt medför en acceptabel säkerhetsnivå. Dessutom behöver förenklad dimensionering utvecklas ytterligare. Ett antal utvecklingsstrategier har diskuterats i denna avhandling. Den riskanalysmetod som därvid har utvecklats kan användas för att analysera de säkerhetsmässiga konsekvenser det får att ändra förenklad dimensionering. En sådan analys är nödvändig för att utvecklingen av förenklad dimensionering skall kunna vara vetenskapligt förankrad.

Följande förändringar av förenklad dimensionering har föreslagits och analyserats för att visa på möjligheterna att minska risknivån och spridningen inom risknivån för en klass av byggnader:

- begränsning av lägsta takhöjden i samlingslokaler,
- begränsning av antalet personer som vistas i en lokal,
- krav på minst 3 utgångar från samtliga samlingslokaler oavsett area,
- krav på 1 meter utrymningsbredd per 100 personer i stället för per 150 personer, och
- krav som formuleras på hur stor den totala utrymningsbredden skall vara som en funktion av en lokals volym.

Analysen utgör även ett exempel på de möjligheter som användningen av riskanalysmetodik medför vid utveckling av förenklad dimensionering. Föreliggande avhandling kan förhoppningsvis inspirera till en fortsatt sådan diskussion och en vidare utveckling inom detta viktiga område, något som i sin tur kan innebära ytterligare framsteg mot en mer konsekvent dimensioneringsprocess.

List of publications

Even though this thesis is a monograph, the content is based on a number of papers published in scientific journals and presented at international conferences together with several reports and articles.

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Contents

1 Introduction

Man's ability to make and control fire distinguishes him from other species. This knowledge is of great benefit, but when uncontrolled, fire poses a serious threat. We must therefore handle fire carefully. In fact, in the context of buildings individuals are not entrusted with deciding what constitutes sufficient care, or the degree of protection required to prevent fire completely, or to prevent it from developing uncontrollably. Our early comprehension that fire could be a major hazard to urban life led to demands on stringent protection measures, even in historical times.

1.1 The historical perspective

Regulations regarding fire safety in Sweden have been traced back as far as the Middle Ages, see for example the first Swedish national law issued by King Magnus Eriksson in 1340 (Donner, 2000; Schlyter, 1862). These regulations placed demands on how fire should be handled and how people should protect themselves against fire. The individual who lit a fire, or who carried burning material from one house or farm to another was held responsible for it until it was extinguished. Towns had their own regulations, founded in the later half of the 14th century. It was decreed that towns be divided into quarters, streets and alleys that were sufficiently wide, and fire watchmen were appointed. Certain kinds of fire hazardous buildings were forbidden, and stone was promoted as a suitable building material by the state. Property owners had to have their own fire-fighting equipment (Nilsson, 1994). Despite this long tradition and demands on fire safety, many Swedish towns and villages suffered serious fires during the 18th and 19th centuries, often destroying whole villages or towns. One example is the fire in Uppsala in 1702, which is illustrated in Figure 1.

Figure 1. Fire in Uppsala on May 16, 1702 (Eenberg, 1704).

The development of fire protection regulations has been governed almost exclusively by experience of earlier fires, which means that development has been slow. Fire safety regulations regarding buildings have traditionally been formulated in terms of *detailed requirements* concerning technical solutions and have left little scope for innovation. Towards the end of the 20th century the need for revision of these regulations became increasingly apparent. The extent of the regulations and degree of detail increased continuously as methods of construction developed. These regulations were gradually changed in the middle of the 20th century from specifying rules for towns, to parts of buildings, so-called fire compartments. The number of detailed requirements grew so large that they became impossible to follow. In order to deal with this situation, thoughts in the construction industry turned to performance requirements. The performance approach is, in essence, the practice of thinking and working in terms of ends rather than means (CIB, 1982). The performance approach is concerned with what a building or building product is required to do, rather than prescribing how it is to be constructed.

Gross (1996) provides a good summary of developments in this field, and puts the whole question of requirements on construction works into perspective by pointing out the existence of performance requirements on buildings in the King Hammurabi code from Babylon, around 3700 years ago. On an obelisk in the Louvre in Paris, there is a quotation regarding a performance requirement on structural safety:

> *"Article 229: If a builder builds a house, and does not construct it properly, and the house which he built falls in and kills its owner, then that builder shall be slain."*

There is nothing stated about *how* the house should be built, e.g. the kind of materials, the dimensions, or the building method; the point being that the final result should be a house that does not collapse and kill someone.

Performance demands regarding fire safety in the type of construction works which buildings constitutes were introduced for the first time in the Swedish Building Code of 1967 (*SBN*, 1967). The use of the term *construction works* throughout the thesis will refer to this particular type (i.e. buildings), and will be used to coincide with the terminology used in the Swedish legislation. The requirements that were introduced in 1967 pertained to the fire protection of load-bearing structures, and were the result of world-leading research in the area. Fire safety regulations in *SBN* (1967) covered over 100 pages and constituted nearly one third of the whole building code. Although performance requirements had been introduced for the protection of load-bearing structures from fire, development proceeded slowly in the rest of the field of fire safety. It was not until the end of 1980 when the current Swedish Building Code (*SBN*, 1980) was replaced by a building code entitled Regulations for New Construction (*NR*, 1988), that the number of detailed requirements was reduced, and some of the demands were expressed in terms of *performance requirements*. As research into fire safety engineering gathered momentum, efforts in Sweden were concentrated on the introduction of performance requirements for safety in case of fire in the middle of the 1990s. This was made in connection with a revision of the building legislation (including acts, ordinances and building regulations containing mandatory provisions and general recommendations). Society's attitudes regarding the responsibility of the builder have become more lenient since the time of Hammurabi, but it is interesting to note that one of the main purposes of introducing performance demands was to clarify the responsibility of the building's developer (owner and/or builder) to ensure that the safety demands were met.

1.2 Reasons for changing the building legislation

The introduction of performance-based regulations in 1994 was the express desire of the Swedish Government. The new building regulations have been published as a building code and will be denoted with its Swedish abbreviation *BBR* through the thesis. *BBR* was the result of a combination of general demands on how regulations should be changed, and specific demands on changes in building regulations. The reasons for these changes, based on a summary of the preparatory work for, and the evaluation of, the revised legislation, are given briefly below (*Boverket*, 1994a, 1997; Prop. 1984/85:161; Prop. 1993/94:178).

- **European Union (EU) harmonisation**
  When the European Economic Area agreement came into force on January 1, 1994, there arose a need to adapt building legislation to the structure and content of the six most important technical requirements for construction works (buildings) given in the Construction Directive. One of these demands was that regarding fire safety. The aim of the Construction Directive was mainly technical harmonisation of buildings regarding approval and control in order to eliminate obstacles to trade. In fire safety, for example, there was

a need to introduce common notations for safety classes and levels of safety requirements (e.g. EI30).

- **Scientific grounds**
  The transition to performance-based regulations is in line with the decision made by the Swedish Parliament to use more scientifically based solutions in building fire safety design and not to rely so much on rules of thumb and experience from previous fires. The intention of the new regulations was that design should be based on the evaluation of what could actually happen if fire should break out in the building in question, and not on mechanical calculations based on standard assumptions. The most recent knowledge in the field should be presented in the form of calculations, experiments and previous experience. Judgements based on previous experience, not supported by scientific fact should be avoided as far as possible.

- **Deregulation**
  There was a general demand at the time for public administration to work towards deregulation and increased efficiency. These demands were very relevant for the area of safety legislation. Constant issuing and updating of detailed safety requirements is very resource-demanding and leads to an increase in the number of regulations, which in turn leads to more complicated and indecipherable regulations. In some sectors deregulation has been an issue for decades, e.g. the chemical industry is still regulated by the second version of the Seveso directive (first version introduced in 1982), while in others the process is just about to begin, e.g. ship fire safety where parts of the International Safety Management Code (IMO, 2002) are about to be changed. As early as in the beginning of the 1990s Sweden was one of the first countries determined to initiate this process for regulations concerning safety in case of fire in construction works in full scale.

- **Simplification of regulations**
  Replacing detailed requirements in building regulations with performance requirements was in line with parliament's decision, contained in the government bill concerning the simplification of the regulations, directions and guidelines issued by government authorities (Prop. 1983/84:119). It is in the interest of both the state and the construction industry that regulations are easy to in-

terpret and applied similarly throughout the country. Uniformity of application is important in guaranteeing legal rights and ensuring the same degree of service for all citizens, but they may come into conflict with other aims, for example, greater local autonomy. Another example of conflict is the nomenclature resulting from EU harmonisation. A surface covering class can be denoted C-s2,d0, which is hardly a simplification, since its previous name was simply class II, and the term *fire protection cladding* has been replaced with the "abbreviation" $K_2$10/B-s1,d0.

- **Local government**
  One of the aims of the revision was to increase the degree of autonomy of local authorities regarding construction, for practical reasons as well as being a matter of principle. Increased opportunity for this was afforded by the revision of the Planning and Building Act (*PBL*, 1987), which allowed municipalities to determine how to best organize planning and building issues. Another reason was to increase the flexibility of the construction process.

- **Clearer division of responsibilities**
  There was an ambition to create a clearer division of responsibilities between the state, municipalities and individuals. One of the measures taken was to clarify the responsibility of the developer (owner and/or builder) has the responsibility of ensuring that building regulations are followed, and that the safety of the building is correctly reviewed. The local authorities (municipalities) are responsible for ensuring that current legislation is adhered to, but have no mandate to approve technical solutions or investigate details if there is no obvious reason for such control.

- **Flexibility, quality and freedom of choice**
  One of the advantages of performance-based requirements over detailed requirements is that the scope for promoting variation in design and thus the possibility of expediting the solution necessary if the prerequisites are changed. It was felt that detailed requirements were hampering development and expansion, while not always resulting in the desired level of safety. Problems arose in the design of modern, more complex buildings. The practical solution was often negotiations with the local authorities, which led to considerable national variation in the level of safety requirements. The revision of building legislation and regulations therefore included

allowing individuals greater choice and scope so that design solutions could be adapted to specific needs, new technology could be introduced more quickly, new knowledge and experience implemented, new ways of using materials and structures created, thus encouraging innovation and creativity. It is also important that regulations are formulated in a way that high-quality construction is promoted.

- Reduction of costs
  The cost of construction increased considerably in Sweden at the end of the 1980s and beginning of the 1990s. By allowing adaptations of solutions to local needs and increased competition it was hoped that rationalisation, gains through coordination and new solutions would be possible, leading to savings in costs without having to make concessions in public interests like safety in the case of fire.

1.3 General principles of new building regulations

The details of the new legislation and building regulations will be presented later, here a short summary is given by way of introduction. The reasons behind the paradigmatic shift in regulations concerning safety in case of fire in buildings led to the introduction of the Building Regulations (*BBR)* issued by the Swedish National Board of Housing, Building and Planning (*BBR*, 1993) in 1994. A number of revisions resulting in amendments have been made since then. These have not caused any significant changes in the structure or content of the regulations. The most recent version, which was published as a building code in printed form, is *BBR* 2002, and unless otherwise stated, *BBR* in the text below refers to this edition. At the same time as *BBR* was introduced, a revision of building legislation was completed, which changed the grounds on which the planning and design of fire safety measures are based for several stakeholders (actors) in the construction process.

Regarding fire safety measures, the main actors are the *developer* (the owner and/or builder), the *fire safety designer* who is often engaged by the *architect* to design the fire protection systems, and the local *building committee* and *building officials*, which supervises the construction process. The *architect* and fire safety designer work together with other design engineers, responsible for other systems in the building, as a design team. The role of the *fire* *and rescue service* (fire brigade) in the construction process varies depending on the policy of the local municipality.

BBR clarified the *responsibility* of the developer and offers better *opportunities* for the designer to come up with innovative fire protection solutions. Plans and documentation would no longer be approved or "rubber-stamped" by a local authority official (the local building committee). It would now be the responsibility of the developer to verify that the proposed solution fulfilled the demands on fire safety. The majority of the previous detailed requirements in *NR* (1988) now became general guidelines, and could still be used to satisfy demands on fire safety (i.e. the performance requirements). This method, after some modifications, became known as *the prescriptive design method*, as it prescribes specific technical solutions. The method is uncomplicated, based on classification, and verification is often carried out by following a checklist. At the same time, the opportunity was created to design completely new solutions, and to use new techniques through the *analytic design method*, also called the *fire safety engineering design method*. The fire safety designer then uses analytical methods and/or experiments to show that the fire protection measures are adequate (i.e. verifies the solution). The demands placed on verification, documentation and review result in an increased need for qualified fire safety engineering competence during the design phase compared to when the prescriptive method is used.

It is in no way self-evident that the introduction of performance-based demands on fire safety into the building industry, which is known for being traditionalistic and conservative, will be successful with respect to objectives mentioned earlier (see Section 1.2). Generally speaking, if new concepts are to be incorporated into an existing field of professional activity it is required that the right infrastructure, composed of some basic conditions, is present:

- "The acting parties recognize the significance of these concepts and their contribution to improving the results of their work,
- clear routines and friendly working tools for smooth incorporation of the new concepts are available, and
- young new professionals are educated to regard the new concepts as an integral part of the profession." (Becker, 1999)

Apart from the above, there is also a need to be able to express the desired characteristics of the building in terms of clear, unambiguous and measurable demands. Creating a set of regulations and design methodology allowing society to control fire safety will be demanding and will take a considerable time. Purposeful and long-term efforts will be needed to meet the requirements in Becker's list. These in turn will require considerable resources. The regulatory system must also be sufficiently adaptive so that the continuous developments in fire safety design can be utilized. If scientific fundamentals are not consolidated in fire safety design, there is a risk that supervision by the authorities will be made more difficult and resource demanding then before.

1.4 Unsolved problems and unanswered questions

Sweden was one of the first countries to introduce performance-based demands for safety in case of fire in the building regulations. The problems in being a pioneer country changing regulations are that there are no examples of how the demands can be formulated, no design methods available and insufficient competence in the area. The development of methods and skills takes time. It may be difficult to convince a conservative industry to devote resources to development when there is no clear short-term benefit.

One possible strategy in such a situation would be to devote resources to the development of design methods and rules before introducing new regulations. Again, it will be difficult for the construction industry to justify these resources when the benefits will not be enjoyed immediately. There will be no demand for the new design method until the advantages of performance-based regulations are made clear, and this will not happen until the regulations have been introduced and adopted.

Another strategy is to introduce the new regulations before the engineering design tools and methods have been fully developed. The construction industry would then be able to evaluate the potential advantages before making long-term investments in development, but also before the knowledge and methods required for quality control are available.

It may be hoped that those involved in the construction industry will contribute to a greater degree to research and development once the advantages of performance-based demands become apparent. However, there is also a danger that the industry will not value high-quality fire safety design sufficiently in monetary terms, and that there will be no research and development effort. This may result in insufficient verification, which means that inadequate solutions may be accepted, and that the quality of fire protection of construction works will be undermined in the long run.

In Sweden, the latter strategy was chosen, i.e. the regulations were introduced before the means of quality control of the design process had been established. The regulations were thus implemented before investigations had been made into the effects on society's ability to control safety in case of fire. Design methods had not been fully developed, and few recommendations or guidelines had been published by the national authority (government agency) involved, that is The National Board of Housing Building and Planning (*Boverket*). When Sweden introduced *BBR*, there were essentially no international examples to follow. A few countries had similar ideas, but no concepts ready for implementation. Some information was obtained from New Zealand, where performance-based regulations had been introduced a year or so earlier, but no systematic follow-up of their experiences had been made at that time.

An iterative process characterized by "trial and error" regarding the development of both regulations and design methods was thus anticipated in Sweden. Skilled fire safety engineers were, however, available thanks to a university programme established in 1986. When *BBR* was introduced about 100 fire safety engineers had been granted degrees. Engineering analysis had already been applied, although to a limited degree, in the design of some kinds of buildings where the previous regulations had proved to be inadequate, before the introduction of the new legislation. The introduction of *BBR* provided completely new opportunities for fire safety engineering design, but the lack of guidelines and know-how was substantial. Accordingly, the authorities responsible for developing the regulations must be active in following up the quality of fire safety measures and ensuring that adequate resources are available for research. It will be necessary to revise the regulations regularly in order to solve problems encountered as they arise. If this is not realized, it will be necessary to limit the freedom of the fire safety designer, for example by re-introducing detailed requirements, in order for society to be able to control fire safety.

1.5 Purpose and objectives of this thesis

Through the introduction of performance-based regulations, society has released its strict control of fire safety and now relies on the ability of the developer and design team in an area where there is a risk of political consequences, e.g. questions raised in parliament and courts of public inquiry, if the new system should fail. The main purpose of this thesis is to elucidate the effects of the introduction of performance-based regulations on the ability of society to control fire safety in buildings. An analysis of possible shortcomings of the new regulations will provide information on the development required. Another aim is to provide recommendations on how these shortcomings can be dealt with. The objectives of this work were as follows:

- to investigate changes in the conditions and prerequisites for the design of fire protection of buildings,
- to identify and summarize the problems encountered in achieving a satisfactory level of safety in case of fire when applying the performance-based regulations, and
- bearing in mind these problems, propose specific solutions and indicate areas where development is required.

1.6 Overview of the structure and contents of this thesis

Following the introduction, Chapter 2 provides some background information on the need for legislation regarding fire protection in buildings. The structure of Swedish building regulations and the design methods that can be used are described at the end of the chapter. Chapter 3 presents some basic perspectives which form the basis for the initial study of the problems introduced by changing the regulations. In this chapter a framework based on three levels, used to analyse how society can control the risks associated with a given activity, is presented. This framework was used to create a general structure for the whole study. Chapter 3 also includes the characterization of fire risk, together with a description of quantitative risk analysis and how the uncertainties in risk calculations can be structured. The perspectives in this chapter are essential to perform a detailed study of how the design method affects the risk in buildings.

Chapter 4 describes the general structure and methods used to analyse how changes in building regulations have affected the ability of society to control fire safety. The analysis is based on a survey of the demands in the building regulations and a study of fire safety documentation from a large number of building projects in which it is apparent that the new regulations have been used. Cases of poor quality identified in the documentation are studied qualitatively and quantitatively. The practical consequences of problems and ambiguities in the regulations are illustrated and investigated through extensive calculations for a certain class of buildings in Chapter 4.

The comprehensive analysis of the effect of changing regulations is based on the three levels described in the framework presented in Chapter 3. These levels correspond to the three different levels at which society can control the risk of fire in a building by issuing regulations. The analysis and results are presented in three separate chapters (Chapters 5-7), one chapter for each level, arranged in the same way as the general structure, which is presented in Chapter 4. First, a brief analysis is made of the changes in the way in which the specific level was regulated in terms of how rules were formulated and how compliance with the rules is assessed. The second step is to identify problems associated with societal control of fire risk in the present situation. Some of these problems are analysed in detail with both qualitative and quantitative methods. At the end of each chapter, solutions to the problems identified and the need for development are discussed.

In Chapter 5 the outlined analysis structure is applied to the level of risk control denoted *safety output*. At this level, demands are placed on the objectives and performance of the building design and the safety systems. In Chapter 6 a similar analysis is performed on the level of risk control denoted *safety procedures & safety case*. At this level, demands are made on the way in which the design is derived and documented. The third and final level of risk control is denoted *direct risk control*. On this level demands are placed on the design solution and safety measures themselves (Chapter 7).

The work described in this thesis is focused on the *design* of fire safety measures, but there are indications that coordination with other phases in the life cycle of a building is crucial. Chapter 8 describes the connections, and need for coordination, between the design phase and the operational phase that are important in order for the building to meet the demands on fire safety once it has been commissioned. Thereafter, the results obtained in this work, including specific recommendations and the tools developed, are discussed in Chapter 9, together with comments on some of the challenges remaining in the area. This is followed by the conclusions in Chapter 10, where specific suggestions are made to improve the efficient control of fire safety.

Finally, a short glossary of translated terms and list of abbreviations is presented containing Swedish translations of English key words, English explanations of the abbreviations used for building (i.e. construction) legislation and regulations, and English translations of names of Swedish authorities. The glossary is followed by a list of the nomenclature used in this thesis and the reference list. Most of the input data and the results of the risk calculations are presented in Appendices A-F, which constitute the final part of this thesis.

1.7 Limitations

Building regulations place demands on the design of a building such that the technical requirements will be met during an economically feasible time, usually the lifetime of a building. The life cycle of a building can be divided into various phases. Figure 2 illustrates the division used in this work, which is based on the definitions of the Swedish Centre for Terminology (TNC, 1995) and The Swedish Environmental Protection Agency (SEPA, 2003).

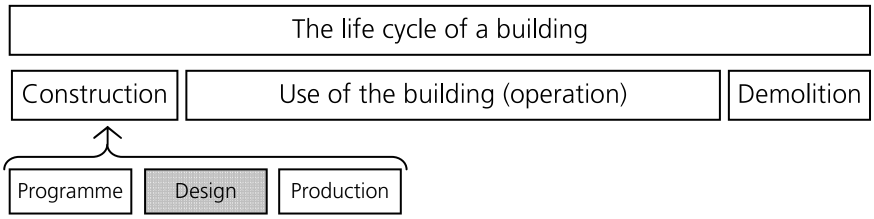


Figure 2. The various phases in the life cycle of a building.

The construction phase is the first, and is itself divided into three subphases; programme, design and production. During *the programme phase*, the technical and functional demands on the building are defined. The costs and expected revenue are calculated, a timetable is drawn up and the information required for design is assembled. During *the design phase*, the architectural drawings and other documentation are produced. An important part of this process is the choice and design of the various fire protection systems included in the building. During *the production phase*, the building is constructed based on the plans and drawings produced in the design phase.

It is often very costly to change a building once it has been built, and it is thus important that the fire protection systems are correctly designed from the beginning. The functioning of fire protection is not only dependent on sound design. The protection systems must be constructed according to the specifications, and must be operated and maintained during the operational phase of the building. As the aim of this work was to investigate the effects of changes in the building regulations (applicable to the design of the building), it is natural to place the greatest emphasis on the design phase, particularly the design of the fire protection of construction works. Connections to the operational phase will be elucidated in some contexts.

Fire protection of the construction work is only one part of the total fire protection of a building. The risk of fire in a building is greatly affected by the kind of activities being performed, and by the company performing them. Organisational factors, e.g. training, organisation, systematic safety activities and safety culture, are of great importance, but are not regulated in *BBR*. Therefore, the effects of organisational fire safety on the total risk of fire are not dealt with in great detail.

One of the most obvious changes in the building regulations is that responsibility now lies with the developer to verify that fire safety demands are met in the design phase. Various methods can be used depending on how the fire protection has been designed. This work deals exclusively with verification using computational methods. This is the dominating method used. Other methods used (to a limited degree) are testing according to standards and ad hoc tests.

The technical requirements for *safety in case of fire* are specified in five points in the Ordinance on Technical Requirements for Construction Works etc. (*BVF*, 1994). It has been possible to apply well-established analytical design methods regarding demands on fire protection of load-bearing structures and prevention of fire spread to adjacent buildings according to previous building regulations. The greatest practical change in the application of the new building regulations has been made in the design of evacuation safety. The limit of applicability of the new design methods are severely tested in the design of evacuation safety in assembly halls in public buildings where large numbers of people gather, but where investments in fire safety improvements cannot be justified by short term cost-benefit analysis. In order to illustrate the problems associated with this kind of design, evacuation safety in assembly halls is studied as examples in the detailed analyses.

According to the fire section in the building regulations (Chapter 5), evacuation must be possible regardless of whether help is available from the fire and rescue services. Therefore, no consideration was taken of rescue operations in the modelling of the course of fire and evacuation in this work.

2 Changes in building regulations

Prescriptive requirements involve demands on the use of specific technical solutions regarding products, materials and design. Performance-based requirements instead focus on the characteristics of a building or structure, parts of it, or a product, when used for a specific purpose, and are expressed in terms of the final result (ends), rather than the method of achieving it (means). Such requirements do not limit the choice of design, material or method (Becker, 1999; TNC, 1995). The Swedish building regulations have been successively changed from exclusively prescriptive requirements to a greater degree of performance-based requirements. As a consequence of the factors mentioned in Section 1.2 *BBR* was introduced, which must be seen as a major step in this process, although the transformation is still not yet complete.

Section 2.1 provides a short discussion on why society needs to place demands on safety in case of fire at all. This is followed by a description of the Swedish regulatory structure for requirements on construction works in Section 2.2. Methods prescribed in the building regulations for the design of fire protection are presented in Section 2.3, and Section 2.4 debates the issue of whether there is cause to question the quality of design when applying new approaches.

2.1 The role and structure of safety legislation in societal risk control

Many types of activities are associated with risks that have the potential to cause accidents resulting in a large number of fatalities. Such risks are normally associated with certain types of major hazard industry or technologies, for example, the transport, chemical, oil or nuclear power industries. However, other kinds of risk can also pose threats of such magnitude, for example a fire in a building. A relevant question is whether it is justified for society to control protective measures against these risks, or whether those involved, i.e. those who create or are exposed to this risk, should deal with the matter.

Section 2.1.1 presents some of the arguments used to justify societal involvement in the control of public safety in general and fire safety in particular. There are a few arguments against the need for society to take responsibility for safety, but no realistic alternatives have been presented in the extensive literature on the subject. In Section 2.1.2 a general discussion is presented of different approaches to societal risk management, followed by a proposed structure for fire safety regulations in Section 2.1.3.

2.1.1 Arguments for societal control of fire safety

In Figure 3 a compilation of data based on statistics from the Swedish Rescue Services Agency (SRSA, 2004a) shows the average yearly number of fatalities during the 1990s for the major accident types in Sweden. Quite surprisingly, the most frequent type of accident leading to fatalities is classified as *Unknown*, i.e. the circumstances associated with the accident were unclear, but after more detailed studies it has been found that falls constitute 75% of this type of accident (SRSA, 2004a). The average yearly total number of fatalities due to accidents for this time period is 2533.

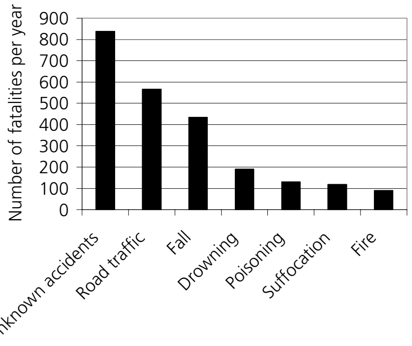


Figure 3. *The average yearly number of fatalities in Sweden caused by the most frequent accident types for the time period 1991-2000 (based on SRSA, 2004a).*

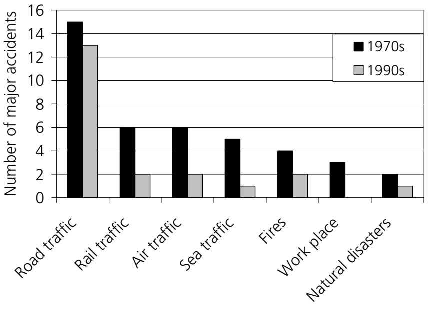


Figure 4. *The number of accidents with five or more fatalities for different accident types for the 1970s and the 1990s (based on SRSA, 2004a).*

Each year, about 100 people die in Sweden as the result of fires in buildings (see Figure 3). Although most fires involving fatalities affect only one or a few people, fire can have disastrous effects, such as many fatalities in one fire (see Figure 4), or considerable material damage. An example of this is the dance hall fire in Göteborg in 1998. Accidents such as this create special needs as additional strains are placed on society compared to the case of smaller fires. Examples are national trauma and depression, despondency, and feelings of insecurity and uncertainty among large groups of people (SHK, 2001); social dimensions that do not normally require intervention in the case of fires with limited consequences. The reasons behind these are that a large number of people are involved (mass psychosis), and that we are reminded of the vulnerability of society and its inadequacies (SHK, 2001). Furthermore, the ability of society to cope with these events is limited. In the case of fire in the home, the public resources available in the acute phase are usually more than adequate, although the accident is dreadful for those involved. The fire and rescue services perform their roles and the general public does not feel that there is any limit on the capacity of these services. In more serious accidents, the demand for resources in the acute phase may be greater than the supply, and it may take time to gather the necessary resources. The Tsunami disaster in Asia on 26th December 2004 is a striking example, as are the fires in the World Trade Center after the terrorist attack on 11th September 2001. As building fires can lead to catastrophes that societal resources (e.g. the fire and rescue services) cannot cope with, this kind of risk must be controlled. The needs that arise must be met through a combination of various crisis management measures, of which preventive measures (e.g. fire protection of construction works) are an important component (FEMA, 1997). Both the yearly number of fatalities and the potential for accidents with serious consequences call for societal control.

Studies have also shown that the risk of unwanted fire is perceived as a serious threat by the public. A study by Enander and Hede (2004) showed that when heads of local authorities were asked to rank the most serious threats, fire was among the top five. One reason for this is that fires occur often and that serious fires are given considerable coverage by the media. We are continually reminded of the risks and the damage caused. Other explanations are that the phenomenon of fire is characterized by being uncontrollable at the time of the accident, those who are affected are exposed to danger unwillingly, the event is connected with catastrophe, and fear is associated with such a horrible death. An example of behaviour as a result of people facing a horrible death was that during the fire in the World Trade Center that led to the collapse of the twin towers, many people chose to jump rather than remain in the burning building (Averill et al., 2005). Several of these factors contribute to the perception of the risk as high, according to research on risk perception (Slovic et al., 1982), and therefore it is reasonable to assume that they also contribute to the feeling that there is a need for society to control such risks, as the ability of the individual to influence his or her exposure to fire risk is limited. In an apartment, for example, the fire risk to which a person is exposed is affected by the behaviour of the neighbours and the kind of protection available in their apartment preventing the occurrence and spread of a fire. The possibility of reducing this risk is small. In public buildings, for example a hospital, library or cinema, it can be difficult to assess how safe the building is with regard to fire. Once you are inside the building it is almost impossible to influence the level of risk, and it is not always possible to use an alternative facility.

In order to determine what constitutes an acceptable level of fire protection, it is necessary to weigh the risk level against the investments in protection. Problems arise when the opinion of the developer differs from that of a societal point of view. From the perspective of national economics, a deregulated market will not always ensure the best balance due to spill-over effects (Mattsson, 2000; Merkhofer, 1987). Spill-over effects, or *externalities*, as they are also called, are costs or benefits not always reflected in the decision maker's calculations. Situations that lead to non-optimal decisions, from the point of view of society, can arise for several reasons. In some kinds of buildings it is possible to assess what constitutes an acceptable risk by performing a cost-benefit analysis of risk-reducing measures (Johansson, 2003; Ramachandran, 1998). The easiest case is that in which damage or injuries can be measured in monetary terms, and the decision maker bears the investment cost of the fire protection and the cost of any damage or injuries. Examples of such buildings are industrial plants and warehouses where the potential material damage is high and the ability of the company to resume production determines if it will survive or not. In such cases, the risk of externalities is low. In other kinds of buildings, e.g. public buildings, the incentive for good fire protection is not as high. The value of public buildings is often lower than that of industrial premises and warehouses, and they are often fully insured (Lundin & Olsson, 2000). Injuries are suffered mainly by third parties, i.e. the people in the building, and this cost is seldom included in cost-benefit analysis by a developer. The level of fire safety demanded by society is often regarded as adequate. This kind of reasoning may appear cynical but appears to be common practice, and in such cases, externalities are common. The question of ownership of the building may also be complicated, and the developer, and design team often adopt a short-term view of the economic situation. In these cases, it is important that society makes minimum demands on fire safety, not only to protect the public, but from an economic point of view to avoid sub-optimization of society's resources (Ramachandran, 1998). The effect of externalities can be reduced through legislation, but opinions are divided regarding the method suitable for determining an acceptable level of risk from a societal perspective. In many cases, the acceptable risk is determined indirectly by political decisions, which are not necessarily optimal from a national economic viewpoint (Ramsberg, 1999).

Another argument for the suitable level of safety to be decided by authorities and not the construction industry is that the optimization of a suitable level of safety cannot be limited to fire safety alone. There is a need for cross-sector coordination since society's resources (e.g. total budget) for managing all types of risks are limited. If too much is devoted to one particular area, this may cause a lack of resources for effective measures in other areas (Mattsson, 2000; Ramsberg, 1999). Therefore, a suitable minimum level must be determined taking into account the distribution of resources in different areas. This is, of course, difficult to achieve, but efforts have to be made. This naturally is the task of the authorities as the developer has neither the breadth of experience nor mandate required.

The need for society to determine what constitutes a reasonable level of fire protection can also be justified by the fact that the behaviour of an individual in the long-term perspective, it not always rational, at least not from the societal perspective. If individuals are allowed to freely choose fire safety levels it is possible that many would choose a level considerably lower than regarded as appropriate from a societal view point. When making decisions, people tend to prefer certain gains over uncertain ones, even if the expected value is the same, i.e. the so-called certainty effect (Tversky & Kahneman, 1981), and vice versa for losses. In other words, a quick profit is in most cases preferable to an uncertain one that may materialize later. The benefit of fire safety can be compared to an uncertain gain in the future, as it is not certain that the need for fire protection will arise. Fire protection may thus seem meaningless, unless a fire actually occurs. The cost of fire protection is, however, felt immediately. Due to the certainty effect, there is a risk that ordinary people would choose to use the money for something else, for example, consumption (a certain and immediate gain), rather than invest it in something such as fire safety (an uncertain gain in the future). This kind of behaviour may lead to non-optimal use of society's resources, and mean that some decisions must be made by society through legislation. In the literature, this is called paternalism (Merkhofer, 1987) and means that individuals are seen as not being capable of making effective decisions by themselves. Whether or not this can be used as an argument in favour of legislation is the subject of discussion as it infringes personal freedom.

Lack of information, or incomplete information, is a less controversial reason for fire safety legislation. Regulations specify, for example, a suitable load-bearing capacity and the appropriate degree of fire protection. If no such demands are made, it may be difficult for an individual to determine what is acceptable and reasonable. Furthermore, it is very costly to correct mistakes or deficiencies in buildings after production, in other words, it is important to get things right from the beginning (*Boverket*, 1994a).

2.1.2 A proposed structure of regulatory regimes for risk governance in general

Risk can be controlled by a number of societal activities. Legislation is one of several instruments that can be used to influence the activities or behaviour of an individual, as well as companies and organizations, and thereby indirectly control safety. Other examples are economic instruments, such as taxes, fees and subsidies, as well as information. The reason why society has chosen to use legislation in this case is that the consequences of fire are serious and irreversible (sometimes leading to death). Full compensation can never be made to the victims or their families. Legislation also provides the possibility of applying legal sanctions when regulations are not followed.

If one reviews how legislation is used to manage the broad spectrum of risks in society with the potential of causing harm to people or the environment, i.e. everything from infrastructure, to BSE (mad cow disease) and genetically manipulated crops, major differences are found. Public risk management strategies, and thus the regulatory approaches taken, vary significantly, which creates totally different conditions for the industries generating the risks (Kirchsteiger, 2002). How can this be? The answer will not be found by studying the methods applied in the various risk management processes or the safety level suggested as acceptable in different areas or applications. A wider perspective has to be used to identify and analyse the underlying differences that determine how different risks are managed and controlled in society. Considerable effort in risk research has been focused on this during recent years, and such a widened perspective has been introduced as the concept of *risk governance* during the past decade. A detailed discussion of the concept of risk governance can be found in Halachmi (2005). In brief terms, risk governance, in the context of public policy making, includes the government's and public authorities' tools and abilities involved in the decision making processes called for by hazardous activities, and their formal and informal means of managing risk. This includes political, social, legal, ethical, scientific and technical dimensions (Heriard-Dubreuil et al., 2002). Risk assessment and management take place in the context of a societal risk governance system where specific actors are entrusted with the task of assessing and managing the risks. The governance system defines many of the fundamental and important requirements for the risk management process in which the objective can be to achieve risk control. Löfstedt and Renn (2004) present the following examples of important issues that should be addressed when developing a governance system for the purpose of public policy making and the management of risks of public concern:

- the use of science in the decision-making process,
- resolution of conflicting interests,
- risk communication,
- social justification of the risk (and the activity generating the risk),
- public involvement in the risk management process,
- social trust and public confidence in the risk management process,
- strategies for the treatment of uncertainties, and
- dealing with accountability.

As previously mentioned, the strategies used to address these issues for different types of risks vary. Löfstedt and Renn (2004) suggested five categories that can be used to systematize different types of main strategies or styles of risk management.

1. *"Routine risk management* for fairly simple risk problems with low level of uncertainty and no ambiguities involved.
2. *Risk-based management* for complex and scientifically controversial risks with some uncertainty and hardly any ambiguity.
3. *Precaution-based management* for highly uncertain and unknown risk consequences but little ambiguity about the social evaluation of these consequences as being positive or negative for society.
4. *Discourse-based management* for those risks where the potential consequences are highly controversial and even the desired outcomes raise concerns and conflict.
5. *Crisis risk management and emergency response* which refers to the coping mechanisms in a crisis situation. Crisis could be triggered by accidents, new challenging studies, communication failures or the sudden erosion of trust."

These risk management styles make use of different concepts in selecting objectives, assessing and handling data, and finding the most suitable procedure for balancing cost-effectiveness with under- or overprotection of the public. Other differences are the actors involved in the process and the types of conflicts that arise.

The management of fire risk in buildings has traditionally been placed in the *routine risk management* group. Fire risks are well known, both the causal chains and the magnitude of the risk. Although uncertainties can be perceived as large for a specific building, the yearly outcome in terms of the number of fatalities on a national level can be fairly well predicted and is quite constant (SRSA, 2003a). With this style of risk management the goal is to ensure that all relevant risk-reduction measures are enforced, which is often achieved by issuing regulations as detailed requirements, i.e. some form of direct risk control. This approach is dependent on data being available through statistical analysis, and is therefore dependent on empirical experience.

Although it may not seem likely, changing risk regulations can affect several of the issues relevant in risk governance, and affect the choice of the most suitable risk management approach. For example, new uncertainties may be introduced, and important attributes of the risk can be affected, e.g. the extent of the consequences. In addition, the requirement of public involvement can be triggered by both scientific development and the way in which the responsibilities of the actors involved in the risk management process are perceived.

If changing the regulations weakens the societal control of risk it may have an effect on public confidence in the process, which can be contra productive to the underlying reasons for changing the regulations. Reduced risk control can, in the long run, lead to serious accidents which also threaten public confidence. In a number of areas major accidents have triggered public inquires and the revision of risk regulations, e.g. The Three Mile Island nuclear power plant accident, the Piper Alpha oil rig accident and the accidental chemical release in Seveso, to mention a few.

One of the explicit objectives of the new building regulations (*BBR*, 1993) is to promote the use of analytical tools and research in order to facilitate the design of new and innovative buildings. The consequences of this might very well be that the fire risk in buildings will become more complex and uncertain, which may mean that the *risk-based management* strategy will be more suitable for managing and controlling fire risk.

Therefore, a thorough analysis of how risk control is affected by changing regulations is justified. As a starting point, a study was made of regulatory frameworks for risk control in different sectors believed to be characteristic of the two risk management styles which seem appropriate for fire risk, i.e. the routine and the risk-based risk management styles. For both these styles the goal with risk management it determined by law or statutory requirements. The role of risk management is to ensure risk control by implement risk reducing measures.

2.1.3 A possible structure of fire safety regulations

A consequence of the arguments in Section 2.1.1 is that a fire safety engineer should not have complete freedom to determine the level of safety that is suitable or acceptable, especially bearing in mind that his or her employer could make considerable savings through a low level of safety. Society must enforce some kind of risk control and determine the minimum safety requirements so that the moral obligation on the individual engineer is reasonable (as indicated in Figure 5). As indicated in the introduction (see Section 1.1) we have had a long history of control of fire risks through legislation.

Figure 5. It can be difficult for the individual engineer to balance safety and costs regarding fire safety in the construction process.

The reasons for regulating fire safety are the same as those in several other areas, for example, air travel, the railways, nuclear power, and the oil and chemical industries. Various kinds of regulations apply to safety in these areas, and these are referred to as *regulatory regimes*. A particular regulation regime is characterized by what the rules are intended to regulate, i.e. how an activity can be controlled by the authorities. Three main kinds of regulatory regimes can be identified (Hopkins & Hale, 2002): *performance-based regulation* (goal oriented), *regulation governing safety management systems and safety cases*, and *prescriptive regulation* (direct risk control of the actual activity). All three regimes have the same aim, namely to ensure that activities are pursued with an adequate degree of safety through the application of external demands. The categorisation provides a topology of "pure" regimes in order to create a structure based on the type of demands made in the regulations. This topology is then used to understand and analyse how the actual regulations are formulated. These categories are not mutually exclusive, and it has been found in various areas that the choice of regime affects the tasks of the authorities, the freedom of the practitioner, and places demands on both the practitioner and the inspector (or reviewer). It is, therefore, seldom efficient to combine regimes, and one type often dominates over the others.

The following sections provide short descriptions of the three regimes defined above. The main body of this thesis (Chapters 5-7) will deal with the questions and problems of applying these regimes in practice in the area of fire safety design.

2.1.3.1 Performance-based regulations

Performance-based regulations define the goals of a particular activity and are usually called *outcome oriented* or *goal oriented*. The focus is on *what* is to be achieved, and not *how*, regarding both technical solutions and the methods used to arrive at these solutions. When applying this regime, the overall safety goals of a particular activity are set out, and it is necessary to demonstrate that these goals are fulfilled. One requirement is that the goals are measurable, and that the characteristic to which the goal is related actually controls what the demand is intended to regulate. There is often a considerable need for guidance in order to avoid arbitrariness and variation in quality and level of safety. This will be investigated in much more detail in Chapter 5.

2.1.3.2 Regulations governing safety management systems and safety cases

Regulations governing procedures and working methods result in the control of safety by defining *how* decisions are to be make, and *by whom*. These regulations can also place demands on the methods to be used to develop or formulate a solution, and the parameters to be taken into consideration when evaluating a solution or a decision. The degree of detail can vary considerably, from specifying what an employer must do to fulfil his or her general responsibilities in a certain area, e.g. providing a safe working place, to detailed specifications of specific working procedures, e.g. the content of training courses. In safety legislation, these kinds of regulations usually place demands on the safety management system in a company, for example, the organisation of the system, or the content. Such a management system offers a means of defining the procedures a company must carry out in order to themselves create detailed regulations, and will be described in more detail in Chapter 3. These kinds of regulations are sometimes formulated so as to place demands on a practitioner to show that he has identified, evaluated and controlled the risks in question. This is usually called a safety case or a safety report. This regime will form the basis for Chapter 6.

2.1.3.3 Prescriptive regulations

Prescriptive regulations provide rules for *direct risk control* of an activity and have a considerable effect on the design of the activity and its safety systems, and the way in which the activity is run. The aim of the regulations is to place demands on the system and its state. This means that there is no freedom to make decisions at the operator level, i.e. those executing specific tasks. Such regulations seldom state the general aim of the demands, and are called prescriptive regulations or detailed demands. In Chapter 7 a thorough analysis of the prescriptive rules in the area of fire safety design will be presented.

2.2 Regulatory structure for safety in case of fire of construction works

Some general perspectives of the new building regulations were briefly reviewed in Section 1.3. In this section a more detailed presentation of the legislation and regulations will be given in order to illustrate how regulations are connected to the design of fire safety in construction works (i.e. buildings) in Section 2.3.

The structure of the current Swedish building legislation is the result of the complete revision of the legislation which was brought about by demands to implement the EU Construction Directive (EU, 1988) and its implementation document, Safety in Case of Fire (EU, 1990) in Swedish legislation. During the course of this revision, which led to the introduction of performance-based regulations in 1994, the so-called Nordic Five-Level System (NKB, 1978) was used to obtain a hierarchical regulatory structure. Most other performance-based regulatory frameworks and structures are variations of the Nordic Committee on Building Regulations (NKB) system. It should be pointed out that the NKB system was developed to aid authorities in drawing up regulations for buildings. The builder, owner or other stakeholders (e.g. insurance companies) may have their own demands in addition to those of the authorities. The Swedish regulatory system mapped on the NKB model is presented in Table 1.

The Swedish legislation regulating fire protection of construction works is as follows:

- the Act on Technical Requirements for Construction Works, etc. (*BVL*) 1994,
- the Ordinance on Technical Requirements for Construction Works, etc. (*BVF*) 1994,
- the Planning and Building Act (*PBL*) 1995, and
- the Planning and Building Ordinance (*PBF*) 1995.

The *BVL* (1994) was added to building legislation and covers mainly the technical requirements, i.e. the essential performance, of the building, which was earlier included in the *PBL* (1987). One of the technical requirements is concerned with fire safety and is laid out in five points in the *BVF* (1994).

"Construction works must be designed and built in such a way that in the event of the outbreak of fire:

i. the load-bearing capacity of the construction can be assumed for a specific period of time,

ii. the generation and spread of fire and smoke within the construction is limited,

iii. the spread of fire to neighbouring construction works is limited,

iv. people in the construction on fire can leave it or be rescued by other means, and

v. the safety of fire and rescue service personnel is taken into consideration."

Table 1. Swedish regulatory structure based on the Nordic five-level system (NKB, 1978).

Level	**Basic heading**	**Descriptions/comments**	**Regulatory document**
1	Goal	The goal addresses the essential interests of the community at large with respect to the built environment, and/or the needs of the user or consumer.	*BVL* (1994) *PBL* (1995)
2	Functional requirement/ statement/ objective	Building- or building-element-specific requirements. A functional requirement addresses one specific aspect or required performance of the building to achieve the stated goal (note that other functional requirements may contribute to achieving the same goal).	Technical requirements in *BVF* (1994) and corresponding main sections in Chapter 5 of *BBR* (2002)
3	Performance requirement	Actual requirement, in terms of performance criteria or expanded functional description. This is also sometimes referred to as *performance requirement*, and whenever possible, should be stated in quantifiable terms.	Mandatory provisions in *BBR* (2002) and *BKR* (2003)
4	Verification	Instructions or guidelines for verification of compliance.	Administrative and computational procedures in *BBR* (2002) and *BKR* (2003). v*entilation system* guidelines (*Boverket*, 1994b) and evacuation guidelines (*Boverket*, 2004b)
5	Examples of acceptable solutions	Supplements to the regulations with examples of solutions deemed-to-satisfy the requirements, e.g. prescriptive requirements on technical solutions.	General recommendations in *BBR* (2002) and *BKR* (2003) or in approved documents.

After the revision, *PBL* and *PBF* were mainly concerned with administrative procedures regarding the construction process, division of responsibility, supervision and control, while some demands were placed on accessibility by the fire and rescue services. However, these changes were made as amendments to the act and ordinance, and the reference is to the year 1995 when these amendments are included, instead of 1987 (when they are not).

The Swedish National Board of Housing, Building and Planning (*Boverket*) is authorized by the government to issue regulations pursuant to the technical requirements for construction works (in the *BVF)* and demands on accessibility for emergency vehicles and for construction, demolition and site improvement work (in the *PBL*). These regulations constitute the Building Regulations (i.e. the building code *BBR*), and the Design Regulations (*BKR, 2003*) which deals with design of load-bearing structures. Both of the above mentioned are implementation regulations, which means that they define society's minimum demands and clarify the meaning of legislation. Clarification is necessary so that the objectives of *BVF* and *PBL* can be realized in design methods and applied in construction, but also to allow architects and designers to demonstrate that the construction complies with current legislation and fulfils the regulations.

It is interesting to study how national legislation is related to the regulatory regimes described in Section 2.1.3 and how this relation is affected by introducing new regulation. The introduction of the building regulations *BBR* made in the middle of the 1990s led to change in focus of the regulatory regime. Although the change has taken place gradually, the emphasis up until the introduction of the former building regulations, Regulations for New Construction (*NR*, 1988), was on regulations for direct risk control, while the demand from political quarters has been for performance-based requirements in *BBR*. This transition and its safety-related consequences will be studied in more detail in Chapters 5-7.

2.3 Design procedures and methods according to the building regulations

The relation between design procedures and regulatory regimes is far from simple and transparent. Building fire regulations are a hybrid mixture of all three regimes. What follows is an attempt to briefly describe the situation. In this section the various approaches to building design, based on the Swedish structure of building regulations outlined in Table 1, are presented. Apart from the fact that the new building regulations allow increased freedom in the choice of technical solution to satisfy the demands, they also include new ways of demonstrating that the building satisfies the demands in *BBR*.

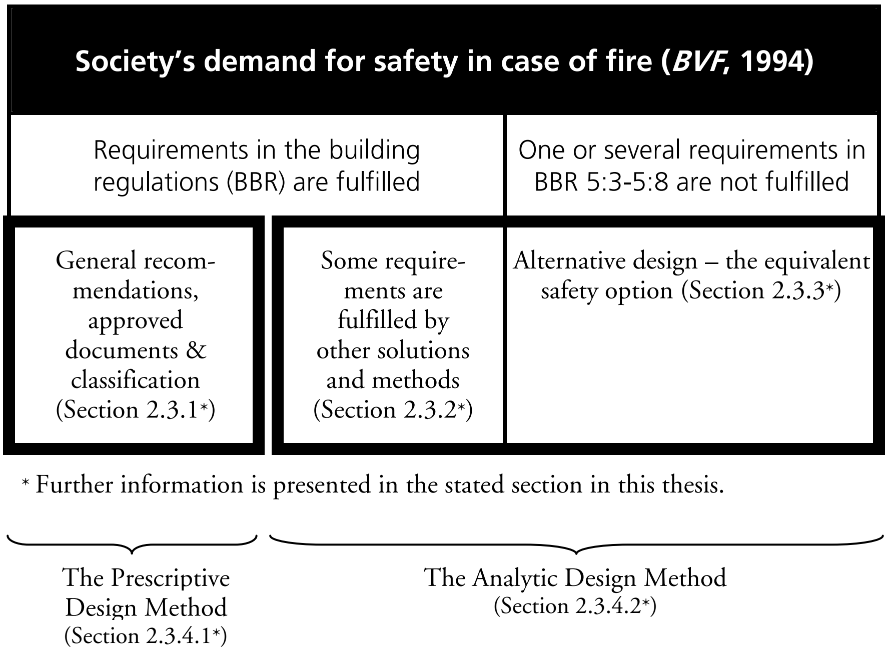


Figure 6. Three design procedures in the building regulations that can be used to fulfil the objectives in the Swedish building legislation.

Society's demands on safety in case of fire must be met, regardless of which design method is used. The technical requirements on fire protection are defined in *BVF* (1994), see level 2 in Table 1, and the level of performance is defined by the demands in *BBR*, see level 3 in Table 1.

The regulatory system is based on the assumption that the demands in the *BVF* are fulfilled as the demands in *BBR* are fulfilled. This can be achieved by using two different procedures. However, there is also an option to use solutions where one or several performance requirements in Sections 5.3 to 5.8 in *BBR* are not met, as long as the technical requirements in the *BVF* (1994) are fulfilled. Society's safety objectives can thereby be fulfilled in three fundamentally different procedures outlined in *BBR*, see Figure 6, which will be briefly described in the following sections. The first is by following the general recommendations associated with the regulations (see Section 2.3.1). This procedure is illustrated in the bottom left-hand part of Figure 6. The second procedure is to use *other solutions and methods* (see Section 2.3.2). The same level of demand must be fulfilled, although by using a different kind of technical solution from those exemplified in the general recommendations. This method can be found in the middle of the lower part of Figure 6. The third procedure is described in Section 2.3.3, and implies that one or more demands in *BBR* are not met. The designer must then be able to demonstrate that the building is at least as safe as if all the demands of *BBR* had been met, i.e. the building must satisfy the demands in the *BVF*. This procedure is shown in the bottom right-hand part of the Figure 6.

2.3.1 General recommendations (prescriptive requirements)

This method is equivalent to the traditional way of designing fire safety. Earlier detailed, or prescriptive, requirements, which are given as general recommendations, describe acceptable solutions to specific problems. These must be followed to the letter, and verification takes place at level 5 in Table 1, i.e. verification that the solutions are identical to those given in the general recommendations. *Boverket* may also give advice, for example, through technical reports. These have the same status as the general recommendations. Two such reports are currently available, one on design for escape (*Boverket*, 2004b) and one on design of ventilation systems (*Boverket*, 1994b).

2.3.2 Other technical solutions and methods (the performance option)

The designer has the freedom to use other technical solutions or methods than the ones specified in the general recommendations to comply with the performance requirements. Verification that the requirements are met is necessary according to level 4 in Table 1. Verification can be performed on component level or system level.

Verification on component level involves demonstrating that the performance of the new safety measure will be as good as, or better than, the prescribed safety measure, e.g. if a heat detector is replaced by a smoke detector. In this case, verification consists of showing that the safety measure is equivalent to, or better than, the prescribed one. The outcome of this exercise depends greatly on the attributes of the component that the designer considers relevant in the comparison.

Verification on a system level means proving that a new solution meets the performance requirements. Problems arise if the performance requirement is not stated in quantitative terms. Then the new solution has to be compared with the solution obtained by using the general recommendations. Parameters representative of the performance have to be identified and compared by the designer. An example of this is evacuation time if the performance requirement concerns life safety. A somewhat longer travel distance to an escape route can be compensated for by early detection, and the total evacuation time shortened compared with that prescribed, but only if the uncertainty associated with both solutions is determined and included in the comparison. Other examples of solutions that *can* meet the performance requirements are:

- the use of class E30 material instead of EI30 for some doors and windows, and
- the use of other critical conditions than those defined in the recommendations of *BBR* 5:361.

These examples, and other solutions and methods published in handbooks and former regulations that deviate from the general recommendations, must be verified in each specific case.

2.3.3 Alternative design (equivalent safety option)

The characteristics of level 2 in Table 1 are clarified by the demands in *BBR* (level 3), but it is possible to deviate from these provided that the functional requirements at level 2 are still fulfilled. This may seem controversial, but in Sweden this option is explicitly stated in the building regulations:

BBR 5:11 Alternative design (BFS, 1995:17)
"Fire protection may be designed in a way different from that specified in this section (Section 5, i.e. the fire section in BBR, author's comment) if it can be shown by a special investigation that the total fire protection of the building will not be inferior to that which would have been obtained if all the requirements specified in the section had been complied with".

When this procedure is used the potential impact on the fire safety strategy is considerable, and therefore the requirements on *verification*, *documentation* and *design review (i.e. control)* are high. Some examples of design solutions that are classified as alternative designs are as follows:

- a single stairway without a protected lobby as the only evacuation route from a block of flats higher than 8 storeys,
- lower class of surface materials in evacuation routes when, for example, automatic extinguishing systems are installed,
- more than two storeys in the same fire compartment without sprinklers, and
- different kinds of activity in the same fire compartment, regardless of whether sprinklers are installed or not.

In order to use any of these examples of alternative designs the designer has to verify that a level of safety is achieved equivalent to that which would have been obtained if the performance requirements in *BBR* had been fulfilled.

2.3.4 Design methods

How the design of a building and its fire protection measures comply with the general recommendations of the building regulations determines the design procedure that can or should be used. According to Figure 6 different design methods correspond to the design procedures in *BBR*. Table 2 presents which design method is required depending on how the fire safety strategy is determined. It is important that the procedures for *verification*, *documentation* or *review* employed in the prescriptive design method are not used when a solution is derived with the analytic design method. This method requires a better basis for verification compared to when performance requirements are fulfilled with the prescriptive design method.

Table 2. Methods of deriving fire protection in the construction process.

The Prescriptive design method	**The Analytic design method**
All appropriate demands and general recommendations in *BBR* are followed throughout the building. *Boverket's* reports and recommendations can also be applied.	All or some of the solutions are based on: • experience • earlier regulations • examples from other countries • well-established practice • calculations, testing and experiments • reduction of existing protection • common sense These methods are called *other solutions and methods*, often described in various kinds of handbooks. **Note: All require verification.**

2.3.4.1 The prescriptive design method

This method is based on the *deemed-to-satisfy* requirements on direct risk control laid out in the general recommendations of the building regulations (*BBR*, 2002) and corresponds to the design procedure illustrated as the box to the bottom left in Figure 6 and presented in Section 2.3.1. Many of these provisions previously constituted the building code itself. In the performance-based code these guidelines become mandatory if the prescriptive design method is used. They are formulated as detailed demands, and affect both the appearance of the building and the activities performed therein. Two different types of general recommendations can be distinguished: recommendations and examples. The practical difference is small, but the recommendations should be seen as suggested ways to fulfil the performance requirements, while the examples are less admonitory and simply provide examples of how the demands can be met.

The demands are often related to specific safety measures or to specific limitations of the building itself. In the prescriptive design method, fire protection is often dealt with in isolation from the other technical areas, and the time allotted for design is short in comparison with that required for design based on fire safety engineering. The solutions and the resulting safety measures are the result of years of building tradition and experience.

2.3.4.2 The analytic design method (the fire safety engineering method)

The other design method is directed towards that which the fire safety strategy in the building should accomplish. A design solution must be completely or partially verified with engineering methods in cases when:

- modifications are made to the prescriptive design,
- traditional recommendations are not available or are inadequate, e.g. if the fire protection measures in a building are designed in such a way that prescriptive methods cannot be applied, or
- the analytic design method is required by *BBR* for specific types of buildings.

Departure from a prescriptive design may very well be motivated by the desire to achieve a more cost-effective design. The designer is able to derive several design alternatives and analyse their cost-effectiveness before a final strategy is chosen. Another reason, which is perhaps even more common, is that fire protection measures are in conflict with other objectives, for example, architectural design or the desired type of use of the building. The engineering method allows for a greater degree of flexibility in the design, and conflicts between safety and other objectives can thus be avoided. Another reason for applying the analytic method in design is when the prescriptive method can not be applied, because it could lead to solutions with inadequate safety or to too conservative solutions. For some types of buildings it is required in *BBR* that the analytic design method is used, i.e. the prescriptive method is explicitly not allowed. This leads to several dilemmas related to safety verification and safety control, which will be discussed in Section 5.3.1.

The responsibility that the building is sufficiently safe rests with the developer, who generally hires a fire safety engineer to design the fire protection system and carry out verification. When the fire safety engineering (FSE) method is used the designer can use numerous ways to achieve a solution, see Table 2. Irrespective of how the solution is derived, it must be explicitly verified to show that the solution meets the demands in the building regulations.

2.3.4.3 Practical design – trade-offs

Although the benefits of the analytical method are many and well known, it is rare that a building is designed completely using this method. The use of the analytic design method does not necessarily imply that the complete fire protection system is new or has been re-engineered. Instead, the design solution resulting from the prescriptive method is used as a starting point. If any of these solutions are too expensive or in conflict with other design objectives then modifications are made to varying degrees. These modifications are in the form of *technical trade-offs*, i.e. deviations from the prescriptive solutions. The concept of trade-offs is simple. One fire safety sub-system is increased and another is decreased, while maintaining the same intended level of safety (Babrauskas, 1998). There are several obvious reasons for using the design strategy with trade-offs. For example, for some parts of the building the prescriptive method has advantages since the method is simple, well-known and not very time-consuming. A design solution can therefore often be seen as a combination of the two design methods. Surprisingly, there is little or no guidance in engineering handbooks on how to deal with the boundary between these methods when they are combined.

Trade-offs made to a prescriptive design solution tend to vary from project to project and, therefore, the need for verification and review varies. Even if the type of trade-offs were to be similar in different projects, the impact on the total fire safety system would be different, since the building design and prerequisites vary. As a result, the impact of a trade-off on the fire protection system and the consequent effect on the safety in case of fire in the building must be analysed in each project. Such an analysis is necessary in order to determine the appropriate need for verification, i.e. *what* has to be verified. This step must be taken *before* the method and criteria for verification can be chosen.

2.3.5 Comments on the regulatory structure

One of the conclusions drawn from the survey of the regulatory system is that it suffers from a lack of transparency. The logical structure is also found to be wanting, to some degree. A single regulatory regime is not used throughout, and, as mentioned at the beginning of Section 2.3, the building regulations are a combination of all three kinds. The ambition of using the structure for regulation as proposed by NKB (see Table 1) has not been entirely successful. The designer has too high a degree of freedom and the room for interpretation is broad regarding what is considered to be a suitable approach to fulfilling the regulations and how they are interpreted. This situation may lead to serious deleterious effects on society's ability to control fire protection in buildings, which may also lead to difficulties in ensuring that the regulations are followed, and national variation in the level of safety.

2.4 Are there any indications that the control of safety has been affected?

The driving forces behind the introduction of performance-based regulations were many, as outlined in Section 1.2. What was the result? Already in 1995, *Boverket* was commissioned by the government to follow up and evaluate the demands on the characteristics of buildings and the new control system that had been introduced. Part of this was concerned with fire safety. The final report was presented in October 1997, and the conclusions regarding safety in buildings were that the regulations in force had not been followed satisfactorily, and that the knowledge available had not been used to a sufficient extent (*Boverket*, 1997). These conclusions applied to technical solutions and their verification, as well as the review during the construction process. The uncertainty regarding whether a building satisfied the demands on safety had thus increased. *Boverket* made the following proposals in their final report:

- guidelines on analytic design methods should be developed and distributed,
- the development of performance-based regulations should be continued,
- the quality of control of designs and their implementation should be improved, and
- risk analysis methods should be more widely used.

Boverket's conclusions highlight serious shortcomings and a considerable need for development. Since then, only limited resources have been made available to realize their proposals, which gives rise to a number of important questions. *Is this a problem? Boverket* made clear that a complete changeover to performance-based demands could only be achieved once ongoing Nordic and international research activities had been completed, which was estimated to be at the end of the 1990s (*Boverket*, 1994a). *What efforts have been undertaken?* As no extensive revision of the initial performance-based regulations has been carried out, one wonders if the conditions have changed. One may also ask whether the performance-based demands are really unambiguous and verifiable. The final report of the NKB collaboration (NKB, 1999) concerning fire protection regulations does meet the above-mentioned expectations, and since then, output from Nordic cooperation in this area has more or less ceased. International development has also been modest, and has not led to any definite answers.

A number of potentially important factors, which poses threats to societal risk control, can already be identified. The possibility of serious damage due to poor design has increased considerably due to the freedom allowed in the new building regulations (*BBR*). The effect of inadequate design may not be revealed until several years after the building has been completed, and by this time, several similar constructions with the same faults may well have been erected. The limits regarding the changes in traditional fire protection that are acceptable are being tested continually in the pursuit of lower costs or other advantages.

Society must have an effective system for controlling fire safety in buildings, but there are several indications that the quality of this control is questionable. Has society lost control over fire safety in buildings? It is now time to investigate whether the misgivings highlighted in the *BBR* investigation (*Boverket*, 1997) were only “teething” problems resulting from the introduction of a new regime of regulations, or whether further negative effects have made themselves known since then. Do we currently have a sufficiently good verification and review system to identify substandard solutions which may lead to unacceptable consequences, so that we can prevent such constructions from being built? A thorough investigation of society’s ability to control the risk of fire in buildings is needed. This thesis presents, for the first time, a structured, comprehensive analysis of the safety related questions raised by the introduction of new building legislation.

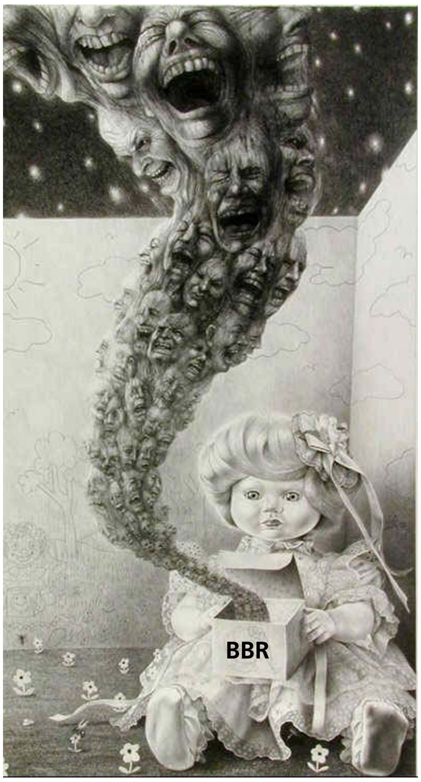


Figure 7. *Can the introduction of BBR be compared with opening Pandora's box? Ironically, according to Greek mythology, Pandora and her box was a punishment meted out by Zeus because Prometheus had stolen fire and given it to man.*

3 A framework for controlling fire risk in buildings

Throughout the thesis four perspectives were used to analyse the ways in which the introduction of performance-based regulations have influenced the ability of society to control fire safety:

- regulation to enable societal risk control (Section 3.1),
- characterisation of the fire risk (Section 3.3),
- quantitative analysis of the fire risk (Section 3.4), and
- structuring of uncertainties (Section 3.5).

Section 3.1 describes the general framework used as the basis for the analysis of how authorities can control the risks associated with an industry or activity using regulations. It is assumed here that it is possible to control safety by external means, namely regulations, and the framework is based on the regulatory regimes introduced in Section 2.1.3.

Before starting on the description of how risk has been analysed and categorized, it may be useful to describe in more detail two of the concepts already used in the first two chapters, namely *risk* and *safety* as used in the area of fire safety engineering design. This is done in Section 3.2.

One of the challenges in regulating fire risk is that the total fire risk in a building consists of a number of risk contributions from various kinds of fires. The fire protection system must be able to deal with different types of fires in order to control the fire risk. Various strategies are required to deal with these risks. Therefore, in Section 3.3 fires are classified into three categories of accidents, and different management strategies are associated with each kind.

The theory underlying the quantitative analysis and evaluation of fire risk, used to investigate and quantify the effects on fire risk resulting from changes in fire safety design, is described in Section 3.4. In risk analysis, it is often of great importance to be able to structure and describe the uncertainties to be analysed, and the final section (Section 3.5) thus presents a model for creating such a structure for the analysis of fire risk.

The four perspectives listed above have been used to form the basis of the methods applied to analyse the building regulations and fire protection documentation from a large number of projects. These methods are presented in Chapter 4.

3.1 Regulation to enable societal risk control

Performance-based regulations regarding safety in case of fire in construction works have been introduced in a number of countries since the beginning of the 1990s, and among the first were Australia, Japan, New Zealand, Sweden and the UK. The international debate on these regulations has until now been mainly focused on two of the three regulation regimes presented in Section 2.1.3, namely the transition from the *prescriptive regime* to the *performance-based regime*. The reason for this is probably that development in the area of fire protection in all these countries has been greatly affected by the development of other technical requirements on buildings, for example, load-bearing capacity (see, for example, CIB (1982) for a more detailed description of the development in this area). For load-bearing structures the performance-based regime has become very successful and dominates societal risk control. However, the circumstances and conditions for controlling fire risk are somewhat different from those regarding the collapse of a building. One such circumstance is the fact that the scientific foundations on which fire safety engineering is based are relatively new, and until recently, fire safety design has been characterized by a low level of scholarship.

Since a major difference between the two engineering fields is their degree of maturity, the prerequisites for design are not the same, and the same concept might not be effective in controlling the different types of risk. In the design of load-bearing structures there are well-established design procedures which cover the relevant aspects of structural safety. For example generally agreed design equations and safety factors are available, which makes it possible to determine quantitative performance requirements in terms of a design criterion that corresponds to a specified target level of risk. Methods for the treatment of uncertainty, e.g. specifying safety factors linked to design values and design equations, are scientifically based and give reliable design results. These design concepts are taught at universities in a similar way all over the world, and well-educated professionals have the knowledge required to apply the theoretical concepts in practical design. There is no need for the regulating authority to specify detailed regulations on quality control of the design procedures or design solutions. It is sufficient to specify the requirements in building regulations in terms of *safety output* as an explicit or implicit target risk.

The conditions described above are far from applicable in the area of fire safety engineering. The scientific and engineering foundations for fire safety regulations are relatively young and regulators formulating rules for risk control only have limited knowledge of them. The differences between the engineering fields must be taken into account as they may well affect the ways in which risks are controlled. Problems may arise if the principles for the design of load-bearing structures are uncritically applied to fire safety engineering, as important aspects of fire safety regulation may be overlooked if they are not relevant in designing the safety of load-bearing structures. Furthermore, approaches that are suitable for the design of load-bearing structures may not be applicable in fire safety design. Few detailed studies of this kind have been carried out. Several of the attempts made to define the level of knowledge in the regulation of safety in case of fire, (e.g. Meacham, 1998) have been limited to describing the conceptual differences between prescriptive regulations and performance-based regulations, and to describing the computational methods available in the two areas without elucidating the link between them. The opportunity of studying the shortcomings in society's actual ability to control fire safety in buildings is therefore lost, at least based on the way in which regulations are applied. This in turn decreases the chances of identifying measures that lead to improvements. Furthermore, there may be a need to use other risk control functions by applying the third type of regulatory regime, i.e. regulations for *safety procedures & safety case*, which act as the basic concept for controlling safety in several other areas, e.g. the chemical and mining industries (Kirwan et al., 2002).

There is thus a need for studies on this kind of regulatory regime and on how such a regime can be used to control the fire safety in buildings. Examples of such regulations involve demands on the procedures necessary to achieve a certain solution, e.g. demands on design methods, verification, documentation and control. In the analysis of how society's control of fire safety actually works a broader perspective must be employed and an analysis must be carried out of how suitable today's methods really are.

This can be done by applying a general structure to the analysis of the relation between regulations and the possibility of controlling risk, which is presented in Sections 3.1.1 to 3.1.4. In order to analyse the effect of building regulations on fire safety, the point of departure adopted is thus how the risk can be controlled in an organisation or activity. Similar points of departure have been used for many so-called major hazard industries to find models suitable for regulating risk. In addition to the widened perspective a detailed analysis of specific problems associated with controlling fire risk is suggested. Definitions of terms and categorization of fire risk are presented in Sections 3.2 and 3.3, and the underlying methodology for such an analysis is presented in Sections 3.4 and 3.5.

3.1.1 Three hierarchical levels

A well-established concept in the management literature for creating a structure for an organisation is based on a bureaucratic type of organisation, often referred to as machine bureaucracy (Mintzberg, 1980). Policy, planning and control, and execution are defined as three hierarchical levels on which the control and government of an organisation can be exercised. Policy is the comprehensive goal of an organisation, planning and control consist of the processes used to organize, structure, lead, carry out and control the work leading to tasks at execution level. These levels are intended to classify different kinds of activities in an organisation, and the relations between the different levels are strong.

A corresponding division into levels can be used to describe the structure of *safety management* in an organisation, see Figure 8. Safety management can be defined as "the total of activities conducted in more or less coordinated ways by an organisation to control the hazards presented by its technology and activities" (Hale, 2003). To achieve well functioning safety management it is necessary that activities are performed on each level in the hierarchy.

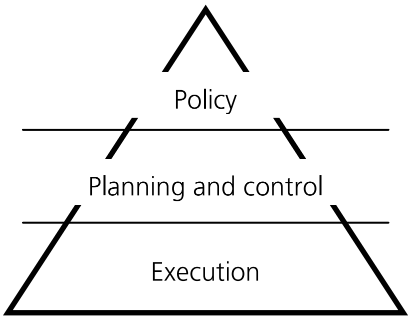


Figure 8. A hierarchical structure for safety management.

Safety issues in an organisation can be dealt with formally or less formally. In many organisations there is a need to carry out safety management in a well-structured way so that the process is efficient and to allow control and follow-up. In order for management to gain control over this process, the same kinds of tools are used as in other areas (quality, economics, personnel, environmental issues, etc.), i.e. by establishing a *management system*, which is a key concept.

A management system, in general terms, is a framework of processes and procedures used to ensure that an organisation can fulfil all the tasks required to achieve its objectives (FreeDictionary, 2005). This concept is used in many contexts and is of the greatest importance for the framework and the ability of an authority to control risk. In this thesis, a definition based on definitions of risk-related concepts in Hale (2003) and IEC (1995) is used.

- *Safety Management System (SMS)*
  A set of elements of an organisation's management system concerned with managing safety. Examples of such sets of elements are; strategic planning, decision making, and other processes for dealing with safety, e.g. business process descriptions, state transitions, risk analysis and risk inventory, risk management, education and training, inspection and monitoring, auditing and management review, incident and accident investigation. The elements of this composite entity are used together in the intended operational or support environment to perform the given task or reach a specific objective.

This is an abstract definition, and in more specific terms a SMS can often be compared to an administrative system for coordinating and leading safety management in an organisation.

Figure 9 shows the division of a SMS into three levels equivalent to those used in the hierarchical structure for safety management (see Figure 8), i.e. objectives, procedures and instructions, which can be seen as a materialisation of safety management. For example, detailed instructions can be used to control activities at the execution level. In simplified terms, *objectives* define what is to be achieved, *procedures* describe how the organisation is to achieve these objectives, and *instructions* what is to be done. The simplified model illustrated in Figure 9 is common in models and guidelines for management systems in general and in SMSs in particular, see for example Hale et al. (1997) and Kemikontoret (1997). The documentation associated with a management system often consists of a description of the contents of the three levels, and can be seen as proof that the *management system* exists. There is, however, a risk that the document will be regarded as the management system itself. The actual report is of marginal importance; it is not until the goals are reached, and the procedures and instructions followed, that anything has been achieved.

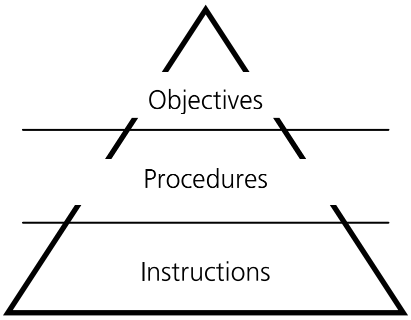


Figure 9. A hierarchical structure for a safety management system.

In any business or activity, decisions are constantly being made at all three levels in the organisation. The hierarchical structure in Figure 9 can be related to the SRK (Skill-Rule-Knowledge) model used to classify human decision making, based on the degree of cognitive control (Rasmussen, 1982; Reason, 1990). The S stands for *skill-based*, and means that the decision of an individual is automatic, and is not governed by conscious decisions. R denotes *rule-based* decision making, meaning that the decision is governed by guidance from experts, e.g. "if… then…". K, finally, denotes *knowledge-based* decision making and means that decisions cannot be based on standard solutions, but are determined by the decision maker's knowledge in a certain area. As the decisions made by individuals in an organisation affect the level of safety associated with an activity, or, more correctly, the level of safety is the result of the decisions made at various levels in the organisation, the SRK model can be related to the hierarchical structure (Hale & Swuste, 1998). Figure 10 illustrates this relation and point out the kinds of decisions made at the various levels in Figure 9.

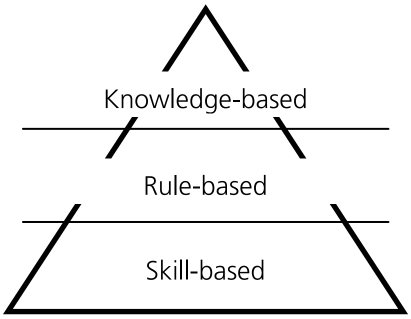


Figure 10. A hierarchical structure for decision making in an organisation.

The prerequisites for authorities to be able to control the safety of a certain activity differ considerably from those operating the activity. They either make their own decisions at the various levels, or have various kinds of instruments of control (e.g. a management system) at their disposal in order to influence the process and the decisions made. Those who may influence the level of safety in a building are, for example; the builder, the owner, the company responsible for operations in an industrial or technical plant, or the tenants, if the building is used as offices or apartments. The aforementioned actors (stakeholders) will be referred to collectively as *the owner and/or users* in the following discussions.

The authorities themselves are not carrying out the activities, they are external actors. The aim of the authorities is rather to influence the SMS of the organisation with the aid of rules and regulations. Various kinds of regulations can be issued in order to influence the management system at the different levels illustrated in Figure 9, which indirectly affect the decisions in Figure 10 providing that the regulations are adhered to. Hale and Swuste (1998) used the hierarchical level system to categorize various kinds of rules (i.e. regulatory regimes, see Section 2.1.3) governing safety presented in Table 3.

The freedom of the owner and/or users in making decisions is affected by the level at which the rules are issued (Figure 10). One consequence of issuing rules on a low hierarchical level (level with a high number in Table 3) is that the degree of freedom of the owner and/or users is limited and tightness of control increases.

Table 3. Different types of rules possible to use in regulations.

Level	**Type of rule**
I.	Rules defining goals to be achieved.
II.	Rules defining the way in which decisions about a course of action must be arrived at.
III.	Rules defining concrete action or required states of the system.

3.1.2 A framework for controlling risk in an activity or system

Hopkins and Hale (2002) introduced a framework based on the hierarchical level structure presented above (Section 3.1.1), which describes the possibilities for a regulator to issue regulations to control the risk (or safety) in an activity or system. In this thesis the framework is proposed to be useful for designing a structure with which an authority can control fire risk in buildings. At first glance the framework looks relatively simple, but in reality it is complex and contains a great deal of information. The framework is based on three levels of intervention in risk control:

- safety output (level I),
- safety procedures & safety case (level II), and
- direct risk control (level III).

A further development of the original framework is presented in Figure 11. This consists of differentiating between different types of information flows and defining the detailed content of the three levels for the new area of application (i.e. safety in case of fire). The three categories of rules (I-III), presented in Table 3, are related to a certain level of risk control in the framework. The numbers in brackets in the shaded boxes indicate the relations and depict different types of rules for safety regulations.

The Activity / system box represents the activity, industry or technology that the authority is to control through regulations. As the activity is performed by others and not the authority itself, there must be some form of influence on the activity. This is achieved by rules applied to one of the three levels, I, II or III.

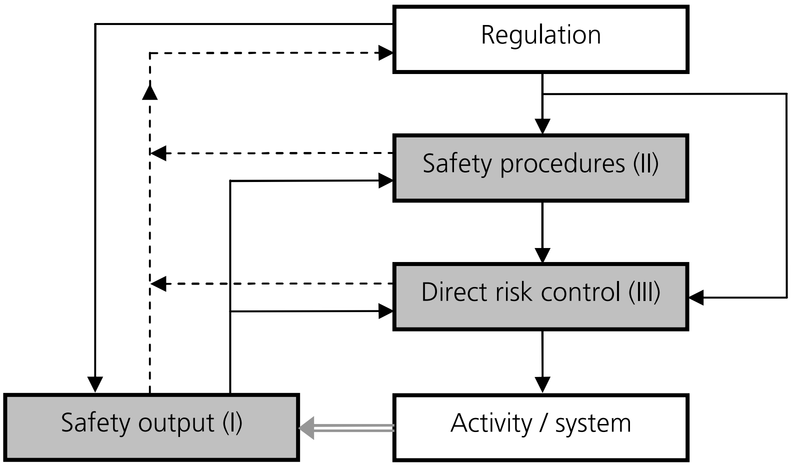


Figure 11. A framework with three levels for controlling risk (based on Hopkins & Hale, 2002).

As discussed earlier, the practical problem is that most regulatory systems are unstructured mixtures or hybrids of rules from all three levels, which sometimes can be contradicting or incomplete. Depending on whether the owner and/or users follow the rules or not, the activity will be affected in different ways (e.g. how the work is carried out, or which protection systems are used in the process). The control enforced if the regulations are followed, is shown by the solid lines in Figure 11. The result of the way in which the activity is pursued is shown as *safety output*, where the level of risk is a measure of this output. If the authority's rules are followed the risk level associated with the activity will be influenced and at least partially externally controlled. This is illustrated by the heavy grey arrow in Figure 11.

The dotted lines in Figure 11 indicate the flow of feedback and describe how regulators can obtain information on the safety performance of the activity. It can be seen from the figure that the authority issuing the rules can use three kinds of feedback to follow up and control the safety, namely, the level of safety, the structure and function of the SMS, and the structure and function of direct risk control measures. Although the regulation of a certain activity is often directed at a certain level, the rules need not be limited to this level alone. Different regulatory dilemmas often arise, depending on the focus chosen. It is not a simple task to issue rules for any one of the levels. Different kinds of demands are used in the regulations depending on the level used to exert control, and thus different kinds of assessment of compliance must be employed. A brief presentation of the way in which the demands can be formulated for each level, i.e. the different type of content of the regulation, is presented below. These levels correspond to the three types of regulatory regimes presented in Section 2.1.3 and characterize the rules used in each regime.

3.1.2.1 Level I – Goal-oriented demands (performance-based)

The risk associated with an activity can be controlled by placing demands on *safety output.* Regulations with rules of this type contain *goal-oriented* or *performance-based* demands which either specify the level of safety required, or specify demands on performance or goals used to characterize the safety output. One example of such regulations are the Dutch demands on the establishment of new chemical plants (VROM, 1988), which specify levels for individual and societal risk (group risk). Another example can be found in the nuclear power industry, where acceptance criteria for core damage frequency are used as demands on safety (IAEA, 1999; OECD, 2002). This kind of demand specifies *what* is to be achieved, but it is left to the owner and/or users to decide *how* to achieve it.

An advantage of such rules is that it opens the way for standardization organisations, interest groups and industry itself to take responsibility for the development of methods and quality control often governed by need. On an international level such efforts are coordinated by ISO, which has published a series of guidelines in the area of fire safety engineering (ISO, 1998b). Initiatives have also been taken on a national level, for example, in the United Kingdom by the British Standards Institution (BSI, 2001). In this way new technology and new solutions can be used more easily, but it requires that the authorities exercise some kind of quality control over the bodies issuing the standards, e.g. by accreditation. One difficulty, however, lies in formulating the goals sufficiently clearly that they can be achieved, without placing demands on any of the other levels of risk control. If the formulation of the goals is too vague, the various actors will not understand what is required of them. It is difficult to draw up legislation allowing proactive companies to develop their own rules and methods, while being able to control the risks in reactive companies.

3.1.2.2 Level II – Demands on safety procedures and/or safety case

Prescribing a complete safety management system for an organisation would be an impossible task. Instead, rules on this level are aimed at certain aspects or elements of the safety system on a procedural level. Planning, procedures, organisation and various methods of controlling safety at the execution level are the kind of rules issued at this level. The degree of freedom can vary considerably, depending on the degree of regulation. This may include anything from demanding presentation of the documentation of the management system, to providing detailed instructions on the use of input data in design methods. Hopkins and Hale (2002) denoted level II as *safety management* in their original framework. In the modified version of the framework presented in this thesis, the concept of *safety procedures* is used instead. The reason for this is that the definition of safety management (Section 3.1.1) includes both safety objectives and direct risk control, which means that the levels are not mutually exclusive using Hopkins and Hale's definition. The description of the aim and content of level II by Hopkins and Hale (2002) is in good agreement with the parts of a SMS in the level labelled *procedures* in Figure 9. Redefining level II does not lead to any change in the structure of the framework.

This kind of regulations means that detailed demands are placed on the administrative parts of an organisation's management system and management structure. Legislation based on this kind of rules was initially questioned by safety experts, but has started to become generally accepted and widely applied in many industrial sectors (Kirwan et al., 2002). The Seveso II directive (EU, 1996) is one example of a regulatory document containing demands directly aimed at this level. These types of regulations would have been practically unthinkable in some areas, e.g. the financial and business sectors, but as a direct result of the Worldcom and Enron scandals legislation containing such rules is also being introduced in these areas, e.g. the Sarbanes-Oxley Act (SEC, 2002) in the USA.

Regulations that aim to control the risk from an activity with the aid of rules on *safety procedures & safety case* can be applied in slightly different ways. One way is to place demands on the establishment and written presentation of a formal safety management system (i.e. a safety case), or to place demands on how a company shall work with direct risk control, i.e. demands on how the SMS is organized and which components it must include. By imposing such demands, a certain level of control can be exerted by authorities on how direct risk control is carried out but the link is implicit and difficult to measure. As mentioned previously, in many sectors demands of this type are used for the control of risk, but in the area of fire safety design the application of such rules is still uncommon.

3.1.2.3 Level III – Prescriptive demands

In a prescriptive regime, regulations are issued for direct risk control, i.e. a system is controlled by detailed technical regulations. Direct risk control is achieved by placing detailed demands on the formulation (components and technical details) and use of the system (instructions), as well as safety regulations and safety equipment. If safety is controlled at this level, the freedom of those using the system to take decisions will be removed. This may result in a loss of interest in developing solutions among those running the business, and they may not feel responsible for the correct functioning of the solutions; in other words, they stop thinking independently. They may well follow the "line of least resistance" and ensure that the detailed demands are fulfilled with as small a margin as possible, instead of trying to control the risk. Responsibility is often shifted from the owner and/or users to the inspector, and the inspector's opinions or views are regarded as law. The earlier building regulations (*NR*, 1988) are a typical example of regulations consisting of rules for direct risk control.

An advantage of regulations of this type is that it is easy to check that they have been fulfilled, although the actual task may be extensive. Review will be clear, identical and equally fair in all cases, and the degree of arbitrariness low. It is also a considerable advantage that the inspector performing the scrutiny is in continual contact with the technology in use and those employing it. This in turn leads to good understanding regarding the conditions under which the technology is used. However, there is also a danger in too close relations between organisations, as the inspector may suffer from divided loyalties in some situations. A disadvantage of this kind of control is that it is often random in nature, and that a special effort is made for the inspection, while the level of safety is significantly lower between inspections. Another disadvantage is that attention is directed to the minimum level, i.e. that required by law. This regulation regime creates a reactive climate in which safety is adapted to the legislation, instead of the need to control the risk associated with a business or activity.

3.1.3 Issuing regulations and ensuring compliance

Issuing regulations at various levels can be seen as a gradual limitation of the freedom of the owner or user. It is difficult for a regulator (authority) to find the right balance between freedom and regulation (i.e. control).

The most important information contained in the framework in Figure 11 can be summarized according to the three levels and the tasks that must be carried out at each level in order to check each level with the aid of the regulations. See Table 4, which is adapted from the work of Hale et al. (2002).

Table 4. Matrix of level of control vs. task in formulating rules and checking compliance.

	Level	Formulate and promulgate rules	Assess compliance with rules
I	Safety output (regulatory goals)	a. Establish goals for safety (risk levels).	b. Check that output goals are achieved.
II	Safety procedures & safety case	c. Formulate rules for safety management systems & safety cases and how they control risks.	d. Check the structure and functioning of the safety management system.
III	Direct risk control	e. Formulate detailed rules for the execution level.	f. Check that execution level rules are carried out.

The three levels of risk control, the three regulation regimes presented in Section 2.1.3, and the three hierarchical levels of safety management can be mapped onto each other very conveniently, and is illustrated in Figure 12.

According to Hale et al. (2002) each of the tasks labelled a-f in Table 4 must be carried out in order to control risk in an activity or system. This is, however, impossible without detailed regulations and supervision of the practical execution. If no one defines these regulations, those who carry out the tasks will define their own rules and follow them as carefully as they deem necessary. Self interests, competing goals, local culture and other factors will then affect the degree of safety and how it is verified. Detailed regulations may be included in the legislation at the various levels of control, but it is also possible to refer to standards or technical reports issued by authorities, interest organisations or other actors. When the formulation of regulations is delegated in this way, it is important to consider the self interests of the parties involved in defining the rules, their qualifications, and who has insight into the process, as well as who is given the opportunity to influence the result.

3.1.4 Application of the framework in fire safety design

In the development of *Boverket's* building regulations (*BBR*), the ambition was to complete the transition from prescriptive regulation (level III) to performance-based regulation (level I), which started with the Regulations for New Construction (*Boverket*, 1994a). An important part of the investigation into how changes in building regulations have affected the conditions for designing fire protection measures is to analyse how the tasks defined in the Table 4 are regulated, and who performs which task(s).

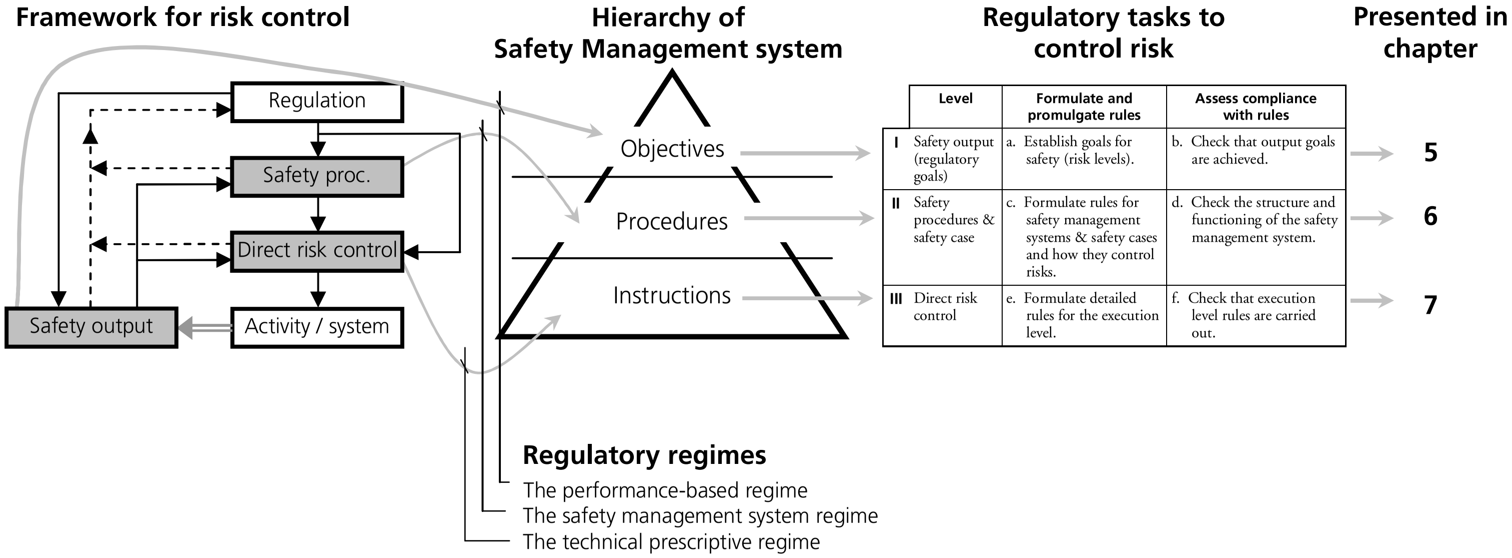
The framework proposed by Hopkins and Hale (2002) has mainly been used to study the regulation of risk control in various kinds of industries, for example, the oil and gas, nuclear power, the chemical industry and the transport sector, with the focus on the operational phase (Kirwan et al., 2002). When controlling fire safety in construction works the emphasis is different, since the major control of the construction works must be exerted in the design phase. Nevertheless, the repeated hierarchical structure is suitable for the analysis of building regulations as it is similar to the structure used in the regulations, see, for example, the NKB five-level model for the structure and control of structural characteristics (NKB, 1978). Levels 1-3 in Table 1 (see Chapter 2), are equivalent to level I in Hopkins and Hale's framework (Figure 11). Level 4 of the NKB model corresponds to level II in the framework, and level 5 to level III. The framework for risk control is thus considered to be useful in structuring the opportunities to control safety in case of fire in the *design phase*. The various levels in the framework are defined as follows and it is once again stressed that the risk control is only applied to the design phase:

- Demands on *safety output* reflect the scale or level of protection required by society. This is regulated indirectly in building legislation by elucidation of the technical demands regarding fire protection in the *BVF*, and by more specific demands on performance in *BBR*.

- Demands on *safety procedures & safety case* are concerned with demands on administrative routines and computation in the design phase, including the procedures employed in the design of the actual building. Examples are the organisation of the construction process, the division of responsibility, the method of supervision employed, or provisions regarding methods, input data, verification, quality demands on calculations, documentation and the presentation of results, etc. Everything that can be considered to contribute to ensuring adequate fire safety in the design phase can be included, in other words, the aim of the demands is to guarantee the quality of the design process and the final result.

- Demands on *direct risk control* are associated with technical solutions, i.e. the actual fire protection systems or limitations on the design of the building. Examples of direct risk control are the maximum distance to an exit, or the specifications of a sprinkler system or fire alarm.

The investigation of the means available to society to control fire safety in buildings is based on the framework which connects regulations for the various levels governing SMSs and the control of safety, see Figure 12. The material presented in Chapter 4 forms the basis for this evaluation. Detailed analysis of the building regulations is performed where each level is studied separately. The results are given in Chapters 5-7 together with a more detailed description of how fire safety in buildings is checked at each level. In addition to the framework, a quantitative risk analysis method is necessary to perform the evaluation. The basis for this method, including the definition and characterization of risk, is presented in Sections 3.2 to 3.5.



	Level	Formulate and promulgate rules	Assess compliance with rules
I	Safety output (regulatory goals)	a. Establish goals for safety (risk levels).	b. Check that output goals are achieved.
II	Safety procedures & safety case	c. Formulate rules for safety management systems & safety cases and how they control risks.	d. Check the structure and functioning of the safety management system.
III	Direct risk control	e. Formulate detailed rules for the execution level.	f. Check that execution level rules are carried out.

Figure 12. The connections between the framework, regulatory regimes and safety management.

3.2 Definition of the concepts of risk and safety

There is no general, unambiguous definition of *risk*, and bearing in mind the fragmented nature of research in this area and the numerous perspectives from which it can be studied, it is indeed impossible to cover the whole area with one single definition. It is therefore necessary for each author to define the concept as it is applied to the situation in question (Kaplan, 1997).

In order to avoid misunderstanding, general definitions of the concepts of risk and safety in the context studied in this thesis are given below. These definitions have been taken from ISO standards.

- *Risk: "The combination of the probability of an event and its consequence" (ISO, 2002).*
- *Safety: "The freedom from unacceptable risk" (ISO, 1999).*

The problem is that probability and consequence can be combined in a number of different ways, leading to different risk measures. Section 3.4 therefore provides a more precise definition of risk, where the assumptions used in quantitative risk analysis in the area of fire safety engineering are presented, and various risk measures are studied.

Assuming that it is possible to quantify the probability and consequences of an accident, and that the combination of probability and consequence can be determined for a specific case, a measure of risk can be calculated and placed on a cardinal scale. No system or human activity is free from risk. Safety measures or modifications of systems can be used to reduce the risk, but this requires resources of various kinds. The problem lies in identifying an acceptable level of risk based on the resources available to reduce the risk.

In some cases, safety (S) is used as the opposite of risk (R), for example, when risk is defined as the probability of a limit-state being exceeded (Thoft-Christensen & Baker, 1982). The relation between risk and safety can thus be expressed: $R + S = 1$. This relation is, however, not applicable when using the ISO definitions presented above. The relation is instead described in terms of two conditions: when the level of risk of a system is below the acceptable limit, the state is described as *safe*; when this level is exceeded, the system is *unsafe* (see Figure 13).

Controlling risk involves designing and governing a system such that its risk level is below the acceptable limit, i.e. the system is in the *safe* state. Figure 13 introduces the concept of safety level, which is the difference between the system's risk level and the acceptable risk level. The level of safety is a measure of the margin between a safe and an unsafe system.

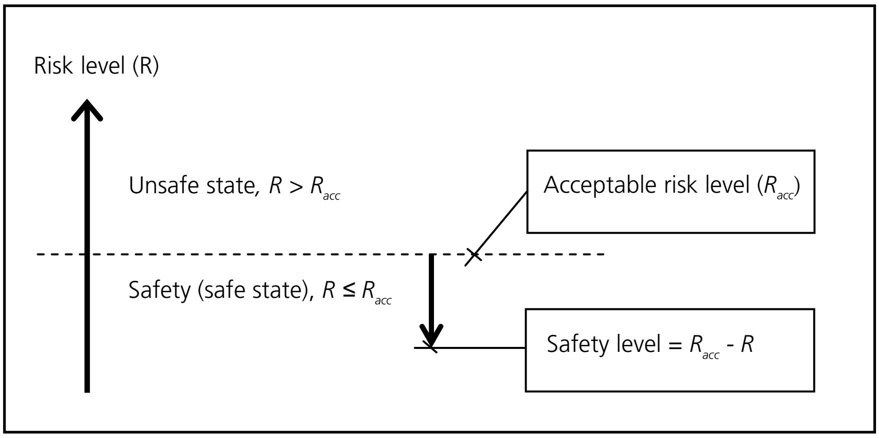


Figure 13. Relation between the concepts of risk and safety.

The above definitions of risk and safety govern the analysis performed in this work. The regulation of fire protection of construction works can be interpreted as society's endeavour to control the safety in case of fire in public buildings so that the risk level resulting from fire is not unacceptably high. Expressing fire in buildings as a risk, and regarding fire protection of construction works as a safety measure provides a good point of departure for studying the opportunities for risk control. By using formal methods of risk analysis and risk assessment, it is possible to study the effects on the level of risk resulting from changes in the regulations on fire protection, and to investigate whether the proposed solutions afford an adequate level of safety or not. This in turn provides the opportunity to analyse the effects of changes in building regulations and the consequences of the method of design used.

3.3 The characterisation of fire risk

When an authority issues regulations to control risks, it is of the utmost importance that the risks be properly characterized so that the correct strategy is applied. Characterisation creates a basis on which to determine how tight a control is suitable, and what should be checked. During the process, relevant personnel employed by the authority learn both the "anatomy" of the risk as such, and that of the activity giving rise to it.

The risk of fire in a building is made up of a broad spectrum of possible accidents, the consequences of which may vary from single individuals being affected by critical conditions, to major catastrophes causing national trauma, e.g. the dance hall fire in Sweden in 1998, or the fire at Kings Cross Station in England in 1987. Different kinds of fires may require different safety strategies to be controlled. It is necessary to take into consideration the differences arising when regulations are formulated such that fire protection is comprehensive, and not restricted to covering only certain types of accidents, such as the most common kind of fire. Section 3.3.1 presents a classification of types of accidents which is used as a basis for the discussion of various management strategies and Section 3.3.2 introduces strategies for dealing with the different categories of accidents in fire safety design.

3.3.1 The broad spectrum of accidents

In an ordered society there appears to be an inverse relation between the frequency of accidents and the extent of the consequences (Johnson, 1973). This indeed seems to be the case regarding fire risk in Sweden, based on an analysis of the fire statistics of The Swedish Rescue Services Agency (see Figure 14). It can be seen from the figure that the number of accidents per year leading to more than one fatality is low for public buildings. Also, there are only a small number of accidents per year in which more than three people sustain slight injuries.

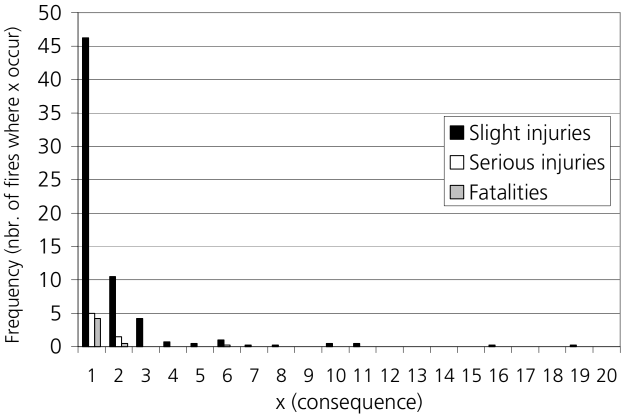


Figure 14. The frequency of different consequences (i.e. the number of injuries and fatalities) in fires in public buildings. The average values for the period 1997-2000 are given, excluding the dance hall fire in Göteborg 1998.

According to Rasmussen (1997) different management strategies have traditionally been developed for different types of accidents in various areas, and he proposes the classification of accidents into three categories based on the frequency and consequences of the accidents. The frequency of a specific type of accident has a considerable effect on the amount of information and knowledge that is available, and that can be used to deal with this kind of accident. Figure 15 shows a similar classification of the different kinds of fires that can arise in a building, and the strategies suitable in fire safety design. The classification is based on a rough division of accidents into 3 categories: small-scale accidents, major accidents and large-scale accidents. The term accident is used here to mean an event that leads to undesirable consequences, and thus includes both the initiated event and the conditions that affect the outcome.

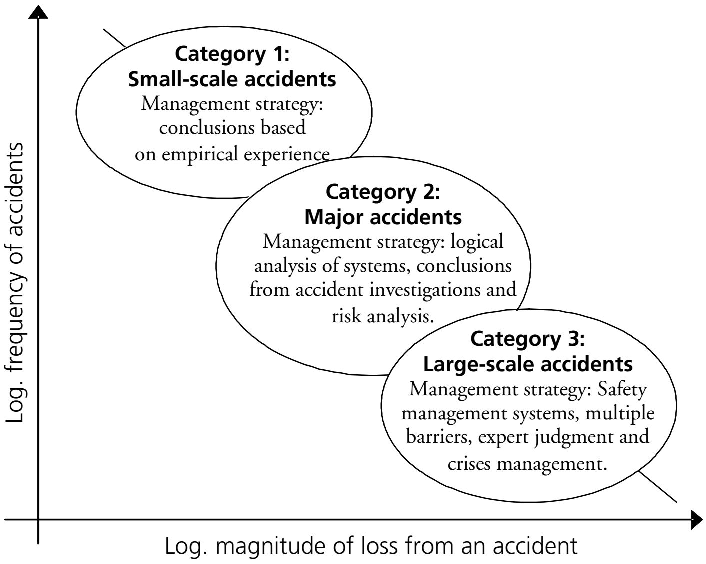


Figure 15. Management strategies for various types of accidents (based on Rasmussen, 1997).

3.3.1.1 Category 1: Small-scale accidents

This category is represented by commonly occurring accidents for which the amount of empirical data is large. The consequences are less serious than for the other two categories. Examples of this kind of accident are small fires which do not lead to many injuries or fatalities. The causes of such accidents are known, there is good opportunity to perform statistical analysis, and the data are often reliable, which means that the estimates, in turn, are likely to be reliable. Such accidents have been taken into consideration in the development of the prescriptive design method, and fires of this type are often used as *design fires* in analytic design.

3.3.1.2 Category 2: Major accidents

Occasionally, major accidents take place which have more serious consequences. The causes and their relationships are usually more difficult to elucidate, but they can sometimes be modelled to some extent. As the empirical data are often limited or inadequate, logical models must be used to estimate the probability of such an event taking place. This kind of accident has also influenced the development of prescriptive design, although in a reactive, and sometimes erroneous, way. There were repercussions on the prescriptive design method only after more serious accidents had taken place. Somewhat surprisingly, this category of accident is seldom included in the verification of analytic design solutions (Lundin, 2001). At the same time, both the need for and the challenges in addressing these scenarios are large. In the case of an innovative or complicated building it can hardly be expected that the prescriptive design method will offer sufficient protection, since the empirical basis is not available. A proactive design approach is necessary. At the same time, those involved in the design can hardly have experience of every kind of system state, i.e. various combinations of sub-system failures, that should be taken into consideration in fire safety design. A system failure or malfunction must be regarded as expected in a complex system (Perrow, 1984) and must be considered appropriately in fire safety design. There may also be a lack of knowledge and experience of how to model new kinds of protection systems. It may thus be necessary to employ new predictive methods. The resources required to address these demands must not be underestimated.

3.3.1.3 Category 3: Large-scale accidents (catastrophes)

Large-scale accidents involving fire are quite rare, but there are some events that can be classified in this category. In such events, it is seldom possible to discern one or a few causes, rather a series of faults and events lead to the accident. According to Rasmussen (1997), these events cannot be predicted with only the simplified models used in risk assessment as the relations between causes are too complicated. Society often acts reactively to this kind of accident, rather than proactively, by making changes in legislation based on accidents that have taken place. In order to cope with such events, protection measures (barriers) are required which are not solely of mitigating character. Other measures for dealing with crises in organisations or society must be employed, such as preparedness, response and recovery (FEMA, 1997). Some of these measures can only be taken or coordinated in the operational phase of a building.

3.3.2 Dealing with the different categories of accidents in fire safety design

Accidents of all three categories should be taken into consideration in the design of fire safety in order to reduce or eliminate risks. This is achieved indirectly in prescriptive design as the solution will have a certain protective effect for all kinds of accidents. The resulting risk can then be interpreted as tolerable, and acceptable from a design perspective. In analytic design, the situation is different. The way in which the different kinds of accidents are considered differs depending on the fire scenario used in the verification procedure. If fires leading to accident of category 2 are ignored in analytic design, it will not be known how the building will respond to such fires, whereas in prescriptive design a certain amount of protection against such fires is inherent. Methods of analysing and dealing with accidents in the various categories differ, which may mean that it is necessary to consider them in different ways in fire safety design. In other words, it is by no means certain that fire safety measures designed to offer protection against category 1 fires will automatically give protection against fires in category 2. In the analyses described below, accidents in categories 1 and 2 are considered using risk analysis. Events classified as large-scale accidents (category 3) are dealt with using other methods, as described in Chapter 8.

3.4 Quantitative analysis of fire risk

In Section 3.2 the general definition of the concept of risk was given. This definition will now be further developed, and a qualitative interpretation introduced. Various ways of creating quantitative measures of risk, by combining probability and consequence in different ways, will be discussed. The quantification of risk makes it possible to compare and measure the contribution of each component to the total risk. It also allows us to make relative comparisons and to rank risks. It will thus be possible to determine whether a solution arrived at using analytic design is as safe as one dictated by the prescriptive design method. This section presents the basic concepts used in the quantitative analysis and assessment of fire risk, which will be further developed in Sections 4.3 and 4.4 for the specific cases analysed in this study.

3.4.1 Risk and risk analysis

The total risk of fire is defined as the risk components from all the fire scenarios that can arise from a combination of different events. Quantitative risk analysis is based on the following three questions (IEC, 1995):

- What can go wrong?
- How likely is this to happen?
- What are the consequences?

The probability and consequences can be calculated for each scenario. The contribution to the total risk is expressed as a function of these, as in Eq.

(1). The quantitative definition of risk originates from Kaplan and Garrick (1981), and has been used previously to define the fire risk in several situations (Frantzich, 1998; Magnusson et al., 1995).

$$R_{tot} = \sum \{s_i, p_i, c_i\} \qquad (1)$$

R_{tot} = the total risk
s_i = the sequence of events in scenario *i*
p_i = the probability of scenario *i*
c_i = the consequence of scenario *i*
i = scenario index

The number of possible fire scenarios in a building is very large. Therefore, it is necessary to make some simplifications using scenarios that are characteristic for a group of different scenarios, see Figure 16, making a simplified representation of the total risk.

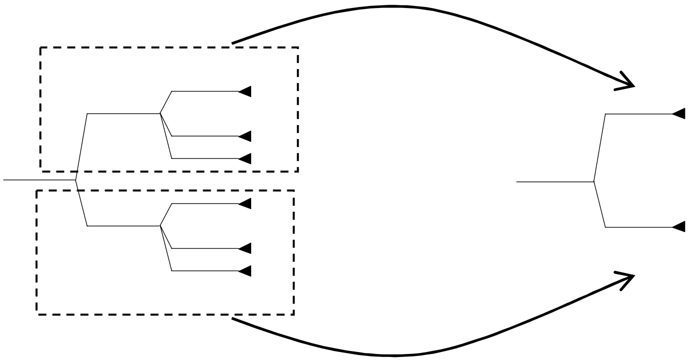


Figure 16. The principle of deriving design scenarios.

These are often called *design scenarios*. The probability of a design scenario is the sum of the probabilities of the scenarios included in the group. The total risk is obtained by summing the risk contributions from the design scenarios, see Eq. (2).

$$R_{tot} \approx \sum_{i=1}^{n} \{s_i, p_i, c_i\} \qquad (2)$$

n = the number of design scenarios

To make a conservative risk assessment, i.e. a risk assessment on the safe side, it is necessary for the design scenario in each group to represent the worst case scenario and its consequence in that group (Lundin, 2001). In this context, *conservative* usually means that the calculated risk must be higher than the actual risk, but the context is governed by the reason for calculating the risk. However, if the intention is to analyse the level of risk of a solution obtained using prescriptive design to be used as an acceptance criterion in a trial evaluation, the conditions will be the reverse. In such a case, overestimation of the risk that defines the acceptance criterion may lead to a solution being verified that may have a higher risk level than the actual risk level in the prescriptive solution, but will still be deemed acceptable since the criterion is faulty.

The degree to which the estimate is conservative compared with the actual risk will depend on the degree of detail of the analysis. If only a few scenarios are considered, the result will be more conservative, i.e. the risk will be overestimated. Refining the analysis through the use of more design scenarios will lead to a more complicated model, but the overestimation of the actual risk will be reduced.

Assuming that a fire occurs, a number of different scenarios may take place, which means that the event *fire occurs* is associated with an uncertain outcome. By using risk analysis it is possible to identify which events have significant effects on the course of the fire, e.g. if technical systems operate properly or not, or if doors are blocked, in order to create a clear picture of the possible course of events.

The risk analysis method that has been employed to model fire risk in this thesis is *the event tree* (e.g. see Figure 17), which is well-documented, see for example *Boverket* (1997) and Frantzich (1998). This risk analysis method is suitable for structuring and describing scenarios in which the sequence of events is known. However, the event tree method is limited in its ability to describe scenarios that arise through dynamic and unpredictable courses, which are characteristic of accidents with serious consequences. For such situations other models can be more appropriate and a brief overview of potential alternatives to the selected risk analysis method can be found in BSI (2003).

3.4.2 Risk measures

Various risk measures can be used to describe the risk based on risk calculations. Such a measure is the quantity used to measure and describe the level of risk. The choice of measure will affect the way in which the information in Eq. (2) will be assessed. In verification, a measure of risk is used to determine whether or not a solution is acceptable by comparing the analysed risk with some form of acceptance criterion (acceptable risk level). The measure of risk must be practical in use, while still reflecting the risk accurately. In order to satisfy the demands in *BBR* the method of analysis used must be able to:

- determine how the total risk has been affected by deviations from prescriptive design, and
- confirm that the risk is not greater than that if all the relevant requirements and guidelines laid out in the legislation are followed.

The choice of a suitable or adequate measure of risk depends on the intention of the analysis and the particular situation being studied. One advantage of modelling the risk using an event tree is that it provides a well-structured overview of the scenarios making up the total risk. One generally differentiates between consequence-based (*deterministic*) measures of risk and risk-based (*probabilistic*) measures of risk (Davidsson et al., 1997). A deterministic measure is suitable when a small number of well-defined scenarios are included in the risk assessment. In other cases, when the contributions from risks in larger numbers of scenarios are considered, probabilistic measures are appropriate.

In many situations where risk analysis is performed, e.g. the risk of the release of chemicals from an industrial plant, two fundamentally different types of probabilistic risk measures are used: the risk to an individual, and the risk to society (group risk). The individual risk can be defined in many different ways (CCPS, 1989). One of the most common is to express it as the probability of becoming a fatality for a person who is in a certain place 24 hours per day, a so-called location-specific risk. This measure of risk can be used to study how the level of risk varies geographically around a plant, as a function of distance from the source of risk. It may also be useful in demonstrating that no neighbour is exposed to an unreasonably high level of risk. The risk to society, or the societal risk, is a measure of how many people will die as the result of an accident, and is generally a function of the probability of the accident occurring and the number of fatalities. In risk assessment it is often necessary to use a combination of individual and societal risk. However, in the area of fire safety design this is seldom recognized.

The conditions governing the use of individual and societal risk when describing the risk of fires in buildings differ considerably from those in the case of chemical release. This means that these measures of risk have to be redefined. The use of location-specific risk measures is not meaningful in the design of evacuation safety, as the person is not likely to remain on the premises in the case of an accident. In the case of fire, the course of evacuation is one of the most important components of the safety strategy and must be taken into account in risk evaluation, in contrast to the case of accidental chemical release. Further considerable uncertainty is introduced into the evacuation calculations as human behaviour will affect the course of evacuation.

When evaluating the risk in connection with the design of evacuation safety, it is not appropriate to measure the consequences only in terms of the number of fatalities. The performance requirement regarding evacuation safety in *BBR* 5:36 is that there should be *no* occupants exposed to critical conditions. As it is possible that some people will be exposed to critical conditions (smoke, temperature etc.) without leading to fatality, the consequences must be measured in a different way, otherwise a solution can be regarded as acceptable even though it is not as safe as a prescriptive solution. Defining the consequences as the number of fatalities would therefore be too crude to evaluate whether a design is acceptable or not. The definition of *individual risk* in the case of fire safety design is thus the probability that a person will be exposed to critical conditions during a certain period in a building, or in the case of fire breaking out. The societal risk expressed in terms of the *mean risk* (e.g. R_{tot} in Eq (1)) can be similarly defined as the number of people predicted to be exposed to critical conditions per year or per fire.

3.4.3 Types of uncertainties

An important component of analytic design is the treatment of uncertainties, for example, how input data are selected and models used, how acceptance criteria are specified, and how design problems are demarcated. If decisions are to be based on the results of calculations it is important to understand which uncertainties are present in the calculations, and how they affect the results. The quality of the design is directly dependent on this as it determines whether a solution is acceptable or not.

In the risk analysis method described in Section 3.4.1, the uncertainty in the course of events in the case of fire was illustrated. This uncertainty is just one component of the total uncertainty in risk calculations. Examples of other sources of uncertainties are those in the input data used to model the consequences, and in the probabilities used to represent the reliability of the technical systems. Sources of uncertainty can be categorized in many different ways and a number of suggestions can be found in the literature.

Blockley (1980) divides possible types of uncertainties into four different classes. If these are generalized they can be applied to other kinds of calculations (Energistyrelsen, 1996), for example in the design of fire protection (Lundin, 1999). The following types of uncertainties can be used to define the uncertainties in calculations, which in turn can lead to undesirable events (i.e. the wrong decision being made on the suitability of a solution):

- uncertainty in resources (Section 3.4.3.1),
- uncertainty in assumptions and decisions (Section 3.4.3.2),
- uncertainty in mathematical models (Section 3.4.3.3), and
- uncertainty in input data (Section 3.4.3.4).

The above should be seen as an example of classification as there are several other examples of categories (Morgan & Henrion, 1990; Notarianni, 2000; Rowe, 1994). The various classes are arranged in a hierarchical system in which the uncertainties in resources are the most general, and the uncertainties in the input data the most specific. These uncertainties may be of different natures, but not necessarily independent of each other. Different kinds of approaches are needed to deal with different kinds of uncertainties. In the more specific classes (i.e. in mathematical models and input data) uncertainties can be dealt with by quantitative uncertainty analysis, while in the general classes other models are required. Brief descriptions are given below of the various classes in the context of fire safety design.

3.4.3.1 Uncertainty in resources

This class is very general and difficult for the engineer to assess in a specific design project. However, these uncertainties have a significant effect on the result. The uncertainties are due to inadequate routines, policy and quality control of a project. Other contributing factors are associated with the computational tools used and the quality of the research data used. These factors are in no way connected to the ability or competence of the engineer in a specific situation, but rather to the limitations of others, e.g. the management of a company. Other factors include lack of time and resources, which have a significant effect on the conditions under which the engineer is expected to work, including the decisions he or she has to make, and are thus reflected in the result of the design.

Some of the tools that can be used to handle these uncertainties are management systems, quality control (e.g. self-regulation) continuous planning of assignments, planning of continuous training and education, commitment and support in research, etc.

3.4.3.2 Uncertainty in assumptions and decisions

This class is related to uncertainties resulting from assumptions and decisions made during planning and design. It is important to define, structure and delineate design problems properly. Knowledge on, and the ability to describe, the process or system to be analysed, the choice of analysis method and the choice of computational method are other examples of factors that affect uncertainties in this class. They are very difficult to assess and deal with quantitatively.

A company can develop plans of action, policy and routines to reduce the uncertainty in this class. If two or more designers work together on a project, there is a smaller risk of error than if one designer works alone. Difficulties can arise in a company that designs fire protection if the result varies significantly depending on which consultant performs the calculations. It is impossible to completely standardize the choice and decisions made by individuals during design, but measures can be taken to harmonize them, for example, by exchange of experience and knowledge, and meetings where the technical aspects of design are discussed. Manuals and guidelines also play an important part.

3.4.3.3 Uncertainty in mathematical models

The results given by a model will still contain a degree of uncertainty resulting from the uncertainty in the model, even if the model is used according to the instructions, and applied to a case for which the model is valid.

Models are used to varying degrees in analytic design. The complexity of these models varies from simple estimates of travel time to advanced modelling of technical and physical processes. The results of a number of different models are often combined in design calculations. The uncertainty and errors in models vary, which means that the model uncertainty is indirectly related to the resources available (in terms of competence and access to appropriate tools), and the assumptions and decisions made regarding the use of models. The uncertainty can be dealt with by influencing the factors in the above mentioned classes, but can also be modelled as it is possible to quantify it (Lundin, 1999). This means that the effect of uncertainty on the result can be explicitly analysed and considered.

In an attempt to compare the precision of various models, experts from different countries were asked to use computer models to calculate a number of well-defined fire scenarios (Hostikka et al., 1998). It was concluded that the differences in the results resulting from the choice of model were much smaller than the differences due to the assumptions and decisions made by the users, even if the task of analysis was the same and very well specified.

3.4.3.4 Uncertainty in input data

The input data used in models are often uncertain. The uncertainty in the data can be due to natural variation or uncertainty in knowledge (further developed in Section 4.3.5). Despite this, most models of smoke spread and evacuation are deterministic. This means that it is difficult to analyse the effects of uncertain input data on the result. This can be done by manually varying the input data, but it is possible to make the analysis more efficient by propagating the uncertainty in the model using statistical methods (Frantzich, 1998). Probabilistic models in which the input data are specified as stochastic variables, i.e. as distributions, are, however, uncommon in fire safety design. Knowledge on uncertainties in the input data can be quantified either by statistical analysis of the data, or by expert assessment (EAL, 1997) when data are not available.

3.4.4 Treatment of uncertainties

It is important to be aware of the fact that the quality of the results given by a model is dependent on how the uncertainties are dealt with at all levels, i.e. it is dependent on the quality of the input data, the choice of model, and how the model is used, etc. If uncertainty analysis is neglected and uncertain parameters are erroneously represented by deterministic variables, then the uncertainty in the result will not have disappeared, but will not be visible in the calculations.

In fire safety design it is often necessary to make assumptions regarding the conditions in the scenarios analysed in order to assess whether the assumption has a significant effect on the result. It is thus important to carry out a sensitivity analysis in these situations, which may require a more sophisticated uncertainty analysis.

The need for uncertainty analysis in risk analysis may thus vary. For example, there is no need when design values, models and acceptance criteria are available, while the need is great when the effect of uncertainties in the input data on the results is being studied. The degree of uncertainty analysis can be divided into different levels. Paté-Cornell (1996) suggests six levels of treatment while Energistyrelsen (1996) more roughly divides the need into three levels, which is often deemed sufficient in fire safety engineering applications (Lundin & Johansson, 2003), which are labelled:

1. No treatment of uncertainties.
2. A rough estimate of uncertainties.
3. Extensive analysis of uncertainties.

If the uncertainties are not to be considered at all (level 1) in fire safety design, the design equations, design values and safety factors must be available. Design is based on calculation algorithms or boundary condition equations including probabilistically deduced safety factors. This is the ideal case, where the uncertainties were taken into account when the values were derived, and need not be considered again. This is the case in only a few situations, for example, in calculating the load-bearing capacity of a structure in the case of fire. In all other cases, levels 2 or 3 must be applied.

In uncertainty analysis at level 2, the output from expressions or computer programs is used directly without any sensitivity analysis and the values of the input parameters are derived by subjective assessment. One disadvantage of this method is that it is not known how conservative the final result is. The uncertainty in the result is estimated using a number of conservative assumptions throughout the calculation process, i.e. in the choice of input data, the choice of model and in the interpretation of the results. It is difficult for the designer to adjust a single value and assess what the effect will be on the safety. An advantage of level 2 over level 3 is that it is less complicated and quicker.

A detailed analysis of uncertainties (level 3) usually involves quantifying the uncertainties, and analysing the effects of different kinds of uncertainties on the results of the calculations. A number of methods are available for analysing uncertainties at this level (Magnusson et al., 1995). The choice depends on whether one or more scenarios are to be included, the kind of model used to calculate the consequences, and the way in which the uncertainties in the consequence calculation are dealt with.

Some kinds of uncertainties, e.g. the reliability of technical systems, are clearly identified when using the event tree method. However, the uncertainties in the variable used to model the course of the fire and subsequent evacuation must be analysed in detail to assess their effect on the final results. This uncertainty can be described using a probability distribution, which defines the values a variable may have, and the probability of each value. The uncertainty in a variable can then be propagated through the risk calculation to give the uncertainty in the final result. This can be done by hand using simple analytical expressions. For more complicated calculations a computer program is recommended.

A limitation becomes apparent when parts of the risk assessment are performed using deterministic computer models, which is common in fire safety engineering. Only single combinations of parameters are studied, and sensitivity analysis is often neglected. In deterministic models the input data are given as single (deterministic) values, which leads to the output values also being deterministic, e.g. the height of the smoke layer as a function of time. In order to investigate the effect on the output of different values of input data in an uncertainty analysis, new calculations must be performed for each new combination of input values. In uncertainty analysis, it is often necessary to vary several variables at the same time in order to study the effect of different combinations of variables. The number of calculations required would thus increase considerably if one wished to study all possible combinations of input variables systematically. In some cases several thousand calculations would be necessary. In many computer programs the input data must be changed manually, and the computational time can be long. Thus, such uncertainty analyses would be unrealistically computationally expensive. The solution is to create a response surface replacement for the computer model, i.e. an analytical meta-model of the computer model. This kind of estimated model is also referred to as a *fitted response surface*, and is an approximation of the computer model within a limited area defined by the interval of one or several input variables. The simplified model is created by calculating output values from the model as the values of the chosen input variables are varied systematically. Using this information, an approximate model can be established using regression analysis. The procedure is described by Iman and Helton (1988) and there are several examples of the use of this method in fire safety engineering (*Boverket*, 1997; Frantzich, 1998; Magnusson et al., 1995). It is, however, not possible to extrapolate beyond the area in which the meta-model applies.

3.5 Structuring of uncertainties

If uncertainties are to be studied at levels 2 and 3 as defined in Section 3.4.3, it is necessary to investigate which uncertainties must be taken into consideration in fire risk analysis. A proposed model for this is presented in Figure 17. The model is based on an event tree where the functioning, or not, of the various technical systems constitutes the events that form branches depending on their states. The uncertainties in the function of the systems are expressed as conditional probabilities, when necessary, i.e. the probability that a system operates, or fails, in the case of a fire. The initiating event is expressed as the frequency of a fire occurring, λ_{fire}, but it may also be a conditional event, i.e. a fire has started. Depending on the way in which the initiating event is defined, the risk is either calculated for a certain period of time or assuming a fire had broken out. The dashed lines in Figure 17 indicate that the continued branches of the event tree have not been drawn, as they are in principle the same as others which have been drawn. Only one scenario (indexed 1) has been drawn completely, with the probability (P_1) and consequence (C_1). In the general case, both the probability and the consequence may be uncertain, and are therefore both considered as stochastic variables.

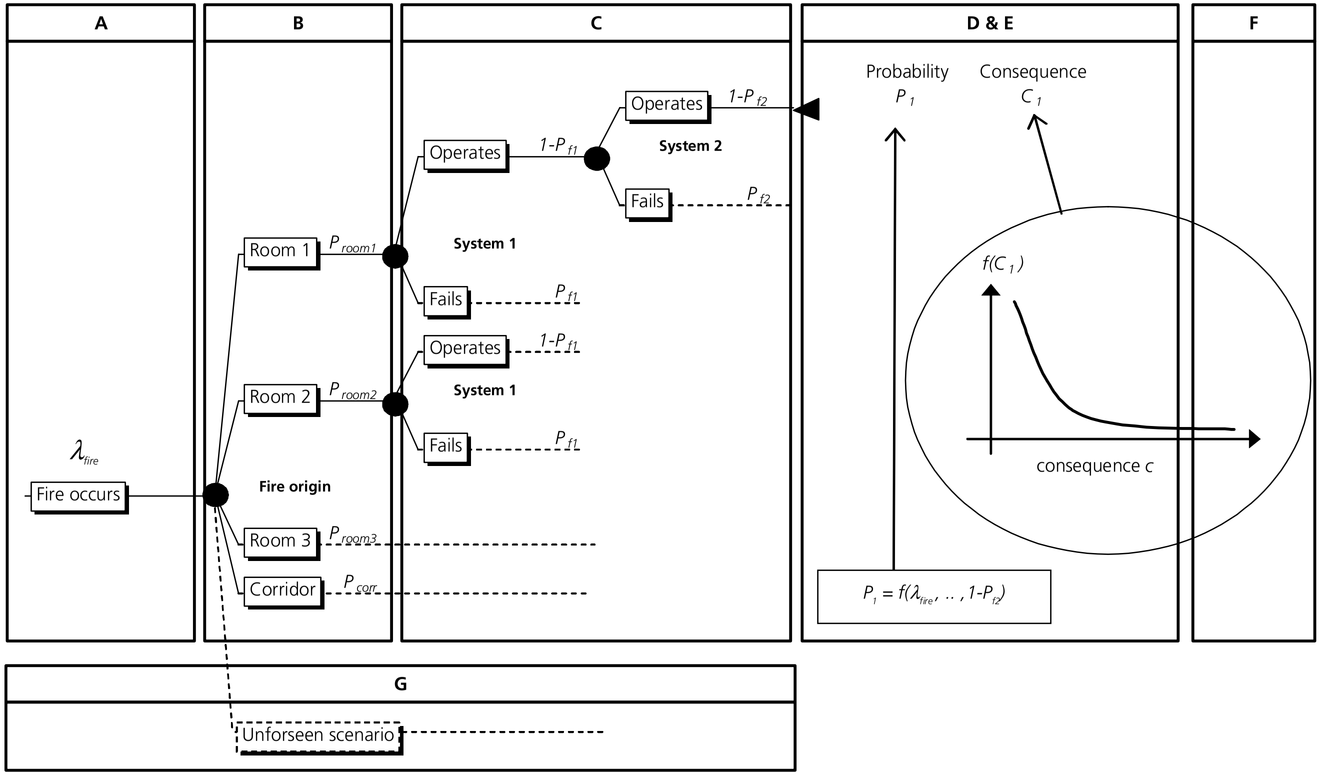


Figure 17. Illustration of the modelling of fire risk in the process of verification (A-G are explained below).

λ_{fire} = the frequency of fire occurring
P_{room1} = the probability that if fire occurs, it starts in room 1
P_{f1} = the probability of failure of system 1 when fire occurs
C_1 = the consequence in scenario 1
P_1 = the probability of scenario 1

Identifying the uncertainties involved in fire safety design using other methods than the prescriptive design method is the key to determining the need for verification. These uncertainties that should be included in the risk analysis in order to properly evaluate the effects on safety and the appropriate method of assessing the risk, are determined by which uncertainties are affected. As resources are usually limited, it is necessary to carefully consider the coarseness of the model used to investigate the uncertainties. One potential danger is that resources will be concentrated on one kind of uncertainty, while others are neglected. An example of this is the use of advanced physical models to study the fire development in a single scenario, rather than studying several scenarios. In such a case, only one scenario contributing to the total risk will be studied. The most suitable course of action must be determined in each case. With this knowledge it is then possible to place demands on the way in which uncertainties are dealt with and the choice of measures of risk so that all relevant scenarios are analysed and evaluated. To make clear which sources of uncertainty are of interest, they are divided into different types (see Figure 17) as described below.

A. *Frequency of fire*
   How often fires occur in a building.

B. *Location of the fire in a building*
   The number of possible locations of fires is large, taking into account the fire compartment in which the fire starts and the location within that fire compartment. The fire will develop in different ways depending on a number of factors such as the fuel available and the geometry, which means that the location of the fire in a building can be of great importance. The course of the fire and evacuation may be very different depending on whether the fire starts in an area where people are present or in an adjacent room.

C. *Reliability of technical systems*
   A number of potential events may affect the conditions governing the development of the fire and the course of evacuation. These

may be of both technical and organisational character. Examples are whether technical systems work as they should (reliability), whether doors and windows are open or shut, or whether trained personnel are available.

D. *Uncertainty in the modelling of probability and consequences*
When uncertainties of the type A, B and C are structured using an event tree, then all kinds of fire scenarios can be drawn, apart from those which cannot be foreseen (type G). The probability of each scenario is calculated in the event tree, and the consequences resulting from the course of the fire and evacuation are modelled. Various uncertainties and limitations must be considered in these calculations. The uncertainties in the model must be considered, as well as other uncertainties associated with the assumptions and simplifications on which the calculations are based. The model must be chosen so that it is sufficiently detailed to achieve the aims of the analysis, but there is also a need for simplification in order to limit the computational time. In the modelling of smoke spread the choice often lies between using hand calculation methods, two-zone methods or computational fluid dynamic (CFD) models. Additional uncertainties are added when estimates of probability are based on historical data from similar systems. This leads to an uncertainty in how well the system being designed is represented by the systems from which the data were obtained. The probability is also dependent on the quality of operation & maintenance, and these cannot possibly be known at the time of design. Assumptions must thus be made regarding how the plant or building will be run. This information must be conveyed, for example, in the operation & maintenance plan so that it can be taken into consideration in systematic fire protection management.

E. *Uncertainty in input data*
The way in which the uncertainty in the input data used for the calculations is handled will affect the risk assessment. Examples of sources of uncertainties in variables that affect the course of a fire and evacuation are the number of people in the building, the area and the rate of heat release. The uncertainties in these variables, illustrated in the density function on the right-hand side of Figure 17, will be propagated through the calculations resulting in an uncertainty in the results. The probability is not usually modelled in fire safety design and is seldom regarded as a stochastic variable (sometimes referred to as a second order probability). This is there-

fore not expressed as a distribution in the model for practical reasons, although it is technically possible.

F. *Extreme events*
This type refers to extreme events, or other extremely serious consequences, not considered in modelling. Although conservative choices are made when estimating variables and uncertainty intervals, there are always cases which are considered too unrealistic to be included (discussed in further detail in Chapter 8).

G. *Gross errors*
Gross errors can cause very unusual courses of events which may consist of a number of combinations of events which are difficult or impossible to foresee (discussed in further detail in Chapter 8).

The models in Figures 15 and 17 can be combined by allowing accident categories 1 and 2 to be represented by scenarios linked to uncertainties of types B, C, D and E, while accident category 3 is represented by fire scenarios linked to type F and G uncertainties. Uncertainties of type A are the same for all categories of accidents as they express the probability of a fire or accident occurring.

4 Methods and material employed in the thesis

This chapter presents the methods and material employed in the analysis of the effect of changing regulations regarding safety in case of fire. The modified version of the framework for risk control (see Section 3.1.2) is used to structure the study and a combination of qualitative and quantitative analysis is used to perform detailed analysis. In Section 4.1 a brief introduction of the structure of Chapters 5-8 is presented. These chapters contain the results and discussion on each level of the framework and the link between risk control in the design and operational phase. Section 4.2 presents the empirical study of fire protection documentation and background material used for the analysis of each level. In order to study the practical consequences of changes in the building regulations, a case study was undertaken in which the risk was analysed in a particular building (i.e. the base case) and in a specific class of buildings. The method used to perform risk calculations is described in Section 4.3 and the class of buildings analysed in the case study is presented in Section 4.4. Since the three levels of the framework are presented in separate chapters, a chapter extending, deepening and summarizing the discussion is presented (Chapter 9), followed by the conclusions (Chapter 10).

4.1 Brief introduction to the structure of Chapters 5-8

The three levels of risk control included in the framework: s*afety output*, s*afety procedures & safety case* and *direct risk control*, are used as the basis for the analysis of how the design of fire safety in buildings, and thus the possibility of influencing and controlling safety, is regulated in *BBR*. Each of these levels is examined separately in Chapters 5, 6 and 7, where a sub-set of the problems is identified in a detailed analysis of each level in the framework during the *design phase*. Chapter 8 illustrates the important connection between the design phase and the operational phase, i.e. the phase during which the building is occupied. A general analysis is presented of this connection followed by a discussion of the dependence of each level of risk control on the others during the two phases mentioned above.

4.1.1 Methods for analysis of the levels of risk control (Chapters 5-7)

Although the focus and scope differ from one level of risk control to another (see Chapters 5-7) the analysis and synthesis were carried out for each of the three levels of risk control according to the procedures outlined below.

- A short description of how the level was regulated in terms of *formulation of rules* for fire safety control and *assessment of compliance* with the rules according to Table 4, before and after the regulations were changed (presented in Sections 5.1-5.2, 6.1-6.2 and 7.1-7.2).
- Identification of *problems and dilemmas* that threaten the ability of society to control the safety in case of fire in buildings in the present situation (presented in Sections 5.3, 6.3 and 7.3).
- A *detailed analysis* of the causes and/or effects of some of these underlying problems (presented in Sections 5.4, 6.4 and 7.4).
- A discussion of *solutions* to these problems, the work required to develop *specific measures* and conclusions regarding *need for development* (presented in Sections 5.5, 6.5 and 7.5).

Bearing in mind the theory presented in Chapter 3, empirical data were collected through the study of fire protection documentation (see Section 4.2) and by extensive calculations using the risk analysis method described in Section 4.3.

4.1.2 Coordination between the design and operational phases (Chapter 8)

The framework for risk control was used to elucidate the problems that may arise from the fact that the legislation regulating the design phase and operational phase of a building are separate. The connections and needs for coordination between different levels of risk control in both phases are described in Chapter 8.

4.2 Empirical study and background material

In order to study how fire safety designers apply the new performance-based building regulations (*BBR*, 2002) in practice, and to obtain data on which to perform the analysis of the quality of fire safety design, as well as identify any possible shortcomings, empirical material was collected and analysed. In Section 4.2.1 the empirical material is presented comprehensively, and in Section 4.2.2 the method use for the analysis is described. As a complement to the analysis of fire protection documentation additional background material was used to study how effectively the regulations control fire risk, see Section 4.2.3.

4.2.1 Scrutiny of the empirical material (fire protection documentation)

Fire protection documentation was collected from forty-six cases (building projects) where the analytic design method had been used. Documentation was selected from a wide range of projects in order to include different types of buildings and technical trade-offs (i.e. changes in prescriptive designs) of different degrees of complexity. The study was initiated in the research project "Elucidation of the Methodology for Fire Safety Design" in 2000, which was financed by The Swedish Fire Research Board (*Brandforsk*). The majority of the cases studied were from the period 1995 to 2001. A report was issued with the initial findings and conclusions in 2001 (Lundin, 2001). In the succeeding research project, "Acceptable Risk in Design of Evacuation Safety" (Lundin, 2004), additional fire protection documentation was analysed. The empirical material used in this thesis therefore consists of fire protection documentation produced in the period 1995-2005.

The documentation was obtained from fire safety consultants and from the fire and rescue services which review documentation on behalf of the local building committee. When the requests to obtain documentation were made, it was agreed that the designer would remain anonymous and would not be linked to potential errors or flaws in the documentation. Therefore, a specific list of projects and the consultancy producing the documentation can not be published. However, to give an idea of the variety of buildings studied a brief overview of the empirical material is presented in Figures 18-20 which contain information about:

- the types of buildings studied (Figure 18),
- the year the designs were produced (Figure 19), and
- the geographical location of the buildings (Figure 20).

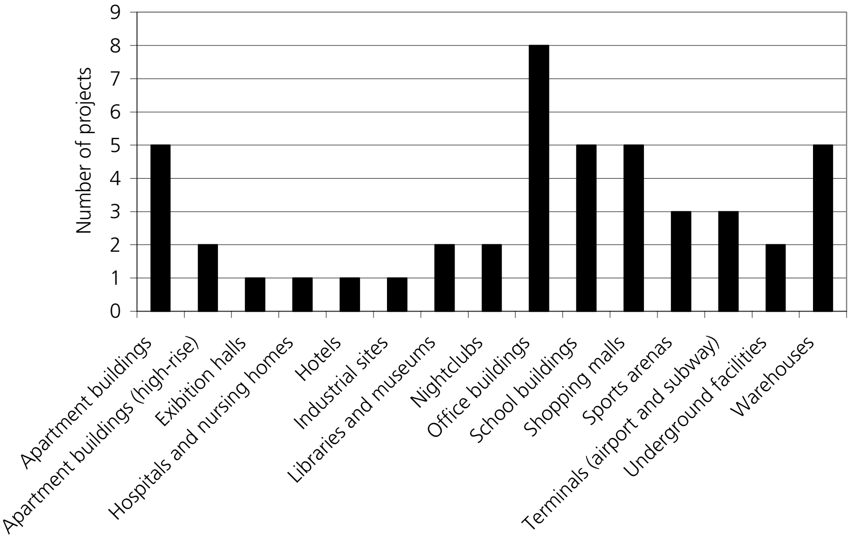


Figure 18. The types of buildings studied.

Information was gathered from various parts of Sweden, but mainly in metropolitan areas, i.e. Göteborg, Malmö and Stockholm, as there are more extensive building projects in these areas, and the potential benefit of applying analytic design is greater in such projects.

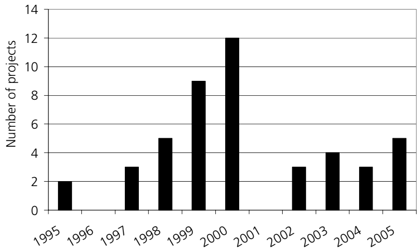


Figure 19. The year the designs were produced.

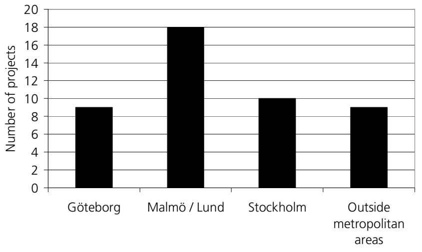


Figure 20. The geographical location of the buildings.

It is difficult to say how representative the documentation is, but this is assumed to be of minor importance since analytic design is most frequently applied in major projects with a significant design budget, and is almost always carried out by one of the fire safety engineering consultants contacted. At the same time, the aim was to carry out a broad survey of possible problems, and not to determine the frequency of occurrence of specific problems or make geographical comparisons. However, in order to identify problems that might be specific outside metropolitan areas, nine projects from smaller towns were studied. Even if the types of buildings studied are not representative of the projects being managed on a daily basis in small communities, it is possible, or in fact very likely, that several of these types will be built occasionally, even in smaller towns. The problems associated with risk control will become very relevant in such cases, especially since experience of this type of project may be limited in the local building committee. Another reason why the findings from the empirical study should be valid in smaller communities, despite the fact that the problems were identified in projects carried out in metropolitan areas, is that most consultancy firms with the competence to carry out analytic design are based in Göteborg, Malmö or Stockholm, or at least their main offices are. It is therefore likely that the design of projects carried out outside metropolitan areas will either be performed by a company from a metropolitan area, or at least by a company which is governed by a company standard developed by designers mainly working in metropolitan areas. A further discussion of the validity of the documentation studied is presented in Section 9.4.

4.2.2 Analysis of the fire protection documentation

The analysis involved establishing how the designers demonstrated that society's demands on safety were satisfied in accordance with legislation through the use of simple and/or complicated calculations, logical reasoning and judgement. The aim of the analysis was to establish whether the methods used by the designer allowed the fire safety of the building to be controlled, which indirectly provides a quality assessment of the verification process. In all the cases studied, the prescriptive design method was used as the starting point, and various degrees of changes were then made and verified using analytic design. The faults and shortcomings revealed are presented as a synthesis of the problems discovered. It should be pointed out that in several cases, the documentation showed that verification and control were good, but as the aim of this study was to elucidate failings these were emphasized.

A generally accepted definition of quality is: "the totality of characteristics of an entity that bear on its ability to satisfy stated and implied needs" (ISO, 1994). The *entity* of concern is the verification and the *need* for analysis in verification varies from case to case, and one specific method will thus never be able to satisfy the needs in all situations. It is therefore not appropriate to relate the quality of verification to a certain kind of method, but should be determined by how well the intention of verification is met. The verification can be regarded as good if it gives a correct assessment of whether the solution is acceptable or not. This is, however, difficult to measure. As no common set of demands can be made in verification, the analysis is based on the general quality demands in risk analysis.

As in risk analysis, the quality of the verification process is reflected in its usefulness, i.e. the degree to which it fulfils the predefined aims and demands (Suokas & Rouhiainen, 1993). The aim of verification in analytic design is clearly expressed in *BBR*: it shall demonstrate that the level of safety is the same as, or better than, that which would have been obtained using prescriptive design. Furthermore, *BBR* includes requirements on independent control and, to some degree, the content of documentation in verification. In the analysis of the fire safety documentation, relevant parts of general quality demands for risk analysis, e.g. IEC (1995) and SRSA (2003b), were used as the basis for the qualitative analysis, as summarized below:

- the relevance of risk analysis,
- the reporting and documentation of risk analysis,
- the uncertainty in the risk analysis, and
- review of the risk analysis.

A more detailed description of the above points, together with what should be included in verification, is presented with the results in Chapters 5, 6 and 7.

4.2.3 Additional background material used in the empirical study

In addition to the extensive study of fire protection documentation briefly described in Section 4.2.1, the author has gained insights into the construction process and the fire safety design process on a practical level through a number of activities that will be briefly summarized in this section.

By supervising fire protection engineering students at Lund University in their course work and in their Bachelor's and Master's dissertations since

1996 the author has come into contact with many relevant design problems, both of practical and theoretical concern. Many of these dissertations have been initiated or requested by consultancy firms.

The author has participated in project teams that have designed and presented case studies on performance-based design conferences (see SFPE, 1996, 1998). In the research projects forming the base for the thesis work reference groups have been involved which has made it possible to gain insight from professionals working with fire safety design on a daily basis, e.g. fire safety designers, reviewers, members of building committees, representatives from the fire and rescue services as well as from *Boverket*.

In addition to teaching and research activities, experience has also been gained by participating in numerous expert tasks for industry and the public sector. For example, the author has participated in the project forming the basis for the "UK Draft for Development, DD240, Part 2, 1997, Fire Safety Engineering in Buildings – Commentary on the Equations Given in Part 1" (BSI, 1997), and the report "Evaluation of the Swedish Building Regulations" (*Boverket*, 1997). Valuable input to the thesis work have been gathered from participating in the Nordic Committee on Building Regulations working group (NKB, 1999) and in a reference group monitoring the development of acceptance criteria for the Öresund region (Helsingborgs brandförsvar et al., 2001).

Practical experience has been gained by working as a consultant participating in design firms' self-implemented control for several major fire consultants in Sweden and Norway during a period of eight years. The background material presented formed the basis for developing design guidelines (Brandskyddslaget & LTH Brandteknik, 2005) and has served as a complement to the study of fire protection documentation presented in Section 4.2.1.

4.3 Risk calculations

This section describes the risk analysis method used to obtain the quantitative results presented in Chapters 5-7, based on the theoretical background presented in Sections 3.4 and 3.5. The purpose of the analysis is to study the practical consequences of changing building regulations, in terms of the quality of design and the societal ability to control risk.

The quantification of consequences and probabilities is described together with the calculation of risk measures. The classification of the uncertainties in the variables is also described. The extent of the analysis can be seen in Figure 21, where question marks indicate uncertainties described in Section 3.5, but not studied in the analysis.

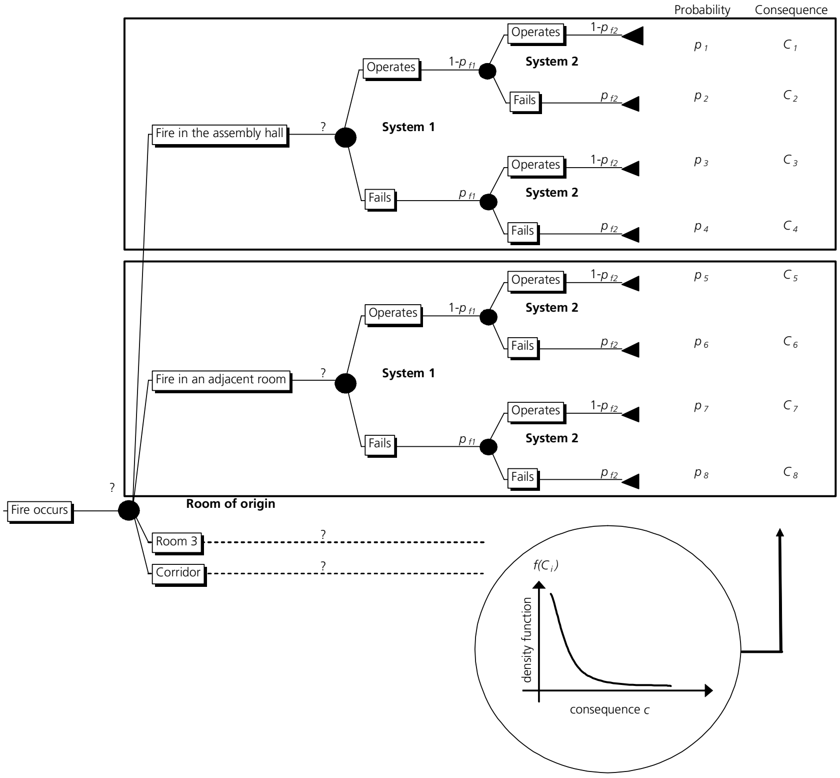


Figure 21. Extent of the risk analysis performed in the case study.

It can be seen from the figure that the risk analysis does not cover the total risk (or all the uncertainties). The aim of the analysis was to be sufficiently comprehensive to give an idea of the risks resulting from accidents in categories 1 and 2 in Figure 15. The reason for choosing this strategy is that fire protection is deemed to be primarily intended for these kinds of accidents, as is discussed in Chapter 8. Another reason for limiting the scope of the risk analysis according to Figure 21 is the lack of reliable data, for example, regarding the probability of a fire occurrence. However, this limited framework is perfectly sufficient for investigating the practical consequences on the ability of society to control fire risk. This can be done, for example, by studying the variation in the contribution to the risk of various scenarios for a group of buildings, and how different kinds of uncertainty affect the measure of risk, which constitutes the output of the risk calculations. A more detailed description of how risk calculations are used to evaluate the safety aspects of changes in the building regulations is presented in Chapters 5-7.

4.3.1 Calculation of probability

The total probability of a particular scenario is calculated as the product of the probabilities of each event in that scenario, see Eq. (3).

$$p_i = \prod_{j=1}^{M} p_j \tag{3}$$

p_i = the probability for scenario i
p_j = probability of event j
i = scenario index
j = event index
M = the number of events leading to scenario i

The probabilities for each branch, e.g. the probability of failure for a fire protection system, were taken from the literature or estimated using expert judgement when there was a lack of data. The analysis was performed for two types of fires, where the frequency of neither type is known. Therefore, the risk is analysed assuming that each type of fire occurs.

Some of the events are correlated, i.e. the probability of an event may be affected by a previous event. With knowledge that the smoke detectors do not function, the probability of the fire alarm not functioning is higher than if the smoke detectors had functioned. Poor maintenance may affect both systems. Such relations are taken into account in risk analysis, but some rough assumptions are necessary due to a lack of data.

4.3.2 Calculation of consequences

The consequences are given in terms of the number of people exposed to critical conditions, and are determined by modelling the course of events during the fire and evacuation for each scenario. This is a simplified approach, since methods are available for deriving the total exposure effect from different toxic substances, radiation and temperature in the smoke, i.e.

the Fractional Effective Dose (FED) method (Purser, 2000). Different exposure effects can be associated with different FED values, e.g. the value of 1.0 is defined as occupants being incapacitated. However, this method is associated with a number of uncertainties. For example, the production term for toxic gases in a fire is very uncertain and depends greatly on the ventilation conditions. The exposure effect varies with the health and age of the occupants, e.g. asthmatic people, children and old people are more easily affected than others. The toxicological effects on the human body are often extrapolated from experiments on animals and must therefore be seen as crude estimates. Therefore, more simple deterministic values are suitable to express the occurrence of untenable conditions for design purposes (Frantzich, 1998). Examples of such values are provided in engineering guidelines and in *BBR*. The most commonly used value is a limit on the smoke layer height when a two-zone model can be assumed valid, or visibility, if the smoke is well mixed in the room. Conditions are defined as being critical as soon as the conditions are fulfilled, and it is assumed that the escape route is instantaneously blocked when these conditions occur.

The method to model consequences used in this study has been well-described (Jönsson & Lundin, 2000; Magnusson et al., 1995). The consequences for each scenario are determined by calculating the time to reach critical conditions, i.e. the available safe escape time, and then studying the course of evacuation in order to determine how many people have not evacuated the building by this time.

The escape time is divided into several phases, namely: detection time, pre-movement (recognition and response) time, and travel time, see Eq. (4).

$$t_{esc} = t_d + t_{pre} + t_{trav} \tag{4}$$

t_{esc} = escape time [s]
t_d = detection time [s]
t_{pre} = pre-movement time [s]
t_{trav} = travel time [s]

Both the detection (t_d) and the pre-movement time (t_{pre}) are affected by the activity being pursued, the characteristics of the group of people in the building, the design of the building and the development of the fire. The detection time is usually estimated by studying the spread of smoke. People in a building can become aware of fire by the automatic or manual activation of an alarm, by seeing the fire or smoke, or if by smelling smoke or hearing the noise made by the fire. The pre-movement time can be difficult to estimate as it depends on human behaviour. This time is usually defined from values in handbooks or by expert judgement. The travel time (t_{trav}) is the time it takes for the occupants to move to a safe location after deciding to begin the evacuation. The travel time can be calculated using various kinds of models, from simple manual calculations to advanced computer models, e.g. Simulex (Thompson & Marchant, 1995) or Steps (Waterson & Pellissier, 2003).

In order to determine the time to reach critical conditions (t_{crit}), the fire development was modelled with the two-zone model CFAST v.5 (Jones et al., 2000). This model is limited in its ability to calculate the spread of smoke in large rooms or halls. For two zones to form in large rooms the fire must be quite large. In the case of a small fire, well-stirred conditions usually arise, where the smoke is mixed with ambient air and spread in the whole room. The two-zone model was originally developed to analyse the conditions in the early phase of the fire, before flashover. Despite the limitation of the model, it was used in this work for both large rooms and flashover fires leading to underventilated conditions. The fire modelling of these conditions are presented in Appendix A. The reason for using this model is that a very large number of simulations is required (over 200) which would make the use of a model with higher resolution, like a computational fluid dynamics (CFD) model, too time-consuming. The validity of this assumption is investigated in Appendix B.

4.3.3 Measures of risk

Several measures of risk can be used in risk assessment, and it is important to use a measure that correctly reflects the difference in risk when comparing two design solutions. A number of methods have been used previously in the analysis of fire safety in buildings (Angerd, 1999; Frantzich, 1998; Kristiansson, 1996; Olsson, 1999). Some measures of risk have serious limitations regarding their suitability for the description of the effects on risk for design purposes. One of the aims of this risk analysis was to study how different measures of risk reflect the changes in the total risk, in order to evaluate their suitability in risk ranking. The following measures of risk were studied:

- the consequences in a scenario when all systems operate correctly ($C_{all\ work}$),

- the maximum consequence when a single protection system fails, i.e. maximum single-source failure ($C_{max\ ssf}$),
- the consequences of the worst-case scenario ($C_{worst\ case}$),
- the mean risk (R_{mean}),
- the risk to an individual (P_{ind} and P_{worst}), and
- the risk profile.

The first three measures of risk are scenario-based. It is difficult to develop general guidelines for the choice of scenario since the possible scenarios will differ from case to case, and may also be dependent on the way in which the risk analysis is carried out. In order to represent the information in an event tree more comprehensively, two individual measures of risk, P_{ind} and P_{worst} (which are actually probabilities that the individual will be exposed to critical conditions) and two societal measures of risk, the mean risk (R_{mean}) and the risk profile, were used. These measures of risk are common in risk analysis, but have to date only been used sparingly in fire risk analysis used in verification.

4.3.3.1 Individual risk

The risk to an individual in the case of fire is defined as the probability of the individual being exposed to critical conditions when in the room, fire compartment or building where a fire breaks out (depending on the objective and scope of analysis). It is calculated by dividing the number of people exposed to critical conditions by the total number in the room (or building etc.). This gives a measure of the probability of a certain person belonging to the group exposed to a defined scenario. The contributions to the total risk from different scenarios differ as the number of people exposed to critical conditions differs. The individual risk from each scenario is weighted according to the probability of each scenario occurring, see Eqs. (5) and (6), in order to calculate the individual risk in case of fire.

$$P_{ind(i)} = \frac{c_i}{N} \qquad (5)$$

$$P_{ind} = \sum_{i=1}^{n} \left(p_i \cdot P_{ind(i)} \right) = \sum_{i=1}^{n} \left(p_i \cdot \frac{c_i}{N} \right) = \frac{R_{mean}}{N} \qquad (6)$$

P_{ind} = the probability that a randomly chosen individual will be exposed to critical conditions should a fire break out, also known as the *individual risk*
$P_{ind(i)}$ = the probability that an individual will be exposed to critical conditions in scenario *i*
R_{mean} = the mean risk
c_i = the number of people exposed to critical conditions in scenario *i*
N = the number of people in the room
p_i = the probability of scenario *i*
n = the number of scenarios
i = scenario index

In contrast to risks specific to a particular place, the risk to an individual according to Eq. (6) will be a function of the number of people in the room. It is thus necessary to study how the risk is distributed in a room, so that a single individual is not exposed to an unacceptable high risk. The risk of being exposed to critical conditions should vary in a room, for example, with the distance to the emergency exit. Using Eq. (7) the individual risk in the worst location can be calculated.

$$P_{worst} = MAX\left(\sum_{i=1}^{n}\left(p_i \cdot P_{m(i)}\right)\right\}_{m=1}^{m=N} \tag{7}$$

P_{worst} = the probability of being exposed to critical conditions for an individual located in the worst position in the case of fire.
$P_{m(i)}$ = the probability of occupant *m* of being exposed to critical conditions in scenario *i*
N = the number of occupants in the room
n = the number of scenarios
i = scenario index
m = occupant index

4.3.3.2 Societal risk

Two kinds of societal risk (group risk) were analysed. The most well-known is the mean risk which is the sum of the probabilities multiplied with their respective consequences for each scenario illustrated by an event tree. In the context of fire risk analysis in trial evaluation it is appropriate to define the mean risk as the number of people expected to be exposed to critical conditions in the case of fire (see Section 3.4.2). This risk measure is a combination of the contributions from all the scenarios representing possible outcomes of the initial event, in contrast to the scenario-based risk measures. This risk measure has been proven useful in the verification of fire safety using fire risk analysis (Lundin & Johansson, 2003). Other denotations for this risk measure occur, e.g. the outcome measure of risk (Hall & Sekizawa, 1991).

$$R_{mean} = \sum_{i=1}^{n} \left(p_i \cdot c_i \right) \tag{8}$$

R_{mean} = the mean risk
c_i = the number of people exposed to critical conditions in scenario i
p_i = the probability of scenario i
n = the number of scenarios

It should be noted that R_{mean}, as defined above, is a single value where some of the uncertainties presented in Figure 17 are represented and some are not. The uncertainty which is inherent in R_{mean} is denoted C in Figure 17 and results from the fact that different courses of events are possible following an initial event (i.e. several scenarios can occur). R_{mean} can thus be interpreted as the expected outcome if the initial event occurs considering all potential scenarios. To study the effect of uncertainties that are not inherent, e.g. uncertainties in the consequence of a single scenario, uncertainty must be treated according to level 2 or 3 (see Section 4.3.5).

An alternative societal risk measure to the mean risk is the risk *f(N)* curve (Frequency Number curve), see Figure 22. This curve describes all the possible outcomes (X) represented in an event tree, in the form of an approximation of the complementary cumulative distribution function (CCDF) of X. As the consequences in fire risk analysis are measured as the number of people exposed to critical conditions, the *f(N)* curve is called *risk profile* in order to avoid confusion with risk analysis results where the consequences are measured in number of fatalities. In many applications, e.g. land-use planning, it is convenient to use a logarithmic scale for the x-axis and y-axis.

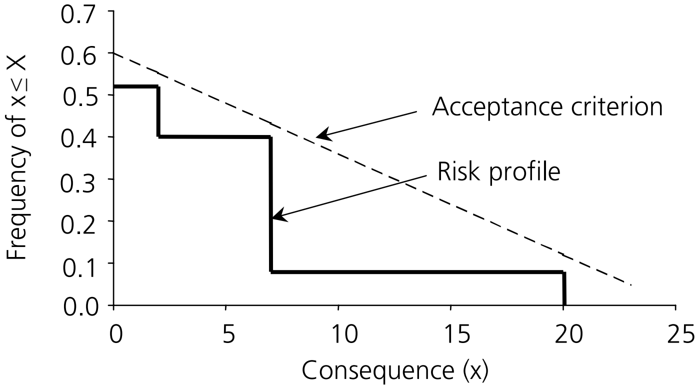


Figure 22. An example of a risk profile.

4.3.3.3 Complementary risk measures

An example that illustrates the importance of using different kinds of risk measures is the case where 100 people are present in a room and 5 do not manage to evacuate before critical conditions occur. This gives an individual risk of 5/100, or 0.05 per fire, and the societal risk is that 5 people will be exposed to critical conditions in the case of a fire. Depending on which risk measure is chosen in a risk comparison, will affect how the risks in the two rooms are ranked. If the exemplified room is compared with another, much smaller room, with 10 people in it, and the consequences are the same, then the societal risk will still be 5 people per fire, while the individual risk will be 5/10, or 0.5 per fire. In other words the risk of an individual being affected is 50%.

This comparison can only be made if the probability of fire occurring in the two rooms is the same. Considering only the societal risk gives the impression that the rooms are equally safe, while the individual risk in the second case is 10 times that in the first. It can thus be seen that it is necessary to use several risk measures in order to obtain a clear picture of the consequences for the individual as well as those for society.

4.3.4 Sensitivity analysis

Sensitivity analysis is normally carried out by varying the input data in a systematic way, in order to investigate the effects on the various risk measures (i.e. the output). The effects of a number of assumptions can also be studied. This kind of analysis provides information useful in identifying the variables that should be given highest priority in a comprehensive uncertainty analysis, and it also indicates which measures of risk are relevant for further study. The approach described is applied to the risk calculations.

4.3.5 Uncertainty analysis of risk calculations

In uncertainty analysis of risk calculations the effects of uncertainties not explicitly modelled in the event tree can be investigated. These uncertainties arise from variables included in the consequence and probability calculations for each scenario and can have quite different characteristics. The variables are therefore divided into two groups, depending on the type of uncertainty associated with them.

4.3.5.1 Group 1 – natural variation and uncertainty in knowledge

The variables in group 1 are those in which there is uncertainty for a *specific building*. The uncertainty in these variables may be due to two different types; aleatory and epistemic (IAEA, 1989). Both uncertainty types can be expressed as random variables and can be described by statistical distributions, even though the nature of these uncertainties is fundamentally different. Aleatory uncertainties are characterized as natural stochastic variations, which can not be reduced, except for dividing the population studied into smaller sub-groups. This type of uncertainty represents natural random variation. Epistemic uncertainties are characterized as uncertainties in knowledge. Typical knowledge uncertainty in engineering applications may be, for example, lack of knowledge of certain parameters, uncertainty in mathematical models due to simplification and assumptions in the model made by the model developer. This kind of uncertainty can be reduced by obtaining more information. Depending on the purpose of the uncertainty analysis, a sub-division between these two types can be made, but in this study the combined effect is of interest. Some variables are of distinctly one type or another, while others can be associated with both types. The rate of heat release of a fire, for example, can vary depending on where it starts and what catches fire. It can be determined quite accurately in specific cases, but as design is concerned with a number of potential fires during the lifetime of the building, the heat release used in design will be uncertain. At the same time, the variation can be affected by a number of factors, e.g. the type of activity in the building and the size of the building. If these relations are unknown, there will be an uncertainty in the heat released which can be reduced. When modelling the uncertainty in the heat release (as well as several other variables) the total uncertainty is a combination of both types. Although these two types are fundamentally different they are treated in the same way with the same method. If there is no need to differentiate between them, e.g. in order to reduce the uncertainty, they can be treated as one group.

4.3.5.2 Group 2 – variation with respect to design decisions

Group 2 includes variables that are uncertain when studying a particular type or *class of buildings*, but which do not vary for a specific building. Examples of these variables are the ceiling height and floor area. The fire development and smoke spread can vary considerably depending on the ceiling height, thus the level of risk may also vary in the prescriptive method. The area determines how many people may be present in the room and will therefore also have impact on the risk level. Large differences in risk levels between buildings within the same class are undesirable, since the buildings are expected to meet the same technical requirements regarding safety in case of fire. A certain degree of variation in risk within a class of building can be expected, since all the variables that affect safety are not included (or controlled) in the prescriptive design method. This variation can be analysed when studying a large number of buildings of a certain type on a national scale (Kristiansson, 1996), but cannot be observed by studying a single building.

In the uncertainty analysis performed in this work the variation in risk level resulting from both groups of variables was studied. Analysis was carried out varying both groups simultaneously and separately.

4.4 Description of the base case

A representative building called *the base case* was used as the basis for the quantitative risk analysis. This section describes the building, the type of fires considered as initiating events in the risk analysis, and the modelling of the probability and consequences. The input data for the sensitivity and uncertainty analyses are presented in Appendix C.

The base case is assumed to be an assembly hall accommodating about 1000 people. This is considered to be representative of the various kinds of activities carried out in assembly halls such as theatres, conference auditoria, lecture halls and churches.

4.4.1 The geometry of the base case

A schematic illustration of the layout and the geometry of the base case are described in Figure 23 and in Tables 5 and 6.

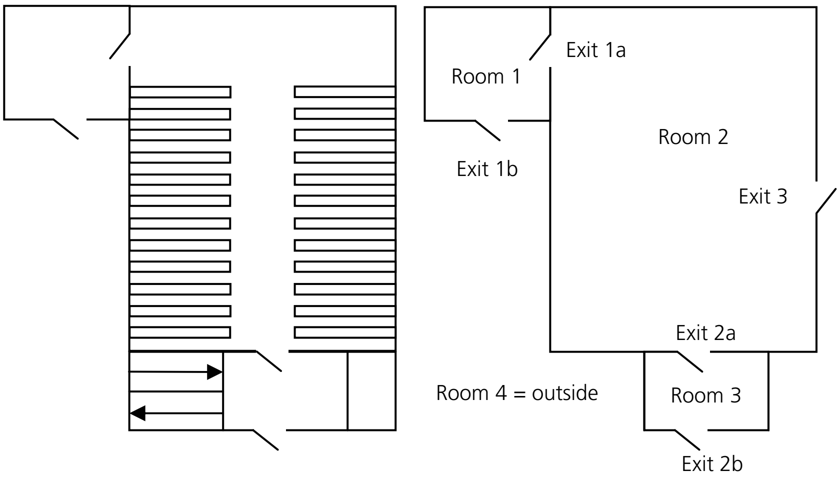


Figure 23. Layout of the base case.

Table 5. Geometry of the rooms and building materials.

	Length [m]	Width [m]	Height [m]	Wall-, floor- and ceiling material
Room 1	2	3	2.4	Concrete
Room 2	25	40	6	Concrete
Room 3	3	6	2.4	Concrete

Table 6. Dimensions of the exits.

	Width [m]	Height [m]
Exits 1a	1.2	2
Exits 1b	2.2	2
Exits 2a	2.2	2
Exits 2b	2.2	2
Exits 3	2.2	2

4.4.2 Types of fires

Two types of fires are considered in order to represent different fires scenarios that may occur in the building. The characteristic of a fire type in this context is defined as the starting point of the fire. Assuming a fire has started, a number of scenarios may arise depending on the course of events, e.g. how different fire protection measures function, which will affect the fire development. The reason for studying two types of fire is that they represent a large proportion of the fires that can occur in a building such as the base case.

The fire development is assumed not to be affected by the people in the building as they evacuate in the calculations, which is a simplification. Conversely, evacuation can be affected by the fire development. For example, the fire may block an escape route. The following section describes the input data and the modelling in the risk calculations performed for the two types of fire.

4.4.2.1 Fires in assembly halls – fire type 1

One type of fire studied is that which starts in the assembly hall itself. In verification of fire safety, this is often the only kind of fire considered. The fire is assumed to be well-ventilated and to develop into a large fire that cannot be extinguished by the occupants of the hall. This kind of fire can be expected to represent accidents belonging to category 1 in Section 3.3.1. The group of scenarios that can arise from this fire (depending on the performance of technical fire protection systems) is called *fire type 1.*

The fire type 1 is characterized by a growing fire that starts somewhere in the assembly hall. Its location is chosen randomly and there is therefore a certain probability that it will block an exit. If there are two or more exits from the hall, one of these may be blocked by furniture or may be locked. The event tree for fire type 1 is presented in Figure 24, and the probabilities of the events shown in the figure are presented in Section 4.4.4.

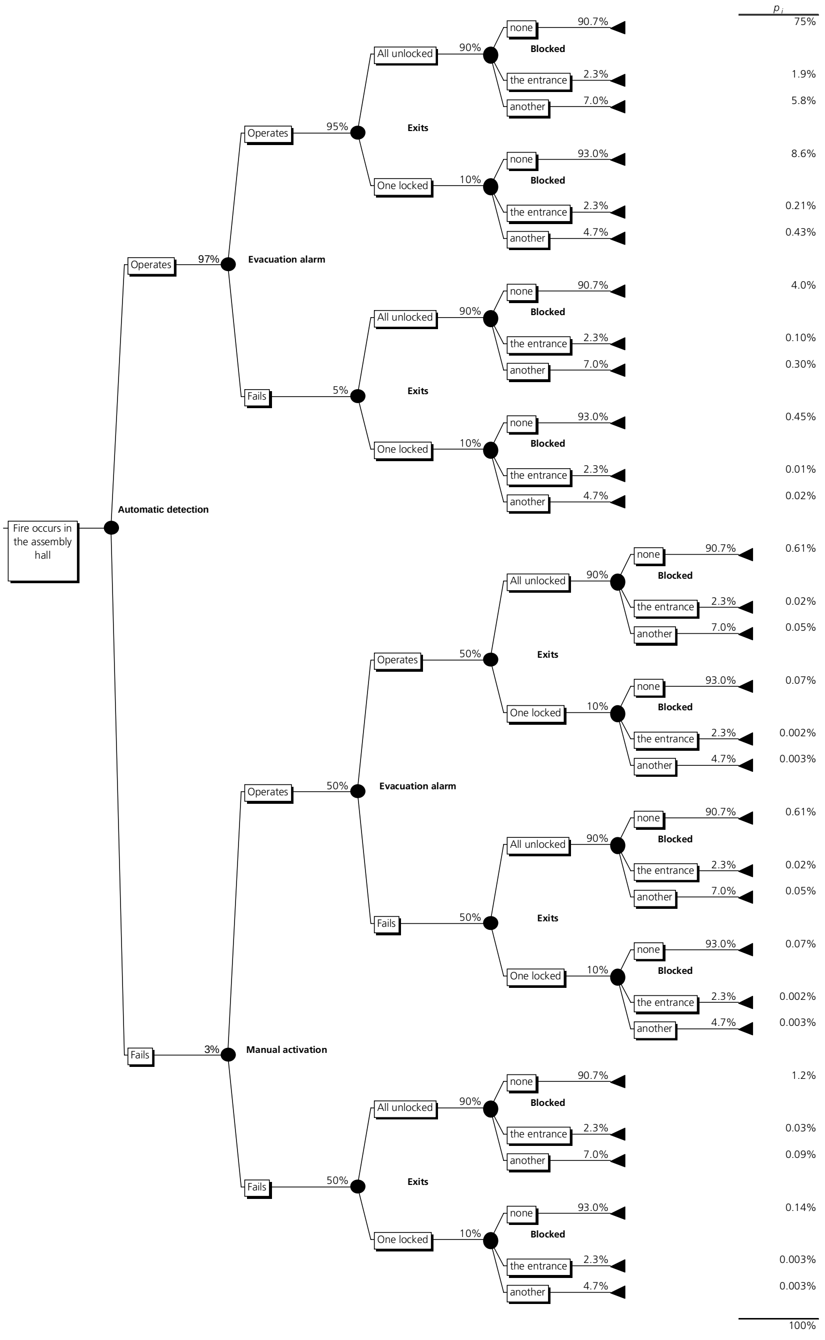


Figure 24. The event tree for a fire starting in the assembly hall.

4.4.2.2 Fire in an adjacent room – fire type 2

Another type of fire, which is not so common, but which has been found to lead to severe consequences, is one which starts in an adjacent room, for example, the cleaning cupboard, staff room, kitchen, stores, basement, etc. It may develop rapidly into a flashover fire before the occupants of the hall have started to evacuate the building. In this kind of fire, the spread of smoke is often rapid, and if the fire is ventilation controlled, the visibility will quickly become poor, and it is thus often more serious than fire type 1. The conditions during this kind of fire were assumed to be vitiated, and represents the kind of fires corresponding to accidents of category 2 in Section 3.3.1. The group of scenarios arising from this kind of fire are called *fire type 2*. The event tree for this type of fire is shown in Figure 25, and the probabilities for the events shown in the figure are presented in Section 4.4.4.

In the case of fires of type 2, it is assumed that the opening between the fire room (Room 1 in Figure 23) and the assembly hall (Room 2 in Figure 23) was 1.20 m, which corresponds to one of two doors being open, or one of the doors being destroyed as a result of the fire burning through it.

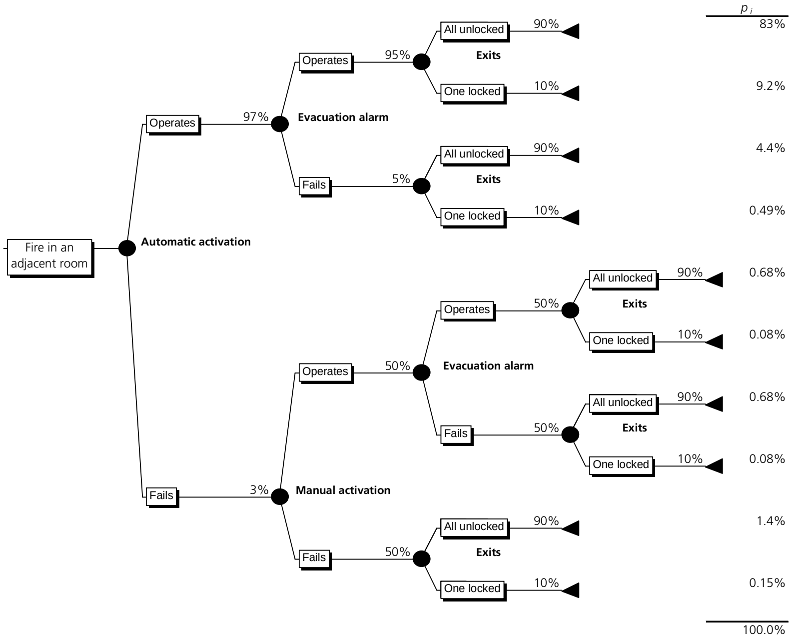


Figure 25. The event tree for a fire starting in an adjacent room to the assembly hall.

4.4.3 Prescriptive design of the base case

The following demands are taken from *Boverket's* report, "Design for Escape" (*Boverket*, 2004b), and have been used to define the prescriptive design for the type of buildings being studied. The building in question is an assembly hall, i.e. a room where more than 150 people may be present, who do not have good knowledge of the premises. Each of the escape routes must have a free width of at least 1.2 m and must positioned so that they are mutually independent (i.e. such that a fire will only block one exit). The total width of all escape routes must be at least 1 m per 150 people. If one of the escape routes is blocked, the others must have a width corresponding to 1 m per 300 people. If the hall has a capacity of more than 600 people, at least 3 escape routes are required, and if the hall can accommodate more than 1000 people at least 4 escape routes are required. The assembly hall must also be equipped with an evacuation alarm which is activated automatically, as well as buttons for manual activation of the alarm.

4.4.4 Reliability data

The effects of the following events and fire protection measures are described using an event tree:

- a locked exit or an exit being blocked by furniture,
- an exit blocked by fire,
- automatic fire alarm,
- manual activation, and
- evacuation alarm.

The reliability data for the systems used in the analysis, in terms of probabilities of failure, are presented in Table 7.

Table 7. Reliability data for the fire protection systems and events modelled.

Fire protection system	**Variable**	**Probability of failure**
Exit blocked by furniture, or locked	p_{f_exit}	0.05
Automatic activation (smoke detector)	p_{f_aut}	0.03
Manual activation	p_{f_man}	0.5
Evacuation alarm	p_{f_evac}	0.05
Evacuation alarm with manual activation, assuming the smoke detectors fail	$p_{f\_evac\_fail}$	0.5

These values are unavoidably associated with great uncertainty. One reason for the uncertainty in the reliability data is that data are seldom available for specific fire protection systems used in a design. Furthermore, new systems are being developed rapidly and there is potential for new malfunctions. Within a period of ten years, fire alarm and evacuation systems have become more software-based, and are controlled via networks or modems, which mean that new kinds of faults and failure modes will arise. There is, however, a concurrent improvement in existing technologies which may improve reliability.

The lack of data is also due to a lack of reliability measurements over long periods, and measurements are seldom made outside the laboratory environment. The result is that the reliability data given in guidelines is mainly based on expert judgement, and the kinds of faults included by the experts may not be known.

Reliability data are also affected by factors that are not governed by the system as such, but are specific to the building in question, e.g. the quality of the planning, installation and operation & maintenance of the system. It is difficult to quantify the effects of these factors on the reliability, but some studies indicate a strong relation between the level of service and the probability of malfunction of smoke detectors (Moore, 1993). Other kinds of faults that should be considered, are the time during which the system is not in operation due to maintenance of the system, or other interdependent systems in the building, or power failures.

Yet another cause of uncertainty in reliability data is the difference in the quality of different components. The choice of components is not usually made in the verification phase, and uncertainties such as differences in the reliability of different products should also be included in the calculations. If the risk associated with a building is to be studied in the design phase, it is advisable to ascribe an uncertainty to the probability of failure, and not simply state a single value.

The material on which the probabilities of failure in Table 7 were based is imperfect, and the above discussion, as well as other studies, indicates that there are considerable uncertainties for the same type of fire protection system (Bukowski et al., 1999). The values assumed were therefore based on a collective assessment of guidelines and research reports in the area, see for example BSI (2003), Bukowski et al. (1999) or Johansson (1999), and discussions with experts in the field at the Department of Fire Safety Engineering at Lund University.

This means that as a starting point the probabilities of failure were based on general statistics from engineering handbooks, which have been adapted to local conditions based on expert judgement. A certain degree of expert or engineering judgement in this situation is unavoidable. For this reason, it is important to carry out a detailed sensitivity analysis in order to investigate the effects of assumptions, and their importance for the conclusions arrived at, before decisions are made as to whether it is necessary to collect further data in order to reduce the uncertainty. Such an analysis has been performed and is presented in detail in Section 6.4.4 and Appendix C. A further discussion of the applicability and validity of the study is presented in Section 9.4.

4.4.4.1 Exit locked of blocked by furniture

When there are two or more exits apart from the normal entrance, the probability of an exit being blocked by furniture or being locked is calculated by multiplying the probability of failure, 0.05, by this number of exits.

When the fire starts in the assembly hall (fire type 1), the probability of the fire blocking the entrance or any other exit is calculated as a function of the area of the premises. A fire is assumed to block an area of 25 m^2 due to heat radiation (Magnusson et al., 1995). The probability of an exit being blocked by the fire is calculated according to Eqs. (9) to (13) in the cases when *no exit is locked* and when *one exit is locked*.

4.4.4.2 No exit is blocked by the fire

The fire is assumed to start at a random location in the hall, which means that the probability of a certain kind of exit being blocked is proportional to the number of exits.

$$P_{EB} = \frac{25}{A} \tag{9}$$

$$P_{OB} = \frac{U \cdot 25}{A} \tag{10}$$

$$P_{NB} = 1 - P_{EB} - P_{AB} \tag{11}$$

A =	the area of the premises, i.e. the assembly hall [m]
P_{EB} =	the probability that the entrance is blocked by the fire
P_{OB} =	the probability that some other exit than the entrance is blocked by the fire
P_{NB} =	the probability that no exit is blocked by the fire
U =	the number of exits (escape routes), excluding the entrance

4.4.4.3 One exit is blocked by the fire

This case is only of interest if there are 3 or 4 exits, as the entrance and at least one other exit is assumed to be unlocked while the building is in use.

$$P_{EB} = \frac{25}{A} \tag{12}$$

$$P_{OB} = \frac{(U-1) \cdot 25}{A} \tag{13}$$

4.4.5 The fire development

The spread of smoke differs when the fire starts in an adjacent room as it is often ventilation controlled, which means that the production of gases increases considerably (Tewarson, 1995). Visibility is also reduced far more quickly than in a well-ventilated fire. However, the smoke must be more thoroughly mixed to be evenly spread in the premises. Two zones are often formed in large fires, even in relatively large rooms, which means that the height of the smoke layer may be a good indicator of when toxicity, visibility and temperature will reach critical levels. It is assumed that no window breakage will occur before critical conditions occur.

A detailed description of how the fire development is modelled for the two types of fires is given in Appendix A, and the input data file for the smoke transport model CFAST is presented in Appendix D. To verify that CFAST can correctly model the conditions in the room in question, comparisons were made with the results from CFD simulations (see Appendix B). These showed that the time to reach critical conditions was predicted satisfactorily by the two-zone model. Despite the fact that the conditions in the fire room are not modelled correctly for fire type 2, the two-zone model gives reasonable results for the larger, adjacent room. If the production of energy and mass in the fire room is the same as those in the flashover fire, then the spread of smoke seems to be in good agreement with the predictions of more complicated models in the case in question.

4.4.6 Detection time

In the case of a fire of type 2 (one starting in an adjacent room) the fire will not be discovered until it reaches flashover. This may be due to the lack of automatic detection in this room, or due to evacuation alarm failure. If an automatic fire alarm is installed in the adjacent assembly hall, the probability of fires of type 2 occurring can be significantly reduced, as staff or visitors may be able to extinguish the fire before it reaches flashover.

When both the fire and evacuation alarms in the hall work as they should, the detection time is estimated to be 10 seconds, as the fire is large when it starts, and develops a large amount of smoke.

If the smoke detectors fail to work, the fire will be detected by someone opening the door to the room, or by the fire burning through the door. The threat will then be visible and obvious, which means that people react quickly and start to evacuate the building immediately. If the evacuation alarm works, the detection time is estimated to be 45 seconds, and if there is no manual activation, it is assumed to be 60 seconds.

4.4.7 Pre-movement time

The type of building considered in this work is assembly halls such as theatres, concert halls and lecture halls, where everyone's attention is focused in one direction. The pre-movement time is therefore short, about 1 minute, regardless of the type of alarm and regardless of whether the occupants see the fire or not (Brandskyddslaget & LTH Brandteknik, 2005; Frantzich, 2001). If the person(s) performing, for example a lecturer or an orchestra, do not react in a suitable way, the evacuation time may be extended. The evacuation process is characterized as one large group of people leaving the premises simultaneously and no consideration is given to sub-groups or phased evacuation.

4.4.8 Travel time

It is assumed in the analysis that the architect and designer wish to limit the number of extra exits, apart from the normal entrance and exit, due to cost savings. Therefore, a smaller number of wider escape routes is preferred over a greater number of narrower ones. For the sake of simplicity, it is assumed that all the escape routes have the same width which, according to prescriptive design means, for 1000 people, 1000/150 = 6.66 m total evacuation width, or 3 exits with a width of 2.2 m each.

During evacuation a queue will form at all exits from the hall as everyone will start to move at about the same time. The course of events is uncomplicated and calculations of travel time can be made by hand or with simple spread sheets. If the fire starts in the hall, the escape routes may be blocked by fire, see Section 4.4.4. If the fire starts in an adjacent room, it is assumed that the fire blocks one exit, as the fire room is adjacent to or close to such an exit. The location of exits is important. When there are only two escape routes, they are often placed far from each other in order to reduce the maximum distance any one person must move to reach an exit. A fire can therefore not block two exits at the same time since they are required to be mutually independent. The density of occupants is set at 1 person/m^2, based on empirical measurements of lecture halls and corresponds to the interval given for different types of assembly halls (*Boverket*, 2004b). The density of occupants may, however, be higher in other assembly halls.

The time required for people to leave the premises by the escape routes is calculated according to Eqs. (14) and (15):

$$t_{ME} = \frac{F_{ME} \cdot N}{f_K \cdot w} \tag{14}$$

$$t_{OE} = \frac{(1 - F_{ME}) \cdot N}{f_{UK} \cdot w \cdot U} \qquad \text{for cases where } U \geq 1 \tag{15}$$

t_{ME} = the travel time for the last person to leave through the main entrance [s]

t_{OE} = the travel time for the last person to leave through any other exit [s]

F_{ME} = the fraction of people leaving through the main entrance

N = the number of occupants

f_K = the occupant flow through the known escape route [person/(s · m)]

f_{UK} = the occupant flow through the unknown escape route, i.e. one that is not normally used [person/(s · m)]

U = the number of escape routes used excluding the entrance

w = the width of an escape route [m]

The following assumptions were made in calculating the travel time:

- those who do not evacuate the building through the entrance are evenly distributed between the other available exits,
- the location of exits does not affect the process of evacuation.

4.4.9 Consequence modelling

A survey of the different definitions of critical (untenable) conditions exemplified in *BBR* has been made for the specific type of building (Lundin, 2004). The smoke layer height was found the most suitable, since it is assumed that a two-zone layer will arise. The critical level is calculated according to Eq. (16) (*BBR*, 2002).

$$h_{crit} = 1.6 + 0.1 \cdot h \qquad (16)$$

h_{crit} = the critical height of the smoke layer [m]
h = the ceiling height of the room where people are exposed [m]

The critical height of the smoke layer depends on the height of the room, according to Eq. (16). This also means that the fire development and the critical smoke layer height will vary within a class of buildings. Simple analytical expressions for calculating the time before critical conditions are reached, as a function of area and height, are presented in Appendix E.

As the two-zone model was used, critical conditions will arise at the same time in the assembly hall, i.e. t_{crit}. The evacuation times will, however, differ, as different proportions of the occupants will choose to evacuate the building through the entrance and other exits.

The consequences for scenario *i* are therefore calculated as the sum of the consequences at the entrance and the other exits, according to Eqs. (17) to (19).

$$c_i = c_{ME} + c_{OE} \qquad (17)$$

$$c_{ME} = \left\{ \begin{array}{lll} 0 & if \quad \Delta t_{ME} > 0 & * \\ -\Delta t_{ME} \cdot f_K \cdot w & if \quad -\dfrac{N_{ME}}{f_K \cdot w} < \Delta t_{ME} < 0 & ** \\ N_{ME} & if \quad N_{ME} < \Delta t_{ME} \cdot f_K \cdot w & *** \end{array} \right\} \qquad (18)$$

$$c_{OE} = \left\{ \begin{array}{rll} 0 & \mathit{if} \quad \Delta t_{OE} > 0 & * \\ -\Delta t_{OE} \cdot f_{UK} \cdot w \cdot U & \mathit{if} \quad -\dfrac{N_{OE}}{f_{UK} \cdot w \cdot U} < \Delta t_{OE} < 0 & ** \\ N_{OE} & \mathit{if} \quad N_{OE} < \Delta t_{OE} \cdot f_{UK} \cdot w \cdot U & *** \end{array} \right\} \quad (19)$$

* = when all occupants escape
** = when some occupants escape
*** = when no occupants escape
c_i = the consequences of scenario *i*, i.e. the number of people exposed to critical conditions
c_{ME} = the consequences at the entrance for scenario *i*, i.e. the number of people exposed to critical conditions
c_{OE} = the consequences at the other exits for scenario *i*, i.e. the number of people exposed to critical conditions
Δt_{ME} = the time margin for people who escape via the entrance [s]
Δt_{OE} = the time margin for people who escape via the other exits [s]
f_K = the flow of people through a known exit [people/(s · m)]
f_{UK} = the flow of people through an unknown exit [people/(s · m)]
w = the width of an escape route [m]
U = the number of escape routes used excluding the entrance
N_{ME} = the number of people escaping through the entrance
N_{OE} = the number of people escaping through other exits

5 Risk control by specifying rules for safety output

According to the framework for risk control, presented in Section 3.1.2, the safety associated with an activity can be controlled by regulations on various levels, so-called levels of intervention in risk control. The regulations can be seen as external rules. If no such rules are imposed, the organisation itself or the people performing the activity, will make their own rules. This chapter describes the regulations issued, and the way in which compliance with the rules is checked, on the level of *safety output* in the building regulations (*BBR*), see Figure 26. Regulations and their requirements on this level form the basis for *goal-oriented or performance-based legislation* and the aim is to define rules for the *safety output* required by the system, in this case the building and its fire protection measures. The rules may express the acceptable risk explicitly, or indirectly by expressing the attributes or functions of a system directly connected to safety. In order to determine whether the demands are fulfilled, it is important to have an unambiguous definition of what is to be measured, and the quantitative level or amount required.

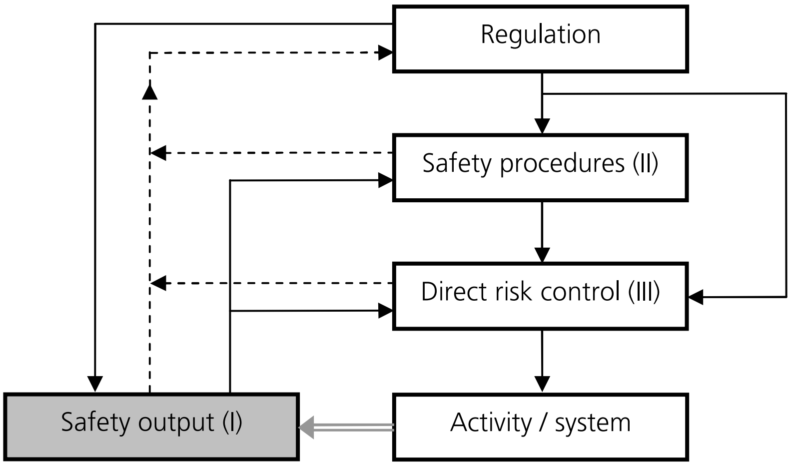


Figure 26. "Safety output" defines a level of risk intervention by which regulations can control safety in case of fire in construction works by placing demands safety objectives and performance.

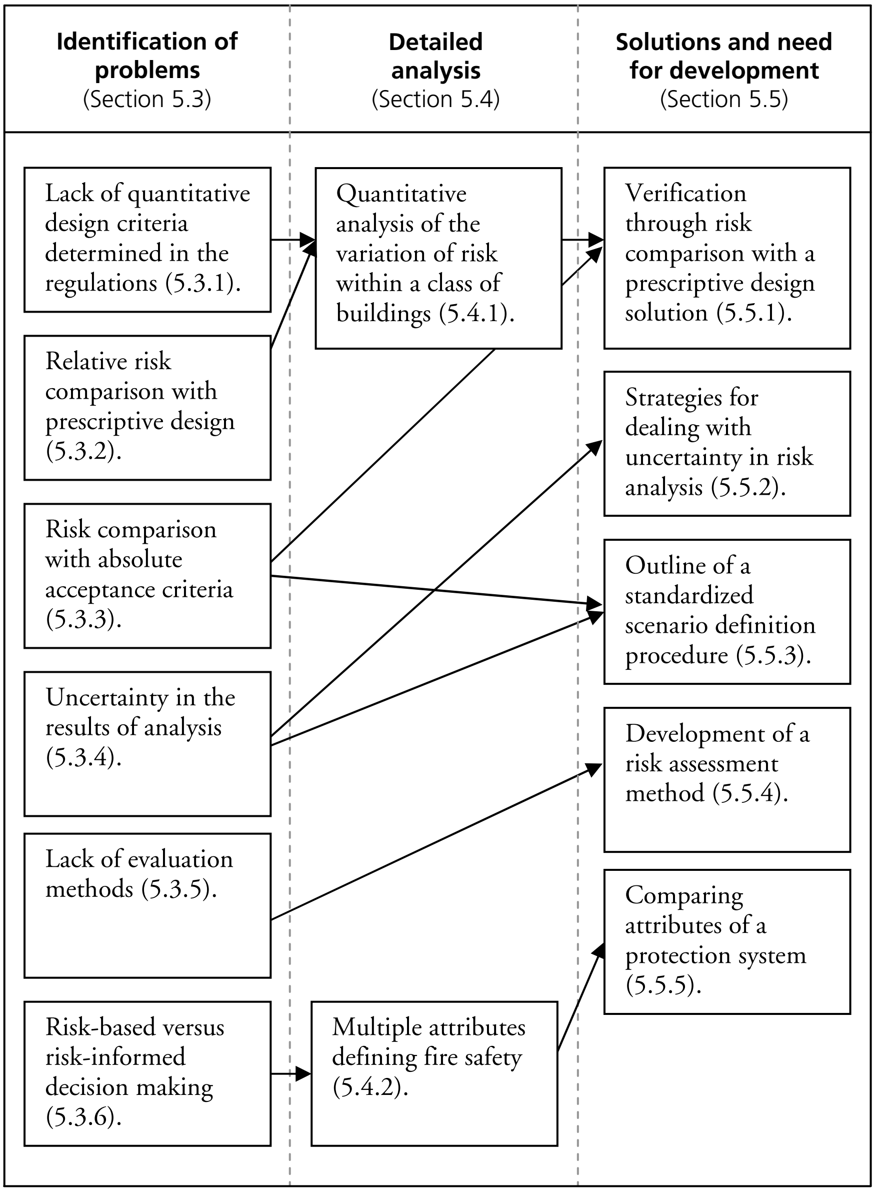


Figure 27. The structure of Sections 5.3 to 5.5 (see Section 4.1).

Analysis of this level of control is carried out according to the procedures described in Section 4.1. After a brief introduction a general presentation is given of the results of changes in the building regulations regarding *safety output* (Section 5.1), followed by a description of how the assessment of compliance with the rules are affected (Section 5.2). Various problems and dilemmas associated with society's ability to control fire safety at this level, based on how the provisions are formulated, and how they are applied in practice, are then discussed (Section 5.3). Some of the problems are investigated in more detail and are presented in Section 5.4. Finally, various strategies for solving the problems identified, together with some specific suggestions for solutions, are given in Section 5.5.

This work has not been carried out as a top-down analysis of the problems formulated in Section 1.4. The results should rather be seen as a synthesis of several independent projects. To clarify the structure of this chapter the links between the different sections are illustrated with arrows in Figure 27.

5.1 Changes in rules for safety output (see Table 4)

By stipulating the demands that the building must fulfil, but not how they should be fulfilled, it is possible for the fire safety designer to choose the most suitable solution to each problem. This possibility was very limited in earlier building regulations.

Fire protection of structural elements was the only functional requirement where fire safety engineering methods could be used. Although the degree of prescriptive requirements had been reduced by the change from *SBN* 80 (1980) to *NR* (1988), most of the requirements in the section on fire safety in *NR* (1988) were still directed towards the detailed design of the building and specific fire protection systems, i.e. direct risk control, for egress safety. As the inadequacy of purely prescriptive regulation started to be recognized, the possibility of designing certain buildings using performance-based requirements was introduced, although only in a few limited cases, e.g. atria, according to *NR* 8:411.

BBR specifies no measurable goal regarding the total safety of a building, i.e. an explicit level of risk. Neither is any such goal specified in the essential *functional requirements for construction works* laid out in The Ordinance on Technical Requirements for Construction Works etc. (*BVF*, 1994). This means that an unambiguous measure of the *safety output* regarding fire safety, in the form of an acceptable quantitative level of fire risk for a building as a whole, does not exist in a general form suitable for design purposes. The functional requirements have instead been broken down into performance requirements in *BBR*, formulated at different levels of detail, and have been translated to varying degrees from the prescriptive requirements in the previous regulations to pure performance requirements. This transition has not been fully completed, and difficulties have arisen in the adaptation of the requirements (this is elaborated on in Section 6.4.2). As a consequence, most of the performance requirements are expressed in vague, qualitative terms with broad scope for interpretation, for example in *BBR* 5:31, "Buildings shall be designed so that satisfactory escape can be effected in the event of fire". There is no measurable demand on the level necessary to fulfil this performance requirement. In some of the demands, it is not only the level that is unclear, but the reasons for the previous detailed requirement are unknown, which can cause considerable problems in verification. During the review process this can cause disagreement or conflict between different stakeholders since the scope for interpretation is considerable.

5.2 Changes in procedures for assessing compliance with the regulations (see Table 4)

Following the introduction of *BBR*, local building authorities (building committees) are no longer required to inspect the design of the fire safety measures in detail for each project, nor do they check, on a regular basis, that the verification of the proposed design solutions is acceptable. Thus, the building committee is not obliged to make sure that the demands in *BBR* have been followed, and does not certify that the solutions fulfil the demands. The main responsibility for ensuring that the fire safety measures really do satisfy the requirements of the building regulations, and that this has been verified in the appropriate way, thus rests with the developer.

The building committees are instead responsible for deciding what is to be reviewed, which documents are to be presented, and the scope of the control procedure. If the local building committee has any doubts as to the capability of the developer and their design team, or finds it necessary to order an independent investigation of the whole design or parts of it, a third party can be called in. If necessary, the local building committee can itself carry out an investigation, which might require technical assistance from the fire and rescue service or other experts.

5.3 Identification of problems in the present situation – structure and discussion

The description of the way in which *safety output* in the framework for risk control is applied in *BBR* bears witness to the difficulties encountered in controlling fire safety in buildings when using analytic design. The ambition of building regulations is to be performance-based, i.e. the regulators have tried to formulate fire safety requirements on this level so that fire safety engineering methods can be applied in the design work. The designers are supposed to verify with calculations that a design solution is sufficiently safe. The regulators have succeeded so far as there are no formal obstacles in the form of administrative rules or restraints which impose restrictions on the fire safety design itself. On the other hand, there are no measurable goals, acceptance criteria or design criteria connected to *safety output*.

In some parts of Sweden the building committees have decided how the performance-based regulations should be interpreted and which level of safety is acceptable in terms of absolute criteria, for example, in the Öresund region (Helsingborgs brandförsvar et al., 2001). Their interpretation is used as recommendations in fire safety design on a local level in the geographical area over which the building committee has control. The acceptance criteria used in the recommendations consist of risk levels based on statistics from other countries. Not only can the relevance of foreign data be questioned, but the level of safety cannot be controlled when the uncertainty in the input data, scenarios and models used is not linked to the acceptance criteria. The suggested procedure is not considered suitable for assessing fire safety on a regulatory level. The consequences of introducing such a system have not been investigated, and it has not been ascertained whether the recommendations lead to a higher or lower standard of safety than that required in prescriptive design. While it provides clear recommendations for designers and developers regarding the demands that have to be fulfilled according to building regulations, local initiatives will lead to local differences in the application of national legislation on fire safety.

A number of problems regarding the possibility of verifying safety have been identified through the study of fire safety protection documentation from forty-six projects (see Section 4.2.1), active participation as a reviewer in design projects (see Section 4.2.3), and discussions with designers and reviewers. These problems can be divided into the following main types:

- lack of quantitative design criteria determined in the regulations (Section 5.3.1),
- relative risk comparison with prescriptive design (Section 5.3.2),
- risk comparison with absolute acceptance criteria (Section 5.3.3),
- uncertainty in the result of the analysis (Section 5.3.4),
- lack of risk evaluation methods (Section 5.3.5), and
- risk-based versus risk-informed decision making (Section 5.3.6).

5.3.1 Lack of quantitative design criteria determined in the regulations

The level of fire safety achieved in buildings will become evident, in the long run, from the number of fires and the resulting number of injuries and fatalities. This type of data constitutes a kind of *safety output*. Today's building regulations contain no quantitative criteria even indirectly linked to *safety output*. As the performance requirements are not expressed as measurable quantities it is difficult to verify that they have been fulfilled, and it will also be difficult to check the verification, irrespective of who performs the review. If it is not known which level is acceptable, it will be difficult (or impossible) to decide whether the requirements have been fulfilled or not. A corresponding problem in checking that the regulations have been followed has been noted in many other areas where performance-based regulations have been introduced, and poses a dilemma that may be difficult to circumvent (Hale, 2001).

In earlier building regulations, the acceptable fire safety level has been indirectly defined by demands on direct risk control in the regulations (prescriptive requirements). Now that the regulations have changed in character and claim to be performance-based, a need for design criterion has been created so that verification is possible. Verifiable performance demands are a prerequisite if it is to be possible to control the level of risk through regulations directed towards this level of control in fire safety.

Despite the fact that there are no acceptance criteria such as quantified performance objectives, or explicit levels formulated in *BBR*, it is still demanded that risk analysis be used when necessary in certain kinds of buildings (*BBR* 5:13), but the demands are not linked to a particular model or type of risk analysis. In *BBR* 5:13 it is stated that only analytic design is to be used when a fire could result in great risk of personal injury, e.g. buildings higher than 16 storeys, buildings with certain types of assembly halls or auditoria, nursing homes, and complex buildings below ground level. It is not possible to use prescriptive design to derive a reference building in order to make a relative comparison in such cases. The obvious question is, what should be used instead? Since the performance requirements are not explicitly stated it is difficult to identify in which situations the prescriptive method is inappropriate.

The authorities could formulate design criteria for the control of safety in two ways. The first is as a probabilistic criterion in the form of an acceptable level of risk, in combination with extensive demands on uncertainty analysis, according to level 2 or 3 in Section 3.4.4. The alternative is to give a deterministic criterion including safety factors for one or several specified scenarios, which means that uncertainties would be dealt with according to level 1 in Section 3.4.4. However, it is far from clear how safety performance should be defined and measured, which means that the application of analytic design brings with it certain problems. Defining a deterministic criterion requires the development of design expressions and that uncertainties can be treated in a suitable way. Attempts have been made to apply design expressions similar to those for load-bearing structures in fire safety design; this is further investigated in Section 6.4.3.

In Sections 5.3.1.1 to 5.3.1.4 a number of different approaches considered to be used to determine a probabilistic design criterion in terms of an acceptable risk, i.e. acceptable level of *safety output*, are summarized, all of which have advantages and disadvantages;

- through political decisions,
- based on accident investigations,
- founded on levels from other areas or applications, or
- derived from the existing implicit level.

Regardless of the approach used, it is important to take into account the general principles of risk assessment. These can be characterized as; reasonable risk exposure, i.e. avoid unnecessary risks, proportional risk exposure, i.e. a higher risk can be accepted if the benefits are greater, fair distribution of risk and avoiding catastrophes (Davidsson et al., 1997).

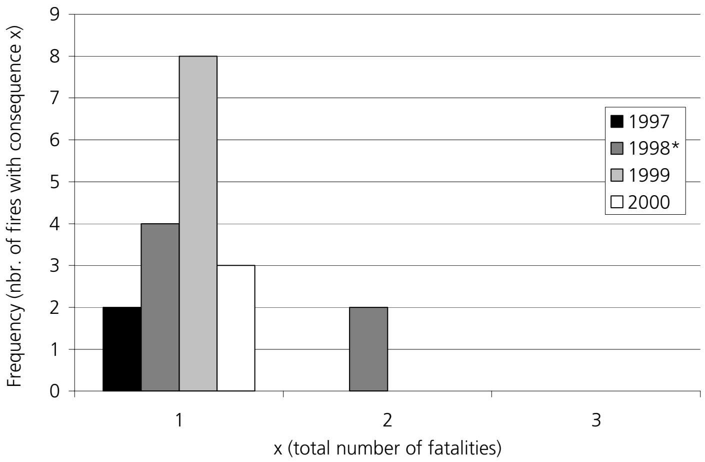
5.3.1.1 Political decisions

An acceptable risk has been determined for some cases through political decisions. The level of risk is either implicitly defined as the consequence of an established strategy (and may vary greatly), or a specific level can be determined explicitly. Examples of ways in which explicit levels are determined are: the likelihood of individuals becoming fatalities as the result of natural catastrophes, the probability of being struck and killed by lightning, or 1/100 of the probability of becoming a fatality as the result of an accident for the age group with the lowest mortality rate in a society. The above example was used in the Netherlands to establish the individual risk (of 10^{-6}) when constructing a chemical plant (Vrijling et al., 1995), but other motives for choosing this level have also been presented (e.g. Ale, 2005). Whether or not this risk actually reflects the values of society, regarding the size of the risk and who is affected, is difficult to say.

5.3.1.2 Accident investigations

If a large amount of empirical material is available, levels of risk and/or acceptance criteria can be calculated using, for example, accident statistics. However, there is often a lack of stable, long-term data from many engineering systems, and risk estimates must then be based on the analysis of the system using logical models, or through expert judgement. Regarding fire death rates both national and international data are available. Figure 28 shows the results of an analysis of fire and rescue service statistics collected and compiled by The Swedish Rescue Services Agency. The figure shows the frequency of fires leading to fatalities for the period 1997 to 2000. For example, in 1999 eight fires occurred in which one person died, while only two fires occurred during the whole period in which two people died, and both these were in 1998 (note that the dance hall fire in Göteborg is not included, since it is seen as an outlier in this context). The number of fires in public buildings during the period in question is just under 2000 per year, and the variation from one year to another is small.

Swedish statistics are not sufficiently extensive to use as the basis for design criteria for the *safety output* of protection systems against serious fires. The number of serious fires is relatively small and the types of buildings, building materials and activities in buildings vary constantly. Protection systems are also being continuously developed and therefore cause and effect are often not investigated in detail or not possible to establish with a degree of reliability.



* The dance hall fire in Göteborg is not included.

Figure 28. The frequency of fires leading to fatalities in public buildings.

It is not possible to see from the compiled statistics the number of fatalities as a result of flaws or failure of the fire protection of construction works, or whether a fatality was due to other causes, for example, drunkenness or suicide. Some important information is lacking in the fire and rescue service statistics collected today, e.g. the total area of the building and the area of the room of origin of the fire, which are required to create input data for modelling the risk in a way that is useful for design purposes. Relevant information of the fire development is also lacking. Another problem in using historical data in fire safety design is that data age. For example, sprinkler reliability data from the early 20th century are sometimes used as input data, and these are probably not applicable to today's modern sprinkler systems.

There are many external conditions that affect the design of fire protection systems. Considerable differences in the design of buildings in different countries can be found, depending on differences in climate and access to materials, or to differences in building traditions. This may lead to significant differences in fire protection of buildings and in levels of fire safety in different countries. The total safety in case of fire depends on various factors such as the fire and rescue service, which means that a solution that is suitable in one country may not be in another.

Another argument for not using solutions from one country in another uncritically is that there are differences in what is regarded as an acceptable risk of fire in different countries. The number of fatalities due to fire per 100,000 inhabitants in various countries is quite different, as can be seen in Figure 29. These figures can be seen as a kind of *safety output*, where the fire protection of the construction work is one of the factors affecting this output. Social conditions and demographic structure are, however believed to be of much greater importance. Note that the reported fatalities cover more than just building fire, e.g. fires in cars.

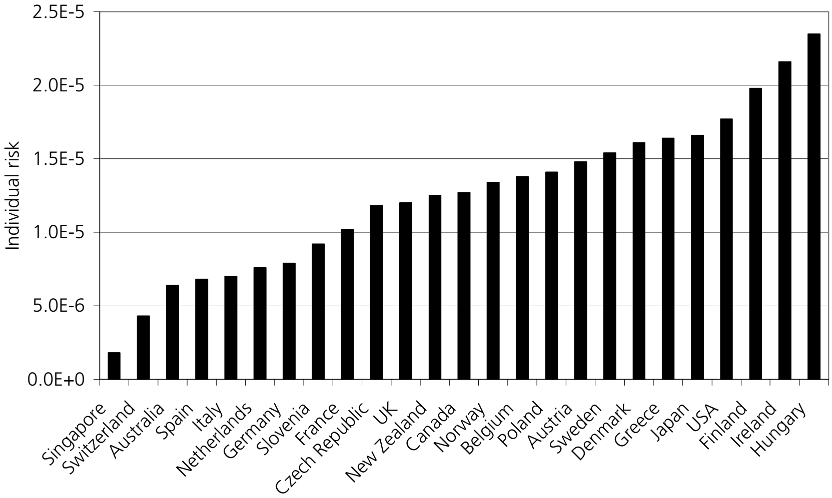


Figure 29. A three year average of the annual number of fatalities due to fire per 100,000 inhabitants in various countries for the period 1999- 2001 (Wilmot, 2004).

5.3.1.3 Other areas or applications

Calculating risks in one area and then comparing them with levels of risk in another may not be appropriate as the level of risk that people regard as acceptable varies depending on the activity. Many studies have found evidence of this, e.g. Ramsberg (1999) and Slovic et al. (1982). Several factors influence how we perceive risk in addition to the frequency and consequence of the risk. The most important factors are whether the risk:

- is taken voluntarily or not,
- is controllable or not,

- is known or unknown,
- will affect future generations or not,
- is acute or chronic,
- is natural or technical,
- is regarded as fair or not,
- the uncertainties involved, and
- the perceived benefit of the activity generating the risk.

It is therefore not appropriate to apply risk levels that are acceptable in one area to the design of fire protection systems without careful consideration. Figure 30 shows examples of the great variation in the levels of risk, where the probability of becoming a fatality as the result of various risks is compared with the probability of becoming a fatality in a fire in a building in Sweden, which is about $1.1 \cdot 10^{-5}$ per year.

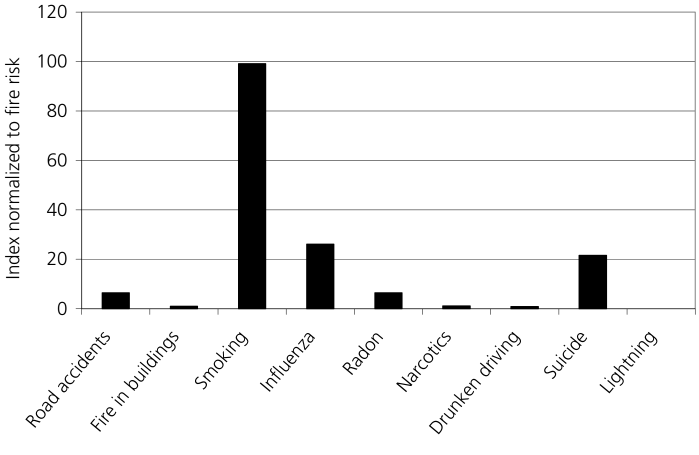


Figure 30. Various risks normalized to the probability of becoming a fatality due to building fires ($1.1 \cdot 10^{-5}$ per year) based on Ramsberg (1999).

Another dilemma is that these factors vary substantially for different types of buildings (Meacham, 2000) which will result in different levels of acceptable risk in different types of buildings. This variation is, to some extent, reflected in the building regulations, since the fire protection requirements are different for different types of activities. Determination of a single level of acceptable risk for buildings appears, therefore, not to be appropriate. However, the different demands for fire protection in different types of buildings are not only the result of different acceptance levels. The hazards also vary significantly between different types of buildings, and some groups of occupants may be much more vulnerable than others, so different amounts of protection may be required to achieve the same safety level.

5.3.1.4 Existing level

Boverket did not have the explicit mandate of improving fire safety of construction works by requiring more fire protection measures when the regulatory regime was changed, i.e. *BBR* introduced. If a level of risk based on what is acceptable in another area is applied, the risk of fire may be higher or lower than it is today. It is not especially likely that the level of risk in other areas really reflects society's values when it comes to the need for fire protection. It would also mean that the levels of risk would vary depending on whether analytic design or prescriptive design was used, which would lead to inconsistent building regulations. It is possible to modify the prescriptive design method to achieve a new risk level, but this would require a considerable amount of work on the part of the regulating authority, i.e. *Boverket.*

Uncertainty in the input data and lack of knowledge on how this uncertainty varies with the type of building, the activities carried out therein and other factors, lead to difficulties in quantifying and applying an absolute level of risk. There is, on the other hand, sufficient knowledge to make relative comparisons based on quantitative analysis and to rank the various alternatives. There is actually no need to determine an absolute risk level for the fire protection of construction works, as long as there is a method of determining what constitutes adequate fire protection. The requirement on such a method is that the fire protection of construction works is equal to or better than when the prescriptive design method is used.

5.3.2 Relative risk comparison with prescriptive design

Even though a relative risk comparison seems promising, basing verification of analytic design on a relative comparison with prescriptive design is not without problems. Having to first design fire protection solutions using prescriptive design takes time, and costs money. Also, it is not certain that prescriptive design leads to good fire protection in all buildings (which will be elaborated further in Section 7.3.2).

Yet another problem lies in choosing the premises from a certain class of buildings to be used as the reference building, i.e. the object with which to compare the risk. Prescriptive design leads to a variation in the level of safety in a certain class of buildings (Frantzich, 1998; Kristiansson, 1996), which is unavoidable since all the variables that affect safety are not included (or controlled) in this design method. As there are no recommendations regarding the choice of reference building, this building may be systematically designed with too low a level of safety. Because the reference building is purely fictitious and will never actually be built, it can be designed neglecting other competing objectives, which means that the fire safety measures can be minimized. Comparison to such a building would be misleading as the risk level used as the acceptance criterion would be too low.

This might seem surprising from a building-specific point of view. All buildings designed with the prescriptive method are regarded as acceptable, and thus the highest risk level resulting from prescriptive design ought to define the acceptable level. On what basis can this risk level be rejected as a suitable acceptance criterion? One must bear in mind that the prescriptive design method was not designed so that each building in the class meets a specific risk target, but was instead developed in a reactive way (see Section 3.3.1) for classes of buildings. The design method will lead to design solutions where the safety level varies between the specific buildings, but where the group as a whole is deemed acceptable. It is by no means certain that the building with the highest risk, as a result of the prescriptive design method, corresponds to the risk level that society regards as appropriate. However, this building can be seen as a necessary result due to uncertainties that can not be reduced in the design method, but is not a good representation of the target level of risk for all buildings in the class. If this risk level is used as an explicit design criterion when analytic design is used, the average risk level in that building class on a national level will be greater than if prescriptive design had been used. If the risk level is increased on a national level, a higher number of fatalities due to building fires are to be expected, which is not a desired outcome of introducing analytic design (*Boverket*, 1994a).

If, on the other hand, the highest risk level resulting from the prescriptive design method defines the minimum acceptable safety, this should be made clear. In such cases it is up to the designer to determine how much safety, in addition to the minimum requirement, is appropriate.

5.3.3 Risk comparison with absolute acceptance criteria

In order to verify the fire protection systems in buildings where the analytic design method is the only option according to *BBR* 5:13 (see Section 5.3.1), the designer must determine an explicit acceptance criterion. In such situations, this is usually done in collaboration with the building committee. This is an unreliable procedure for many reasons. For example, legislation provides no recommendations on the correct level of safety. The process often suffers from a lack of time and is not scientifically-based, which results in considerable variations on a local level, which is in conflict with the intentions of both the building regulations (*BBR*, 2002) and the Civil Protection Act (LSO, 2003). The need for development and guidance in this area is thus considerable. If the designer defines the level of safety required in order to satisfy the mandatory provisions, this means that society is not in control of safety, and this is undesirable for several reasons (see Section 2.1.1). The appropriate level of safety should be determined by investigating the level of safety in prescriptive design in building classes where this design method is suitable. Current knowledge of this level, and how it varies in different building classes is poor, but will be analysed in detail in Section 5.4.

5.3.4 Uncertainty in the results of analysis

By stating goals for *safety output,* e.g. specifying a target risk level, uncertainty in the risk analysis can cause major problems in exercising risk control. During the process of risk analysis, a number of subjective choices and assumption must be made, which means that different designers may obtain different results. The results of such analyses will, to some degree, be arbitrary. Apart from this, there are uncertainties in both the models and the input data that contribute to uncertainties in the final results. Even if an acceptable level of risk can be established, the resulting risk of fire in the building with this approach will not be controlled due to the uncertainties in the risk analysis calculations. Rules on how to assess these uncertainties are necessary. In practice, this means that regulations must be issued at a lower level of intervention in the framework for risk control, i.e. demands on the *safety procedures & safety case*, in this case by placing demands on the use of a certain design method. Such a regulation would indirectly mean that the required level of safety would be attained. This is dealt with in detail in Chapter 6.

5.3.5 Lack of risk evaluation methods

One of the difficulties in comparing risks, e.g. in verification, is that it is unclear how trade-offs should be made between probability and consequences in the risk calculations. This problem originates from the difficulties of how to combine probability and consequence into an adequate risk measure (see Section 3.2). The mean risk is used as the risk measure in risk comparisons in many areas, which assumes that the decision maker's attitude is risk neutral. This means that the risks are ranked according to magnitude based on the product of the probability and the consequences. If the probability is halved while the consequences are doubled, this would have no effect on the magnitude of the risk, according to this approach. In a *f(N)* diagram this risk attitude would be characterized by an acceptance criterion defined by a line with the slope equal to -1. There is, however, evidence that this is not the way in which society regards risk, e.g. the risk criterion used in the Netherlands (Vrijling et al., 1995). However, questions that arise in risk evaluation in verification are:

- If it is reasonable that serious consequences with a low probability are regarded in the same way as slight consequences with a high probability?
- How can several small injuries be compared with one event leading to severe injury?
- Should scenarios with severe consequences be assessed on the same grounds as other scenarios, i.e. based on the risk, or do we assess catastrophes as being more serious than the risk indicates?
- How then can the risk of a serious accident be limited by design criteria?
- Should a limit be set on the extent of the consequences regardless of the probability of such an accident happening?
- Is it reasonable to determine this limit based on the worst case scenario in a building designed using prescriptive design?

The lack of guidance on how to assess these issues in practical design work indicates that the design procedure for analytic design is incomplete.

Today it is not clear how trade-offs can be made between probability and consequence. In analytic design new protection systems are sometime used, which have several positive effects. If the intention is not to improve current safety levels, but to use the protection system to replace another system or to compensate for an increase in risk, e.g. allowing more people in the premises, then the questions posed above become pertinent. Since any kind of system can fail, there is a certain probability that a scenario will occur in which the consequences are greater than would have been the case before the system was installed. The question is, to what degree we can allow this, and this will be touched upon again in Section 6.4.4.

5.3.6 Risk-based versus risk-informed decision making

The conclusion drawn from the analysis of fire protection documentation is that verification is often limited to comparing the functions of different safety measures or, at best, the quantitative level of risk. This may be insufficient, since several attributes of the protection system can be affected. For example, it is not self-evident that two separate escape routes in a high-rise building can be replaced by one wider staircase and a sophisticated ventilation system to pressurize the single staircase. Even if a quantitative risk analysis shows that the high reliability of the ventilation system will result in a lower risk than in the prescriptive solution, there may be other concerns indicating that the safety level is not deemed to be equivalent to that obtained with the original solution. The possibility of a fire blocking the only exit can be perceived as a very high risk, even if the probability is low and thus also the risk measure.

In several other areas, such as the nuclear power industry and land-use planning, the attitude towards how the results of risk analysis should be used as the basis for decisions has changed during recent years. At the beginning of the 1990s there was a trend to use risk-based decision making in safety legislation. The decision as to whether or not a solution should be accepted or not was based on whether risk analysis could show that a certain acceptable level was not exceeded, or that the risk would not be higher than in an acceptable solution. During recent years, other attributes apart from the risk-reducing effect influence the way in which protection systems are evaluated. The same applies to evaluation of risk levels due to hazardous industries. When several dimensions of the risk are included in the decision, and not only the technical ones (i.e. the quantitative risk level), the method is called *risk-informed decision making*. In such a method, the level of risk together with additional aspects are considered in making the decision as to what is acceptable. The risk level still plays a very important role, but a “go/no-go” decision is not based on it entirely.

Examples of the aspects that can be included in protection systems in general when approving plants or activities regarded as *major accident hazards* are:

- the possibility to intervene in a sequence of events potentially leading to a catastrophe (Reason, 1997),
- inherent safety (Kahn & Amyotte, 2002; Turney, 2001),
- the number of barriers (Harms-Ringdahl, 2003; IAEA, 1999), and
- the extent of the uncertainty in the risk analysis (Christou et al., 2000; Slovic et al. 1979).

The possibility of revealing that an accident is about to happen or has just happened but there are means of preventing it from developing into a catastrophe, is regarded as important. In such case additional safety strategies can be applied, evacuation procedures started, other consequence reducing options initiated. Inherent safety means constructing the plant or building so that situations which may lead to accidents cannot arise. A principle of multiple barriers is often used when an accident can lead to severe consequences. Having several independent barriers affords greater flexibility to the protection system and the chances of being able to cope with problems not anticipated in the design of the system are also improved. Such a method also allows for more options to improve the system if deemed necessary, as the number of opportunities for improvement generally increases with the number of barriers. The mere fact that there are several safety measures is of great value. Several independent systems provide protection against common-cause failure, i.e. a single fault disabling several protection systems. The extent of the uncertainty in the assessed risk level also affects the way in which the risk is assessed. A high uncertainty is often regarded as undesirable in this context. Another reason for using risk-informed decision making is that the effect of several important kinds of protection measures is not captured in quantitative risk analysis. Examples of this are: the quality of maintenance work, whether contingency plans are available in the case of a catastrophe, whether a safety management system is being used, and how well it is adapted to the activities in question. The American nuclear power industry was early in formulating legislation in which risk-informed decision making was applied, e.g. in connection with the licensing of nuclear power plants following changes to the plant (Caruso et al., 1999). During recent years, similar development has taken place in other areas, for example, through the Seveso II Directive (EC, 1996).

Traditional provisions in fire protection of construction works have been enforced on attributes of protection systems other than the risk level, e.g. the requirement of two independent escape routes. Even if acceptable risk levels can be determined, insight from risk analysis should be used in combination with documented experience and basic safety principles. Formulating legislation as risk-informed regulations creates the possibility of doing this. At the same time, it is important to identify the underlying safety principles for the design of the fire protection measures which would constitute secondary provisions in decision making. One cannot simply apply principles from one engineering area to another, although they may provide a good starting point. With the current legislation there is a risk that safety principles already established in previous building regulations will be disregarded by the application of the alternative design (i.e. the equivalent safety option) in *BBR* 5:11, and that only the level of risk will be used as the starting point for risk assessment. It is therefore advisable that it be made clear in a revision of *BBR* which principles are to be applied, and to stipulate whether alternative solutions must satisfy these principles or not. The first step in developing such principles should be the investigation of the attributes of fire protection systems with regard to life safety. A suggestion is presented in Section 5.4.2, and in Section 5.5.5 an example is given of the tools that can be used to analyse how the attributes are affected in safety design.

5.4 Detailed quantitative and qualitative analysis of specific identified problems

From the problems identified in the previous section (Section 5.3), it is clear that our ability to verify performance requirements is inadequate. It should be a long-term goal to develop absolute criteria against which safety can be assessed in analytic design, in combination with a risk evaluation method of dealing with uncertainties and including basic principles of safety. The first stage in such a process, before general design methods have been developed, is to demonstrate, with the aid of risk analysis, that the level of safety is sufficient. It has been pointed out that the risk level resulting from prescriptive design may be used as the basis of verification. In Section 5.4.1 a study on the risk level arising from the prescriptive design of a certain class of building, *assembly halls*, is presented.

Concurrent with the analysis of the implicit risk level in prescriptive design, a complementary method should also be developed for the analysis and comparison of how attributes other than the quantitative risk level are affected by changes in prescriptive solutions due to the introduction of analytic design. Such an analysis is important when safety strategies are developed for new kinds of buildings, where experience and established solutions are lacking. It would then be necessary to start from basic principles regarding what constitutes good fire protection. A survey of attributes that can be used to describe fire protection of construction works is presented and discussed in Section 5.4.2.

5.4.1 Quantitative analysis of the variation of risk within a class of buildings

In order to study how the risk level changes within a class of buildings when using the prescriptive design method, the risk analysis method presented in Section 4.3 was used in combination with sensitivity and uncertainty analysis to study the effect of variation in the input data. The analysis was performed as a case study of assembly halls where the risk resulting from the two different types of fires presented in Section 4.4.2 was studied. The basis for the conditions applied in the sensitivity and uncertainty analysis are presented together with the input data for the chosen class in Appendix C. In the uncertainty analysis, the propagation of uncertainty in the input data and its effect on the output represented by three risk measures is studied, as well as the variation in the risk level in this class of buildings when prescriptive design is used.

5.4.1.1 Risk measures investigated

Based on the conclusions from the sensitivity analysis, the variation in the following risk measures (R) as a result of different types of uncertainties was investigated:

R_{mean} = the mean risk (the expected number of people exposed to critical conditions).

P_{ind} = the individual risk (the probability of a randomly chosen person being exposed to critical conditions).

P_{worst} = the probability of being exposed to critical conditions for the most vulnerable individual.

These risk measures are described in detail in Section 4.3.3 and the end-point defining consequences is measured in terms of exposure to critical conditions, i.e. non-lethal conditions. The reasons for rejecting the other measures of risk are discussed in Section 6.4.4.

5.4.1.2 Method employed in the uncertainty analysis

The uncertainty analysis of the risk calculations was performed using the software Precision Tree (Palisade, 1997) and @Risk (Palisade, 1996) in which the risk measures of interest are described using analytical expressions, and thus software-based sub-models (e.g. the smoke transport model CFAST) can not be directly linked to the risk calculations. Therefore a response surface replacement of CFAST is used, i.e. an analytic model is derived to approximate CFAST for specific range of input data. The derivation of the analytical expressions for the time to critical conditions is given in Appendix E. The other equations used to calculate the probability and consequences of the scenarios have been presented previously in Section 4.3 and Section 4.4, respectively. The uncertainty in the input data is modelled by assigning distributions to the input data variables (presented in Appendix C), i.e. treating them as stochastic variables in the risk calculations. Two different types of uncertainty were analysed. One is the uncertainty in the risk calculations for a single building, i.e. the uncertainty in variables of group 1 (see Section 4.3.5). Since almost every input variable in the risk calculations is uncertain, the sensitivity analysis described in Appendix C was used to estimate which variables had the greatest effect on the results. The other type of uncertainty is the variation in risk in different buildings within the class. By varying the area (A) and ceiling height (h) (i.e. variables of group 2 see Section 4.3.5) different buildings within the class of assembly halls can be modelled. The variable area (A) in group 2 affects other input variables, according to the prescriptive design method, which must be taken into account. The design occupant load is a function of area, which determines the total required minimum exit width in the building. Therefore, these variables are calculated based on the area of the building and are assumed to be constant once the building is completed, i.e. they do not vary with the variables in group 1.

In the uncertainty analysis of the risk calculations the variables were varied simultaneously, among them the variables of area (A) and ceiling height (h) which define this class of buildings. These uncertainties are propagated through calculations of the various risk measures using the Monte Carlo sampling technique. This is a technique based on the random selection of values from the distributions describing the uncertain variables. The uncertainty analysis is performed as described below.

1. The input data variables are sampled resulting in a set of input data.

2. The fire protection is designed using the prescriptive design based on the set of input data.
3. The risk calculations are performed.
4. The results, in terms of risk measures, are saved together with the sampled input data.

The procedure is repeated a specific number of times. Since the input data vary the output data will also vary. Based on the output data, statistics and distributions can be estimated for the calculated uncertain risk measures, e.g. mean and standard deviation. A sufficient number of iterations of the procedure presented above have been made when the statistics do not change significantly from one iteration to the next. The change depends on the complexity of the risk calculations and the uncertainty in the input data. During the uncertainty analysis a convergence criterion was used to check that the change in the estimated mean, standard deviation and percentiles (0-100% in 5% steps) for the predicted output was less than 1.5% over the last 100 simulations. Ten thousand iterations were used in each uncertainty analysis, and the convergence criterion was fulfilled with good margin.

5.4.1.3 Analysis of the output data

The uncertainty analysis consists of several different analyses of the two types of fires (see Section 4.4.2), and the combined effects of aleatory and epistemic uncertainty for the base case and the effect of uncertainty due to variation within the class of assembly halls (see Section 4.3.5) are also investigated separately. The following analyses are presented in Sections 5.4.1.4 to 5.4.1.7:

- the uncertainty in the case of fires of type 1 in assembly halls as a class of buildings (the fire starts within the assembly hall),
- the uncertainty in the case of fires of type 2 in assembly halls as a class of buildings (the fire starts in an adjacent room),
- the uncertainty in the case of fires of type 2 in a specific building (i.e. the base case where only variables in group 1 are varied), and
- the uncertainty in the case of fires of type 2 in assembly halls as a class of buildings with respect to design decisions (i.e. only variables in group 2 are varied).

The results of the uncertainty analysis for each of the three risk measures calculated (which are described in Section 5.4.1.1) are presented in terms of three different parameters. The first parameter is the expected value of a risk measure, R, for the range of outcome generated in the analysis, which is denoted E(R). This value can be used to compare the magnitude of the risk obtained from the different analyses. Many of the combinations of the input variables sampled will lead to situations where no one is exposed to critical conditions, and thus the risk measure will be zero; for example, both the number of people and the fire growth rate are defined as uncertain variables in the consequence expressions in the event tree. If a small number of people and a slow fire growth rate are sampled from the distributions used to represent the uncertainty in these values (see Appendix C), the resulting risk measure is likely to be low or zero. A single risk measure that equals zero might seem counterintuitive if interpreted as the risk being zero, but using a single R_{mean} value to express the result of randomly drawn values of the input data (i.e. a single set of input data) does not provide a suitable representation of the total risk and its variation. A better representation of the risk and the uncertainty in the risk measure is given by studying the distribution (i.e. the histogram) of R_{mean} and calculating on or several central values for the distribution, e.g. E(R).

For practical reasons, cases in which the risk measures are zero are separated from those where the risk measure is greater than zero. This is because the cases that contribute to the total risk, which are the ones of interest, would be difficult to analyse in a histogram where a large number of iterations would be represented in the bin R = 0.

The second parameter that is used to represent the risk as a single value is the average value of the risk measure from the iteration when this value was greater than zero, $E(R)|_{R>0}$. The third parameter is the proportion of the total number of iterations when the risk measure is greater than zero, P(R>0). This is also a measure of how great the probability is that someone, i.e. at least one person, will be affected by critical conditions in the case of a fire. The values of the parameters for each risk measure are compiled in a table for each uncertainty analysis.

The variation in each risk measure is illustrated by a histogram, in cases of the ten thousand iterations where the calculated risk measures are greater than zero. The histogram can be seen as a representation of the probability function illustration the uncertainty in the risk measure. The uncertainty analysis allows conclusions to be drawn regarding:

- the size of the risk,
- the variation in the risk measure, and
- the variables that have the greatest influence on the uncertainty in the risk.

The bin sizes used for the histograms are presented in Table 8 and are different between the mean risk and the individual risk measures.

Table 8. The bin sizes for the histograms illustrating the variation of the risk measures

Risk measure (R)	Bin size
R_{mean}	5
P_{ind}	0.005
P_{worst}	0.005

The purpose of the histograms is to illustrate how the risk measures vary for the range of cases included in the uncertainty analysis, and not to study specific risk levels in detail. Therefore, the histograms are presented with low resolution.

5.4.1.4 Uncertainty in the case of fires of type 1 in assembly halls as a class of buildings

Table 9 shows the values of the parameters described in Section 5.4.1.3. Figures 31 to 33 show the histograms for the three measures of risk, for cases where the risk measures are greater than zero. As both the variables in group 1 (natural variation and knowledge uncertainty) and group 2 (variables affected by design decisions) are varied, this means that the variation in level of risk reflects the variation in the whole class of buildings represented by the input data. The results represent an estimate of the *safety output* resulting from the prescriptive design method for the class of assembly halls in the case of fires of type 1.

Table 9. Parameter values from the uncertainty analysis for selected risk measures.

Risk measure (R)*	E (R)	E (R) | $_{R>0}$	P(R>0)
R_{mean}	21	45	0.46
P_{ind}	0.024	0.052	0.46
P_{worst}	0.15	0.31	0.46

* The risk measures and parameters are described in Sections 5.4.1.1 and 5.4.1.3.

Figure 31 shows the uncertainty in the output, in terms of the risk measure R_{mean}, from the risk analysis performed on the event tree with fire type 1 (see Figure 24). The probability of the mean risk falls exponentially, which means that a high level of risk is not probable. This seems reasonable in view of the fire statistics available. On a national level, very few, or no people are injured due to fires in assembly halls.

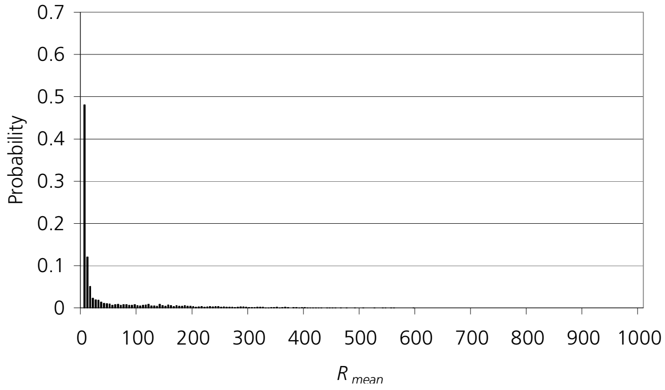


Figure 31. Histogram for $R_{mean} |_{R>0}$.

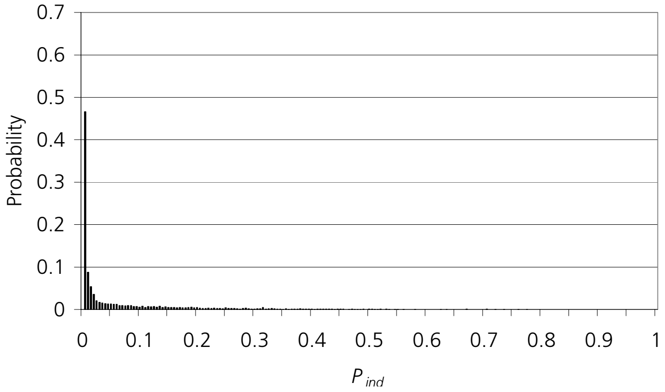


Figure 32. *Histogram for* $P_{ind}\,|_{R>0}$.

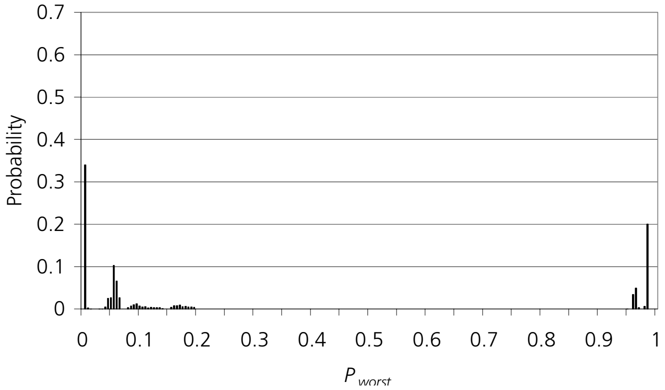


Figure 33. *Histogram for* $P_{worst}\,|_{R>0}$.

Uncertainty analysis does not provide information on whether the risk is large or small in relation to other risks in society, as the frequency of fire occurring in a certain building is not included in the analysis. However, a relative comparison is possible between different kinds of fires and the types of uncertainty.

The histogram for the individual risk (Figure 32) has the same appearance as the mean risk. It is worth noting that for the person at the worst location, the probability that he or she will be exposed to critical conditions is very high (Figure 33), as illustrated by the bars in the far right of the figure. This can indicate an unreasonably high risk exposure for an individual (P_{worst}), which is not seen in the risk measure individual risk (P_{ind}) as the level of risk is distributed evenly over all the people in the building. This thus means that the risk varies considerably depending on where a person is in the hall.

Through correlation analysis it can be seen that the variables fire growth rate (α), number of occupants (N), ceiling height (h) and area (A) have the greatest effect on the variation of all measures of risk in fires of type 1, see Appendix F. As can be expected, the fire growth rate, and the number of people in the building have considerable affects on the risk, and therefore uncertainty in these variables have large effect on the uncertainty in the output. More surprising is that the area has such a large effect on the risk, as the area is taken into account in the prescriptive design method when determining the width of the escape routes. It may thus be appropriate to study these variables in more detail in order to reduce the risk in buildings with a high risk, as a basis for modification of the prescriptive method. The complete correlation analysis between all input variables and the three measures of risk can be found in Appendix F.

5.4.1.5 Uncertainty in the case of fires of type 2 in assembly halls as a class of buildings

Table 10 gives the values of the parameters previously described in Section 5.4.1.3. Figures 34 to 36 show the histograms for the three measures of risk when these measures are greater than zero. As the variables in both groups 1 and 2 (see Section 4.3.5) are varied, this means that the variation in risk presented in the histogram reflects the variation of the risk measure for the whole class of buildings studied in the case of fires of type 2.

Table 10. Parameter values from the uncertainty analysis for selected risk measures.

Risk measure (R)*	**E (R)**	**E (R) $\|_{R>0}$**	**P(R>0)**
R_{mean}	80	150	0.53
P_{ind}	0.11	0.20	0.53
P_{worst}	0.34	0.60	0.53

* The risk measures and parameters are described in Sections 5.4.1.1 and 5.4.1.3.

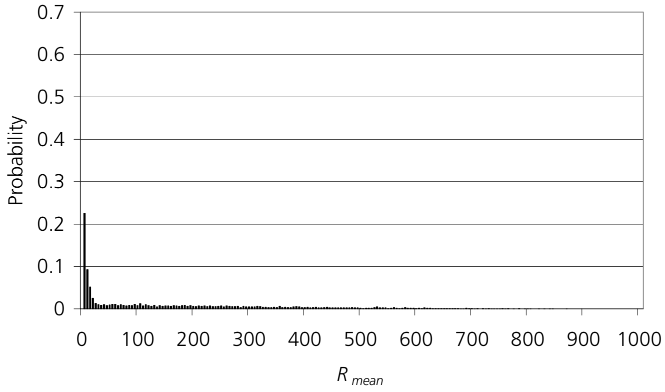


Figure 34. Histogram for $R_{mean}|_{R>0}$.

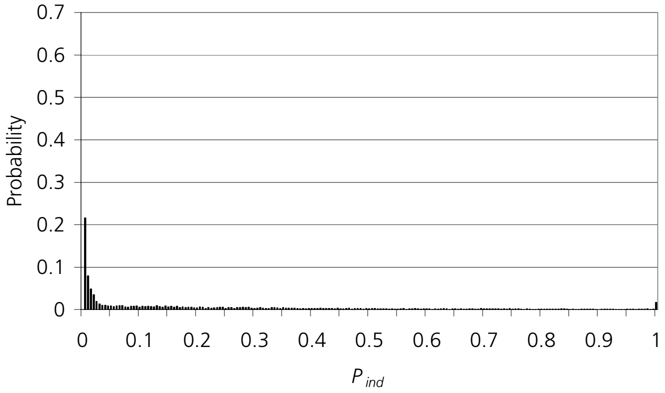


Figure 35. Histogram for $P_{ind}|_{R>0}$.

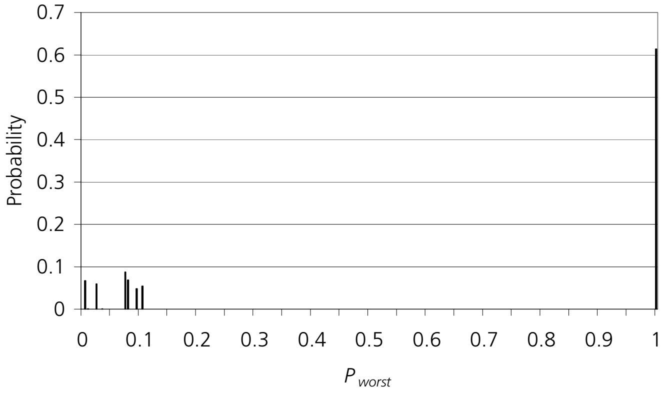


Figure 36. Histogram for $P_{worst}|_{R>0}$.

The histogram for the mean risk falls exponentially for this type of fire, see Figure 34, but the mean level of risk is higher and the spread greater compared to the results from fire type 1. There are a significantly greater number of cases with a risk higher than the mean value than in the fires of type 1. The expected value of the mean risk, $E(R_{mean})$, is almost a factor 4 higher than for fire type 1 (compare R_{mean} in Tables 9 and 10).

The equivalent increase in the level of individual risk can be observed in Figure 35, and there are even cases where P_{ind} is equal to 1, i.e. all the occupants will be exposed to critical conditions if this type of fire breaks out. The assembly hall will be filled with smoke quickly, and critical conditions will occur before people can start to evacuate the premises. It can be expected that people's behaviour will be affected by the rapid smoke filling and will not respond in the manner assumed in the modelling. It is not very likely that people will remain sitting unconcerned in a room that is rapidly filling with smoke. Despite the fact that the consequences are probably exaggerated in these cases, the results indicate a higher potential for catastrophe in fires of type 2 than in fires of type 1. The increase in risk is also seen for the worst located person, where the probability of being affected by critical conditions when a fire breaks out in the next room increases dramatically, as can be seen in Figure 36. This clearly demonstrates the need to study fires in adjacent rooms in order to evaluate the level of risk when verifying the fire safety design.

Through a correlation analysis, it was found that the variables having the greatest effect on the variation of all measures of risk in fire type 2 were ceiling height (h), number of occupants (N) and area (A), see Appendix F.

In order to study how the various kinds of uncertainty affect the variation in risk in the case of a fire in an adjacent room (fire of type 2), for the class of building under investigation, the variables in group 1 and group 2 were studied separately (see Section 4.3.5 for a description of the two groups). The extent of the variation in the level of risk for a particular assembly hall, see Section 5.4.1.6, can be compared with the variation in risk level within the class of assembly halls being studied, see Section 5.4.1.7.

5.4.1.6 Uncertainty in the case of fires of type 2 in a specific building (the base case)

In this section the variation in the risk measures due to uncertainty associated with variables in group 1 for a specific building is discussed (see also Appendix F). Since the variables in group 2 are constant the geometry of the assembly hall is constant, and the analysis shows the variation in risk in one and the same building. This building is called *the base case* and its geometry is described in Section 4.4.1.

Table 11 gives the parameter values previously described in Section 5.4.1.3. Figures 37 to 39 show the histograms for the three measures of risk for the iterations where the risk measures are greater than zero.

Table 11. Parameter values from the uncertainty analysis of various risk measures.

Risk measure (R)*	**E (R)**	**E (R) | $_{R>0}$**	**P(R>0)**
R_{mean}	44	89	0.49
P_{ind}	0.030	0.061	0.49
P_{worst}	0.32	0.66	0.49

* The risk measures and parameters are described in Sections 5.4.1.1 and 5.4.1.3.

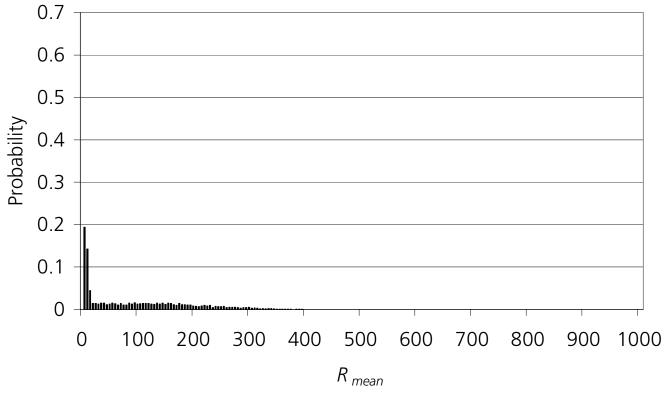


Figure 37. Histogram for $R_{mean} |_{R>0}$.

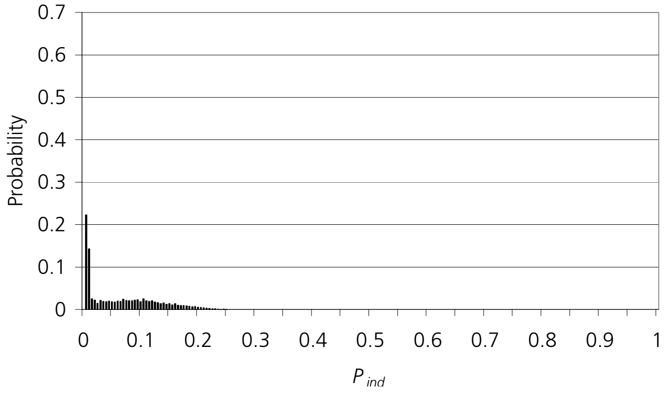


Figure 38. Histogram for $P_{ind} |_{R>0^*}$

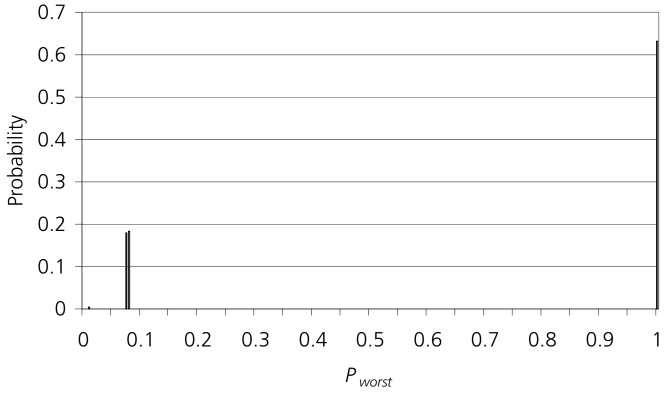


Figure 39. Histogram for $P_{worst} |_{R>0^*}$

The histograms for the mean risk and the individual risk are similar to previous results, see Figure 37. The probability of a high level of risk falls exponentially. The mean risk for the base case is lower than the mean risk for the whole class of buildings. Both the mean risk and the individual risk for the base case show considerably less spread than the variation in the level of risk for the whole class of buildings. There is no case where all the people in the assembly hall are affected by critical conditions for the base case, see Figure 38.

The individual risk to the worst located person is admittedly high in several cases, see Figure 39, and in the same order of magnitude as when the variables in group 2 are varied at the same time as those in group 1, see Section 5.4.1.5.

According to the correlation analysis (Appendix F) the variables with the greatest effect on the level of risk are the actual number of occupants in the building (N) and the portion of the occupants that chose to evacuate the same way they entered the building (F_{ME}).

5.4.1.7 Uncertainty in the case of fires of type 2 in assembly halls as a class of buildings with respect to design decisions

In this section the variation in measures of risk when only the variables in group 2 are varied, i.e. those affected by decisions made in design process, but do not change once the building has been built, will be studied. The variables in group 1, i.e. variables with aleatory and epistemic uncertainty, are kept constant at the values used in the base case, and thus the variation in risk due to differences between buildings within a class of buildings is studied. However, the design effect according to the prescriptive design method is taken into consideration, i.e. the design occupant load and exit width etc. is affected by the size of the building. The analysis shows how the level of risk varies in the class of buildings defined by the variation intervals for the area and height.

Table 12 gives the parameter values described in Section 5.4.1.3. Figure 40 to 42 show the histograms for the three risk measures for values greater than zero.

Table 12. Parameter values from the uncertainty analysis of various risk measures.

Risk measure (R)*	**E (R)**	**E (R) $\|_{R>0}$**	**P(R>0)**
R_{mean}	68	110	0.61
P_{ind}	0.11	0.18	0.61
P_{worst}	0.34	0.57	0.61

* The risk measures and parameters are described in Sections 5.4.1.1 and 5.4.1.3.

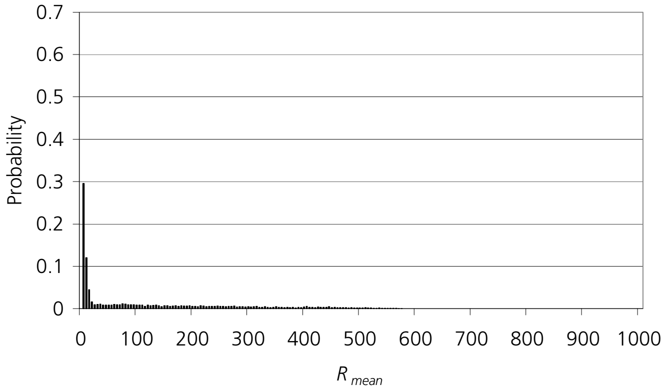


Figure 40. Histogram for $R_{mean}\,|_{R>0}$.

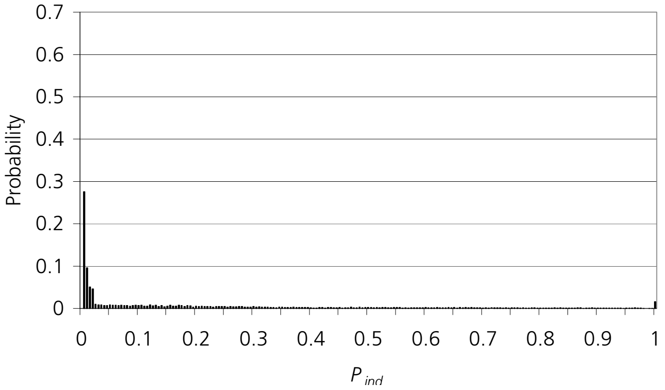


Figure 41. Histogram for $P_{ind}\,|_{R>0}$.

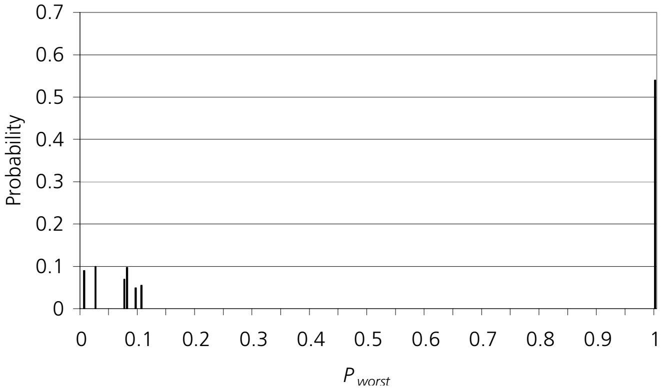


Figure 42. Histogram for $P_{worst}\,|_{R>0}$.

The expected value of the mean risk, $E(R_{mean})$, is of the same magnitude as when variables in both group 1 and group 2 are varied together. The appearances of the histograms in Figures 40 to 42 are also similar. The fact that the variation in the risk measure is high in this analysis means that the level of risk in different buildings in the class varies considerably. Some buildings will thus be associated with much greater risks than others, almost 100 times higher than the base case studied in Section 5.4.1.6.

A considerable proportion of the variation in risk level for the class of buildings originates from variables affected by decisions in the design process. Prescriptive design takes these decisions into account to a certain degree, e.g. in that the area determines the number of people allowed in the building, which in turn provides the basis for the design of the escape routes. This analysis confirms that despite the fact that such relations are taken into account in prescriptive design, there are still wide variations in the level of risk. The correlation analysis in Appendix F shows that all the variables in group 2 have significant effects on the level of risk.

5.4.1.8 Concluding remarks from the uncertainty analysis

The results of the uncertainty analysis are clear. The level of risk can vary considerably within a class of buildings, when using the prescriptive design method. The level of risk in one particular building may also vary much, which indicates that the dilemmas with uncertainty in calculations pointed out in Section 5.3.4 are relevant. Furthermore, it was found that the variation in the risk due to serious events (fire type 2) is large within the class studied, i.e. assembly halls. Several of the variables used to define a particular class of building, e.g. area and ceiling height, have a noticeable effect on risk when the fire protection is designed using the prescriptive method.

The results of the sensitivity and uncertainty analyses can be applied in different ways depending on how they are interpreted. It is not at all clear which interpretation is the "correct" one, and therefore their application according to both interpretations is discussed, as illustrated in Figure 43.

1. The average risk level for the class of buildings is acceptable, but not the large variation in risk. If the aim of the prescriptive design method is to obtain similar levels of safety within each class of buildings the risk levels for some of the cases in the analysis may be far too high. The consequences of this interpretation are discussed in Section 7.5, where various ways of changing prescriptive design in order to reduce the risk in the most vulnerable premises are studied.

2. The level of risk and its variation reflect society's objectives regarding fire safety in assembly halls and is equivalent to the performance requirement *satisfactory escape* in *BBR* 5:31. Equivalent levels of risk should be achieved when analytic design is applied. The consequences of this interpretation are discussed in Section 5.5.1.

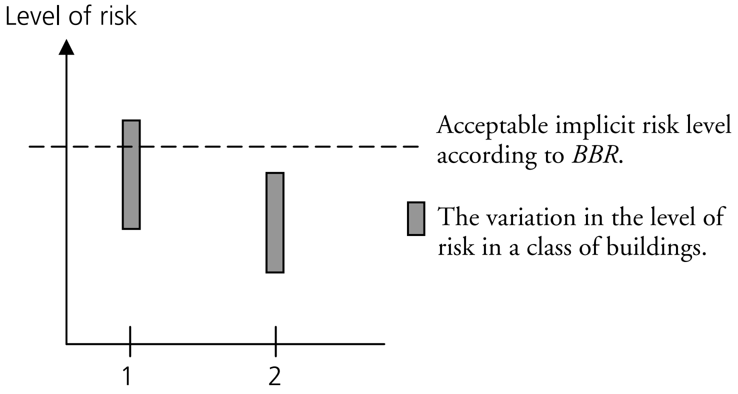


Figure 43. Two interpretations of the analysis results, i.e. the variation in the risk level in a certain class of buildings resulting from the prescriptive design method.

A possible third interpretation is that neither the risk level nor its variation are acceptable, but this is regarded as improbable. When *BBR* was introduced *Boverket* was not given any mandate to increase the level of fire safety required. The safety level resulting from prescriptive design is the same as that before *BBR* was introduced, i.e. in the period between 1988 and 1994. It is therefore reasonable to believe that this level is still acceptable for this class of buildings.

5.4.2 Multiple attributes defining fire safety

As pointed out in Section 5.3.6, other attributes must be considered in the verification, in addition to determining a quantitative level of risk suitable for verification. Fire safety is a multi-attribute characteristic. Obviously, when searching for a system of attributes suitable for ranking or grading fire safety, a number of such systems can be proposed. In this thesis the methodology chosen was based on a system analysis model proposed by Meister (1991). He suggests that a system as a whole can be described by a number of attributes characterizing the system and its performance. He used a very general definition of the term system, but this concept can be applied to the whole fire protection system of a building. A rough translation to the area of fire safety engineering leads to the following suggested attributes:

- function,
- human action/performance,
- complexity of the fire safety strategy,
- complexity of the fire protection system,
- flexibility,
- sensitivity,
- reliability, and
- vulnerability.

5.4.2.1 Function

When the safety strategy is changed, many factors must be considered to ensure that the protection system will work according to the demands. Example of relevant questions to analyse this are:

- Have new risk sources been introduced?
- Have the conditions that affect the need for protection changed?
- Have the safety objectives changed, e.g. are there more occupants in the building?
- If so, are additional protection systems, in terms of number of exits, needed to achieve the same level of safety as before?

5.4.2.2 Human action/performance

Human actions and organisational measures are often an important part of the fire safety strategy, for example, in complex environments like high-rise buildings, large shopping malls or subway stations where phased evacuation (evacuation of different groups of people in a particular sequence) or routing is necessary. At the same time, there are many catastrophic fires clearly related to erroneous human actions or lack of action. Traditionally, technical and organisational safety measures have been dealt with separately. Today, the effectiveness of a protection system is often dependent on both technical systems and human action in an integrated way. At the same time it is important to design both the building and the safety system so they are not unnecessarily sensitive to human errors and mistakes, since these are impossible to eliminate (Reason, 1990, 1997). Responsibilities, routines and training are other aspects that must not be forgotten, and are important in ensuring that the protection system works as planned. Adopting a fire safety management system that deals with organisational and administrative aspects of the fire protection in a building is one way to address this attribute, as will be addressed later in Chapter 8.

5.4.2.3 Complexity of the fire safety strategy

A number of small changes in a fire safety strategy often have a marginal impact on the safety, as long as the changes are independent. If a trade-off is characterized by the reduction or elimination of several independent safety measures and replaced by a single measure, or a measure that is linked to several other sub-systems, a single failure can occur which will render the entire fire protection system useless. This failure can be seen as a common-cause failure. Such a failure threatens the function of several other sub-systems. As the fire safety strategy becomes more complex when the fire protection system is integrated with other building functions, safety measures generally have multiple purposes and are dependent on the functioning of other measures. The consequence of errors in the design will be more serious and, therefore, the need for verification will increase with increased complexity.

5.4.2.4 Complexity of the fire protection system

A complex fire protection system increases the probability of error since there are more sources of error and more possible combinations of errors. A safety measure may be dependent on several sub-systems functioning correctly, e.g. smoke control in atria. Detectors, control systems, opening devices for ventilators and inlet air, are all sub-systems that have to work in order for a fire protection system to operate properly. Complex systems may also require additional coordination to achieve their purpose, e.g. ventilation to assist escaping people, or sprinklers in combination with smoke control systems. Additional requirements of inspection and control might be appropriate for a complex fire protection system. Due to complexity and the importance of the system for the overall safety strategy, tests or experiments designed for the individual project might be an option in the verification process. The hot smoke test (Australian Standards, 1999) is one example of such a test used in practice.

5.4.2.5 Flexibility

The attribute of flexibility indicates whether a safety measure is directed towards a single hazard, or covers the whole or a large part of the building, such as sprinklers. A flexible system covers a range of scenarios and has the potential to deal with new, or unforeseen scenarios. The fire and rescue service can also be seen as a flexible safety measure, since it is mobile and can act on the basis of the events occurring at the fire scene. As a flexible system has the ability to deal with unforeseen events the performance of the protection system will be more robust. The fire protection demands of society normally include some degree of flexibility. Fire spread between buildings, for example, is prevented with both passive measures, such as separation distances, and by the fire and rescue service. Arson is another threat that is linked to this attribute. A large proportion of fires in public buildings are caused by arsonists, but there are no specific design requirements intended to deal with this threat. It is unclear whether or not it is acceptable to decrease the flexibility of the fire protection system such that the risk due to arson is drastically increased.

5.4.2.6 Sensitivity

Suitable questions to ask oneself in the design process can for example be: To what extent is the solution sensitive to the assumptions made in the design process? Will different use of the premises result in an unacceptable level of safety? How dependent is occupant safety on the interior layout, which might be rearranged without consulting a fire safety designer? For example, sports arenas are rarely used only for sporting activities. Exhibitions and concerts are likely to take place, and the premises may be used to provide sleeping accommodation for competing teams. Can temporary protection be arranged for such occasions or is a permanent installation necessary? The issue of responsibility is also of great concern. Is it the tenant's or the owner's responsibility to guarantee fire safety for special occasions? How will information concerning these arrangements be communicated to the various stakeholders? By considering sensitivity, the designer is able to ensure that important safety aspects will be safeguarded, by taking into account potential events that may make design assumptions invalid. Assumptions found to be crucial for safety must be analysed in detail. This type of sensitivity analysis should not be confused with a sensitivity analysis of the calculations, which provides the basis for a more detailed uncertainty analysis.

5.4.2.7 Reliability

Reliability can be defined as the probability that the system will fulfil its purpose. If a fault occurs in the system, or if the system is exposed to higher stress than it is designed for, failure can be expected. It is necessary to investigate the effects of any kind of failure. If the impact is predicted to be high, measures to ascertain whether the system is working or not might be needed, and increased service and maintenance necessary. Questions that can be used to elucidate how this attribute is affected are:

- Which conditions must be met to ensure that the protection systems will work during the lifetime of the building?
- What is the lifetime of the fire protection system?
- How will the function of the protection system be affected by time?
- To what extent are service and maintenance necessary?
- Does the reliability differ between the measures exchanged in a trade-off?

The consequence of failure must be considered when the safety is evaluated otherwise the scope of the risk analysis will be insufficient. This can be done with a quantitative risk analysis, event-tree analysis, for example. Reliability can often be easily increased, e.g. by activating an evacuation alarm with both smoke detectors and by manual intervention. In the Life Safety Code (NFPA, 2000a) this problem is recognized and explicit demands for multiple safeguards are made.

5.4.2.8 Vulnerability

This attribute describes the conditions for the survival of the safety system itself when exposed to internal and external stress, i.e. the stress in terms of threat to the conditions necessary for the system to operate (Einarsson & Rausand, 1998). Questions to illuminate this aspect are for example:

- What will happen if the power is cut off as a result of the fire, or if the fire and rescue services or police cut off the power during an emergency operation?
- How will the fire protection system respond if a fire occurs at the same time as a software failure, or if the communication equipment (PA-system) malfunctions?
- How will the system operate if a water pipe is broken, or if it is windy or cold?
- Sprinklers outside a building can freeze and wind can cause pressure conditions that prevent a smoke control system from operating.
- What can threaten a protection system or the design solution itself?
- Is the system vulnerable, and what measures should be taken to reduce its vulnerability?

It is not possible to eliminate all threats to the system and there are no foolproof systems. Nevertheless, it is possible to reduce the vulnerability of the fire protection system in the design process. For example, the inlet and outlet openings of a smoke control system should not be located on the same side of the building. When analysing vulnerability, experience from previous fires is very important. Through experience it is possible to learn which measures look good in theory, but do not work in practice. All fire protection systems must be evaluated and judged not only on their expected performance but also on the basis of history. An increase in interdependency can lead to an increase in the vulnerability. Interdependency can be the result from integrating different systems in the building, e.g. fire detection system, public announcement system, telecom system, local area network, heating system, ventilation system etc., both in terms of the physical systems but mainly in terms of control and communication system. This concept is labelled *intelligent buildings* and is increasingly applied in large and complex buildings (Bushby, 2001).

5.5 Solutions and need for development

The inventory of problems in Section 5.3 and the detailed analysis in Section 5.4 show that the need for development at this level of risk control is considerable, and that today there is no patent solution regarding the control of fire safety in buildings based only on *BBR* performance requirements. An unambiguous definition of risk is lacking in the building regulations, and it is therefore not possible to formulate a level that constitutes an acceptable risk against which the system or solution can be verified. In absence of such a level, comparison with the risk level resulting from prescriptive design appears to be suitable (see Section 5.5.1), although this method is not always applicable. One of the problems associated with such a comparison is that the calculations have considerable uncertainties. This must be handled in an appropriate way in order for the verification procedure to be reliable. A short description of various methods used in other areas is presented in Section 5.5.2. One of these methods consists of standardized risk-based methods of verification. The development of such methods requires a considerable amount of work. Such methods will not be available in the near future for practical use, but an initiative for such a method is presented in Section 5.5.3.

A further area in which development is necessary in order to be able to review the fire protection system of a building is risk evaluation (see Section 5.5.4). Furthermore, the attributes of risk that affect assessment, apart from the quantitative risk level, must be surveyed and included in the assessment. As part of the development in this field, a simple tool for this is presented in Section 5.5.5.

5.5.1 Verification through risk comparison with a prescriptive design solution

BBR places demands on the use of risk analysis as well as general demands on analytic design such that a building must be as safe as if the prescriptive method had been used. However, it has been established that design criteria or risk levels are lacking in *BBR*, while there are several different methods of establishing an acceptable risk level. Few specific suggestions for levels of risk have been made for design of evacuation safety. One practical suggestion has been presented by Rasbash (1984/85) in which an *f(N)* curve similar to the Dutch model (VROM, 1988) was proposed, but where the acceptable levels were associated with fire statistics from the UK. Several of the problems discussed in Section 5.3 and Section 3.4.2 mean that such a criterion provides limited control of the actual fire safety related to the construction works, and the actual level of risk that the criterion attempts to define can also be questioned. Since the level of safety afforded by the prescriptive solution is de facto the *acceptable safety level*, it would appear to be a natural starting point and provide a way of circumventing some of the major problems presented. Therefore, a comparison of the safety, or some aspects of the safety, in a building can be made on the basis of specific hazards or identified scenarios.

The suggested approach immediately raises the question of how the results from a risk analysis using prescriptive design can be used in analytic design. This depends largely on whether the variation in risk level allows *acceptable evacuation* to be achieved or not, i.e. whether the interval in which the risk level varies is acceptable or not (see Section 5.4.1.8). In the detailed study of fire type 2, it was found that most of the variation and the greatest contribution to risk for the class of buildings studied arose from variables affected by the design of the building (group 2). The variation in risk level in one particular building due to natural variation is small in comparison to the variation in risk between different buildings.

Given that the calculated risk level is in agreement with that acceptable to society, this can be used as the basis for verification using analytic design. Lack of knowledge regarding some input data and uncertainties lead to limitations in the applicability, e.g. regarding the possibility of including the effect of the probability of a fire occurring. As an engineering tool the method must thus be used with caution. At the present time the method suggested is best suited to relative comparisons (trial evaluation) between different solutions, where the design according to the prescriptive method is one such solution.

The variation in risk level within the class of buildings studied makes it necessary to place demands on the choice of reference building in the verification process. It is important to consider this choice carefully, so that a reduction in the risk level for a class of buildings will not go unnoticed when analytic design is applied. It is suggested that an appropriate choice of reference building is one whose level of risk is equivalent to the mean value for a particular class of buildings, in order to avoid the risk of choosing the worst case (see Section 5.3.2). However, this will most certainly not be the preferred choice of developers since it would lead to higher costs for fire protection than when choosing the highest risk level that can be derived with prescriptive design. If cost-cutting of fire protection governs the way in which the acceptance criterion is derived, the result will be a higher average risk level for the class of buildings if comparison is made with the prescriptive design method. This is likely to cause an increase in the number of lives lost in building fires and must therefore be addressed by *Boverket*. Clear advice should be given to the designer regarding what is a suitable level (i.e. how to chose reference building) in order to avoid large variations or the abuse of the flexible design of buildings offered by performance-based provisions.

All the variables that affect safety cannot be included in a simple design method. However, it is not clear how variables not included in the design, but which have a significant effect on safety, should be dealt with in analytic design. The ceiling height is an example of such a variable. If the total width of door openings in an exit is increased, then, according to prescriptive design, more people can be admitted to the premises. Can one reason in the same way regarding ceiling height? Through the use of analytic design, it should be possible to show that the level of safety would remain the same as with the prescriptive method when raising the ceiling, and thus more people could be admitted without making the escape routes wider.

Perhaps someone may reduce the total exit width in exchange for raising the ceiling. If a level of risk is determined as the design criterion, the result will be that the height of the building will have a considerable effect on the need for other protection systems, or the maximum walking distance allowed to an escape route. This will be possible as it can be shown using analytic design that the safety in the building will be adequate.

5.5.2 Strategies for dealing with uncertainty in risk analysis

When a risk analysis is performed, a number of uncertainties of various kinds are unavoidably introduced. If nothing is done about them, the subjective features of the calculations will cause such a large variation in the results that the whole process will become meaningless. Examples of this can be found in several benchmarking exercises where the results of the analysis of risks in the process industry were compared (Amendola et al., 1992; Christou, 2000). Teams from different countries took part in both these exercises, and the analysis was based on well-defined assumptions and boundary conditions. The variations in the results were considerable. Similar observations have been made in fire safety engineering. At a conference organized by the international organisation Society of Fire Protection Engineers, five design teams from different countries designed fire protection for the same buildings using analytical methods (SFPE, 2004). A coarse comparison showed that the design fires used in the verification procedure varied by several orders of magnitude, which had significant effects on the fire protection in the building. Another example of a benchmarking exercise showing large uncertainties in fire safety modelling has been presented by Hostikka et al. (1998).

The possibility of reviewing the safety of various activities through legislation is largely determined by the demands placed on the treatment of uncertainties. If excessively high demands are set the extent of the analysis will be unreasonable and too expensive, but if uncertainties are not dealt with it will be impossible to have control over the safety of the building or activity. The level of control must thus be a compromise, and the situation is made more difficult by the fact that the need to deal with uncertainties varies from one situation to the next.

There is a great deal of experience in quantitative risk analysis aimed at trying to control safety in the process industry. The approaches used by authorities in different countries to ensure that regulations are followed vary considerably. The UK and the Netherlands are examples of countries where two completely different methods are used.

The system employed in the UK is relatively resource demanding. When constructing a new plant involving chemicals that can cause serious accidents, the company must submit a safety report to the authorities according to the Seveso II Directive (EU, 1996). Based on this report, the national authority Health and Safety Executive carries out a relatively detailed analysis and then makes recommendations to the local authorities who decide whether a licence is to be granted or not. Although this process is demanding in terms of human resources, it means that the authority has the opportunity to make a detailed investigation of whether the performance requirements on *safety output* are met. A more detailed description of this strategy can be found in HSE (1989).

In the Netherlands, on the other hand, a standardized risk analysis method has been implemented and the authorities stipulate the acceptance criteria, scenarios, models and input data to be used. The reason for doing this is to ensure that the results of the analysis are reproducible, repeatable and comparable. Any deviation from the method must be approved by the authority. This method will lead to a certain degree of uncertainty in the results, but this is unavoidable as the method has been standardized and is applied to a number of different cases. The uncertainty must therefore be considered acceptable, and can be regarded as being the responsibility of the authorities as they have developed the method and demand it be used. A more detailed description of the standard method used in the Netherlands is given by Laheij et al. (2000) and Uijt de Haag et al. (1999).

In other countries, for example the USA, greater responsibility is placed on the designer to choose suitable methods. The strategy employed by the US Environmental Protection Agency involves minor control of the treatment of uncertainties by placing greater responsibility on the designer, but the authorities publish a large number of guidelines and recommendations where scientific demands are placed on the analyses. The arguments in favour of this are that it should be possible to use the most recent knowledge in the area. Although the authority does not regularly carry out its own analysis or regulate the methods of analysis used, their intentions are made clear which reduces uncertainty among practitioners, while allowing other methods to be used as long as their suitability can be demonstrated.

None of the above mentioned methods is today actively promoted in the performance-based building regulations or applied in fire safety engineering which is quite surprising. In order to control fire safety on a national level it is necessary to be able to deal with the uncertainties that arise in verification calculations. Clearer guidelines offer one solution, and this is discussed further in Chapter 6. Once knowledge has been gained on the acceptable variation in the level of safety, analytic verification methods can be developed and standardized. The conditions necessary to develop such a method are discussed in Section 5.5.3. A serious challenge facing the authorities is gaining the general acceptance of the verification methods, which in turn requires that they be developed by standardization committees that are accepted by the public. One requirement for such a process is that a broad spectrum of factors be considered, and that several kinds of stakeholders are involved in the decision making.

5.5.3 Outline of a standardized scenario definition procedure

It is clear from the uncertainty analysis that calculations which are limited to quantifying the consequences of a fire starting in the assembly hall give a poor prediction of the total risk. It will not be possible to assess how modification of the fire protection will be affected by trade-offs with such a limited analysis, as the change or changes made may affect the contribution to the risk from scenarios other than that being assessed. It is difficult to determine just what is a sufficient analysis to ensure that the level of risk has not increased as the result of a change in the prescriptive design solution. One method is to start with the description of the total fire risk, as depicted in Figure 17, and systematically identify which uncertainties must be considered.

To specify a single risk measure, in which the risk contributions from both types of fires are included as the acceptance criterion, demands that the probability of each type of fire be determined. It is necessary that all of the following components be standardized in order to achieve verification of a specified level of risk (target risk): the scenarios, the design equations, the input data and the acceptance criterion. A simplified event tree model which can form the basis for doing this is illustrated in Figure 44.

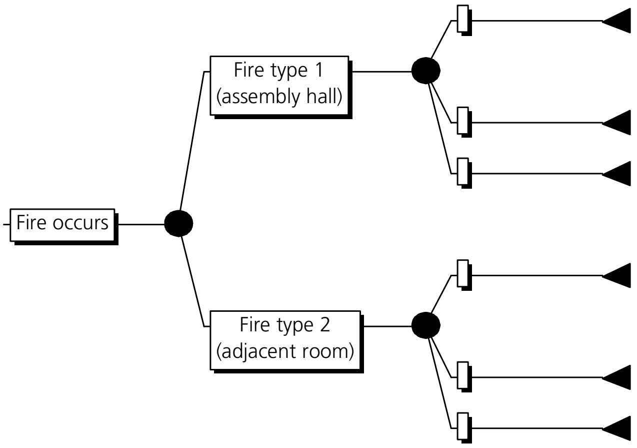


Figure 44. A total fire risk including the probabilities of two different types of fires.

By using this model, the differences between alternatives where the frequency of fires is affected can be analysed. The number and kind of adjacent rooms are examples of factors that could affect the total risk. The area and the activities carried out are others. From a design perspective, there may be a need to further refine the model as all fires that can occur must be represented, if the risk is to be represented correctly. If there are many fires not developing as rapidly as the type of fire chosen as representative and which have smaller *consequences*, the model will be too conservative. In such case sub-division into several types of fires may be suitable.

The model shown in Figure 45 is one means of creating a standardized, risk-based verification model. This means that certain types of fire to be investigated are specified and cannot be discarded by the designer. The probabilities of each type of fire will be affected depending on the kind of fire protection system installed. These could be given as design values in design handbooks or in other guidelines. If there are no adjacent rooms then x = 100%.

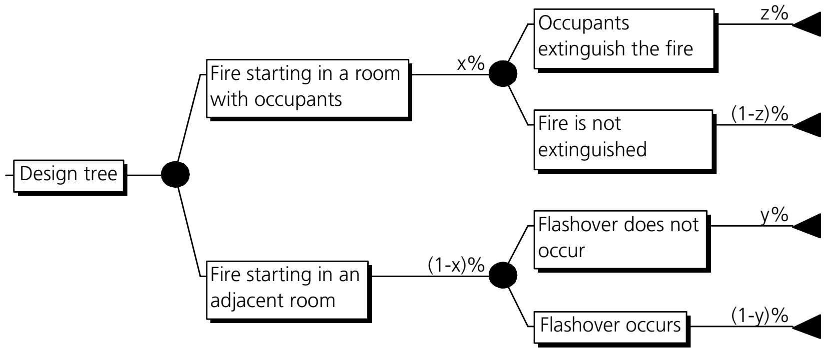


Figure 45. Simplified model for the design of safe evacuation.

Factors such as performance, reliability and level of maintenance of the protection system together with training of personnel and installation of fire extinguishers give different values of x, y and z. Design criteria can be formulated either for the event tree as a whole (e.g. the mean risk), or for each type of fire. Further data are thus required, as well as a systematic way of collecting them.

The uncertainties in the consequence analysis for each scenario must be dealt with appropriately. If the same design values are used for a whole class of buildings, the level of safety will vary considerably, in a similar way to how the risk level varies when the prescriptive design method is applied. One way to reduce the spread in the risk level is to link either the acceptance criteria or the design values for variables with natural variation and knowledge uncertainty (group 1) to variables whose uncertainty arises from the decisions made during the design of the building (group 2). Different design fire growth rates or numbers of people allowed in the hall can be used for different buildings in the same class, depending on the height, area or even volume of the building in question. These values constitute the input data for a verification model that can be applied to the building class using an event tree, as illustrated in Figure 45.

5.5.4 Development of a risk assessment method

Regardless of whether verification takes place using standardized verification methods or by risk analysis, it is necessary that the risk be assessed in a uniform way. In order to assess risk quantitatively in a way that the risk can be controlled, a risk measure must be calculated based on the risk contributions from all relevant fire scenarios (e.g. the mean risk). Since there is no explicit level of risk or design criteria with which to compare this risk measure, alternative approaches to evaluation have to be found.

At the moment, the most promising risk assessment method seems to be to compare the mean risk of different trial designs and then ranking them quantitatively. The greatest objection to using the mean risk to rank the level of risk is that it assumes that the decision maker is risk neutral. The fact that uncertainty is present affects the way in which decision makers assess the consequences of different scenarios. In many situations, for example, a serious accident is deemed much worse than several small ones, even if the total number of people killed or injured is the same. In such cases, the attitude to risk is aversion.

One way of taking this into consideration in risk assessment is to assign a higher penalty (weight) to serious scenarios, i.e. the contribution to the risk does not increase linearly with the consequences, but more rapidly. The question is how high a penalty should be assigned to a certain scenario, in other words which attitude to risk is representative.

The lack of a credible method has led to difficulties in evaluating technical trade-offs leading to scenarios where the worst consequences are more severe than the for the reference cases. In some cases such a solution will not be accepted no matter what the probability of the scenario with the worst consequences. This may be counterproductive if the solution would have lowered the consequences of other scenarios, such that the total risk was reduced.

There are several examples of formal and scientifically established methods of measuring the attitude of people to risk, see for example Farquhar (1984). One method is to measure the attitude of a number of representatives of various groups, for example the fire and rescue services, the local building committee, consultants and central authorities. The attitude to risk of people who work or spend their leisure time in various kinds of buildings should also be investigated. People's attitude to risk can be determined in connection with the evaluation of technical trade-offs made to fire protection systems. Such changes can be compared with a choice between two risks. These kinds of measurements are based on proven methods, but require some adaptation as they have not previously been applied in this area.

Another alternative is to determine the attitude to risk inherent in prescriptive design, based on a number of typical technical trade-off by studying a number of different scenarios. This could be achieved by investigating the corresponding attitude to risk associated with the technical trade-offs that are acceptable within the prescriptive design method. This attitude to risk should form the basis in analytic design to ensure that the two design methods lead to the same level of risk.

By studying the attitude to risk, so-called utility functions can be created which can be used to weigh the contribution from different scenarios to give a single measure of the total risk. This can be compared with the mean risk, but includes the perception of risk and how it is affected by the magnitude of the consequences. To date, little work has been done in this area so the need for research is great.

5.5.5 Comparing attributes of a protection system

Although it is possible to demonstrate, using risk assessment, that the level of safety is the same as, or better than, that obtained with another solution, there may still be a need to assess other attributes of the protection system. Examples of such attributes were presented in Section 5.4.2. It is difficult to give general guidance on how to deal with the attributes discussed earlier in practical design situations. There may be an overlap between the attributes depending on how they are defined. For some attributes there are well-established quantitative analysis methods on a detailed level, e.g. reliability and sensitivity analysis, while for others qualitative methods seem more suitable. For many attributes there are no explicit acceptance criteria in the building regulations or in other literature. However, it is obvious that when significant trade-offs are made from prescriptive solutions these attributes can not be neglected.

As a starting point a tool is presented as an attempt to assist the designer in making a systematic qualitative analysis of how the attributes of the system are affected, see Table 13. This tool forces the designer to examine each trade-off and consider how the overall safety of the building is affected, by analysing the attributes presented in Section 5.4.2. If an attribute changes such that the safety is affected in a negative way this must be investigated further. If an attribute of the overall protection system is affected this is indicated by an asterisk (*). If the attribute is not affected the box is left empty. When an attribute is affected the designer considers the impact on the safety and enters a minus sign (–) if further analysis is necessary or a zero (0) if no additional analysis is necessary. An example of the application of the tool to a simple case is presented by Lundin (2005).

Table 13. A tool used to evaluate the effect of trade-offs on the attributes of the protection system.

Attributes of the overall fire protection system * Attribute status is affected – Safety negatively affected 0 Safety not significantly affected	**Trade-off**					
	Is the overall protection system's attribute affected by the trade-off?			What is the impact on the fire safety?		
Index no.	1	2	…	1	2	…
Function						
Human action/performance						
Complexity of the fire safety strategy						
Fire protection system complexity						
Flexibility						
Sensitivity						
Reliability						
Vulnerability						

As noted there are several problems associated with controlling safety in case of fire for construction works by regulating the *safety output*. In the next chapter (Chapter 6) the level *safety procedures & safety case* in the framework for risk control will be analysed in a similar way. Subsequent to this chapter the final level of intervention will be studied, i.e. *direct risk control* (see Chapter 7).

6 Risk control by specifying rules for safety procedures & safety case

The building regulations are limited to placing demands on the construction work (building), and not on the activities performed therein or those performing the activities. One consequence is a limitation on what can be regulated on the *safety procedures & safety case* level in the framework for risk control, see Figure 46. In *BBR* no demands can be placed on the safety management system of the user (tenant and owner) of the building, how it should be designed or the way in which it can control the safety. However, demands can instead be placed on the *procedures for planning and designing* the building and *documentation* of this work and the results.

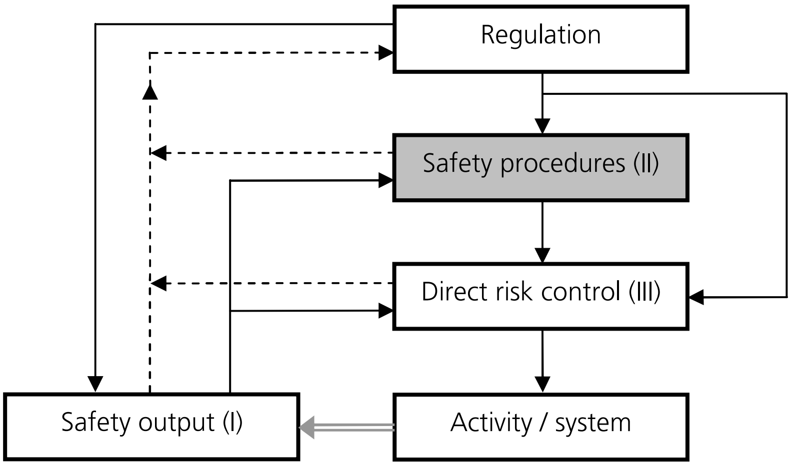


Figure 46. "Safety procedures & safety case" defines a level of risk intervention by which regulations can control safety in case of fire in construction works by placing demands on how technical solutions are derived in the design process.

The level of risk control labelled *safety procedures & safety case* controls the building fire risk by procedures for quality control in the design phase and by procedures for controlling compliance with these demands. The regulations may govern documentation of the suggested solution, and also design calculations and methodology, assumptions regarding input data and methods of calculation, what should be reviewed, how and by whom. Rules on this level focus on administrative rules and routines. The demands are directed towards procedural provisions that lead to a safe building in the case of fire, instead of *direct risk control* (technical solutions) or the level of *safety output* (objectives of the design). By placing demands on procedures and their content, a certain level of control of the final product or activity can be achieved, but there is still a large degree of freedom for the designers to make their own decisions.

The structure of Chapter 6 follows that of Chapter 5 and is outlined in Section 4.1. The method employed is also described in Section 4.1 and takes the form of a short description of how the rules for *safety procedures & safety case* are affected by changing regulations and how compliance with the rules is assessed (Sections 6.1 and 6.2). Following this, problems and dilemmas are identified in Section 6.3 by going through fire protection documentation from forty-six cases. Some of these problems are analysed in more detail in Section 6.4. Finally, some specific suggestions for means of facilitating the control of the safety in case of fire using this level of risk control are given in Section 6.5. To clarify the structure of this chapter the links between the different sections are illustrated in Figure 47.

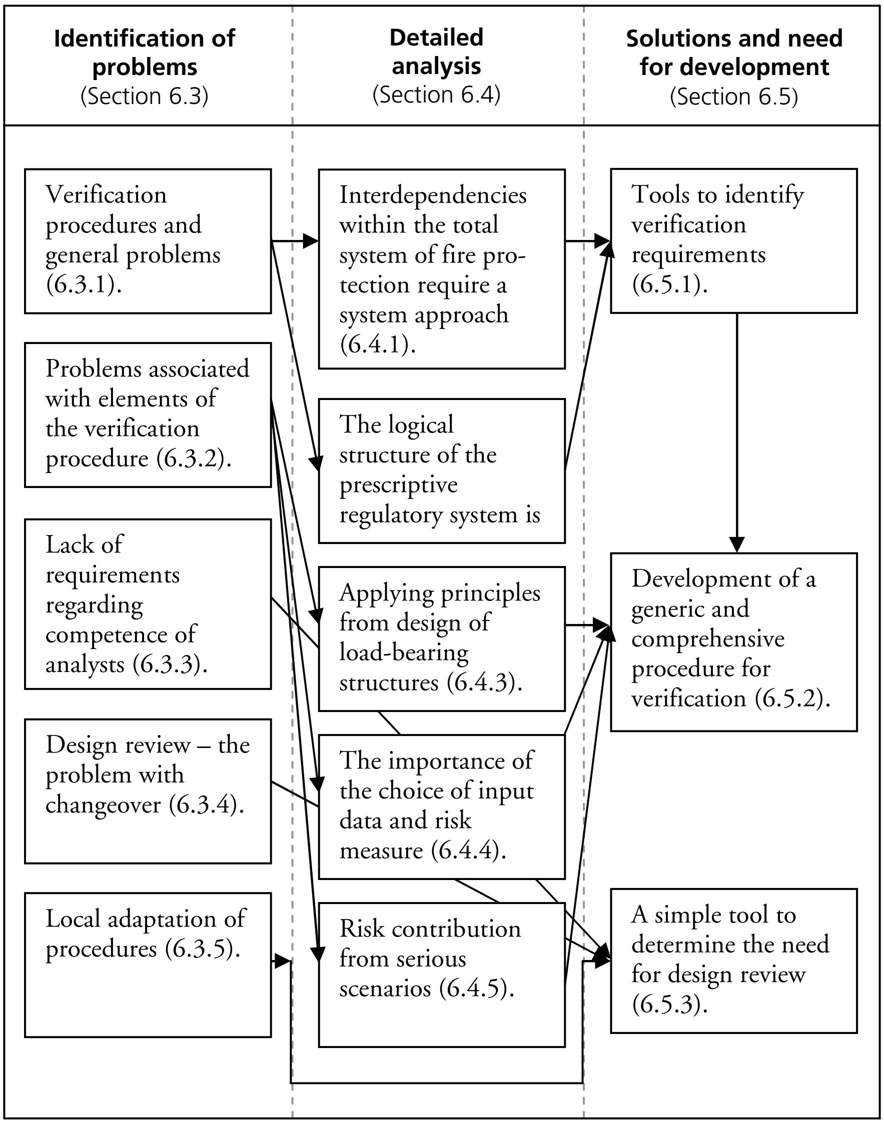


Figure 47. The structure of Sections 6.3 to 6.5 (see Section 4.1).

6.1 Changes in rules for safety procedures & safety case (see Table 4)

BBR (2002) contains a number of regulations aimed at this level of risk control, which place higher demands on the actual design process than the previous regulations *NR* (1988). The tasks and responsibility of various actors are made clearer, and demands are placed on documentation (e.g. fire protection documentation including control and maintenance schedule should be drawn up) which can be seen as a simplistic type of *safety case*. In many industrial sectors (e.g. railways and the off-shore and chemical industries) the purpose of a safety case is to demonstrate that an activity or operation, to be or being undertaken, will, so far as is reasonably practicable, be safe and without risks. A safety case constitutes extensive documentation of an installation's: safety policy and objectives, risk assessment, safety management systems and risk control measures (HSE, 2003). In the area of fire safety design this is a much more demarcated and limited process.

However, it is explicitly required in *BBR* that verification is performed when analytic design is used (see Section 2.3.4), which is the most important demand for society to be able to control safety. Verification can be seen as a safety procedure and defined as "confirmation that a proposed design meets the established fire safety goals" (NFPA, 2000b), i.e. the exercise in which the designer explicitly demonstrates that the required level of fire safety is satisfied in the design solution.

Building regulations clearly state that when analytic design is used, verification of fire safety and the evacuation safety is necessary when fire may cause great risk of human injury. This verification must be based on analysis, either supported by calculations, testing or special tests (i.e. experiments) designed for the individual project, or combinations of these (*BBR* 5:13). However, several of the decisions in this process which may have considerable effects on the results, e.g. the scope of the analysis, the choice of risk analysis method or method of modelling the consequences, the input data, acceptance criteria or handling of uncertainties, are not regulated. These are decisive for the quality of the verification.

At present, *Boverket* gives no, or little, information on how these choices should be made. In *BBR* 5:13 it is stipulated that the calculation model selected must be stated and in the general recommendations associated with this mandatory provision the designer is encouraged to illustrate uncertainties by means of sensitivity analysis. However, it is not clear *where* the results of the calculations, i.e. the actual verification, and description of the uncertainties should be documented. The requirements on documentation concern the technical solution. In *BBR* 5:12 it is stated that, "the conditions on which the fire protection is to be based" and "the design of fire protection" are to be documented in the fire protection documentation. This leads to several unanswered questions regarding key elements in the verification procedure.

- How should the fire safety be measured?
- What is defined as sufficient safety?
- How should it be demonstrated that sufficient safety has been ensured?
- How should the process be documented?

An alternative for *Boverket* to specifying the above points in detail in the form of general recommendations or in technical reports, is to refer to suitable standards or handbooks. At present, no such references are given in *BBR* for analytic design. The result is a lack of clarity which creates room for arbitrariness and disagreement among those involved in the design process, which can obviously lead to poorer control of the fire protection of constructions works.

In previous building regulations (*NR*, 1988), there were some rules on this level of control to tighten the construction process, but these regulations were mainly directed towards direct risk control as analytical tools were not available.

6.2 Changes in procedures for assessing compliance with the regulations (see Table 4)

The designer's verification can be seen as confirmation that the building meets society's demands regarding safety in case of fire. However, there is still a need for both internal and external review of this work to ensure high quality. Many things may be inadequate in building design jeopardizing the fire safety, and the review of the design is therefore an essential part of the quality control. Verifying that the regulations are met is an area in which considerable changes have taken place due to changes in legislation. In contrast to many other countries, in Sweden the local building committee no longer performs an independent review of the design solutions on a detailed level, i.e. the *direct risk control*. Instead they are supposed to determine what has to be controlled and the appropriate level of review for the specific project. They can choose between relying on the developer's internal control, requiring that the developer hires a third-party reviewer (independent peer reviewer) or in special cases perform the review themselves. The focus on the review activities by the building committee is on administrative procedures rather than the verification that the design meets the requirements. On a local level it has been difficult for many building committees to adapt to this new role. Their expertise has traditionally been on a detailed technical level, but their responsibility has shifted towards process-oriented quality control tasks. This change has had negative impact on the quality control of design solutions. There is no explicit guidance in the regulations as to what the building committee should control in detail. At the same time, there has been little support in terms of the development of tools and recommendations for the building committee, as will be discussed further in Section 6.3.

The design review carried out by a peer reviewer does not imply that this person must re-calculate everything in detail. The aim of the design review is to check how the designer has approached the design problem, which tools were used, his or her competence, and to assess whether the results are reasonable or not. One important task in the review is to question whether the hazard identification, which forms the basis for the verification, covers all the important aspects, or whether the designer has missed or forgotten something. If errors are suspected or if inappropriate models have been used, re-assessment may be necessary, but these calculations should not be done by the reviewer, since that jeopardizes his or her objectivity.

In addition to the normal procedures for review presented above, additional review is required in buildings where fire may cause great risk of human injury and the analytic design method must be used to design for evacuation safety (*BBR* 5:13). In such cases *BBR* demands that the correctness of the calculation must be demonstrated by design control, which constitutes a review of the design assumptions, construction documents (including the fire protection documentation) and calculations (*BBR* 5:14). It is also required that this review be undertaken by a person who has not previously been involved in the project.

6.3 Identification of problems in the present situation – structure and discussion

The ability to control fire safety through specifying rules at a certain level within the framework is affected by the extent, to which the activity is controlled on the specific level, as well as how the regulations are formulated and how they are implemented by the professionals involved. Drawing up regulations involves a compromise between being in control, from the authorities' point of view, and affording freedom to the designer and user of the building. By studying which regulations govern safety on this level, and how they are applied, problems and flaws in society's ability to control fire safety protection can be identified.

In the study performed on fire protection documentation and the relation between documentation and regulation (see Section 4.2), a number of problems were identified. These were divided into different categories and are discussed in the following sections:

- verification procedures and general problems (Section 6.3.1),
- problems associated with elements of the verification procedure (Section 6.3.2),
- lack of requirements regarding competence of analysts (Section 6.3.3),
- design review – the problem with changeover (Section 6.3.4), and
- local adaptation of procedures (Section 6.3.5).

6.3.1 Verification procedures and general problems

An abundance of methods and models are in use today in verification, in some cases proprietary software. The question is whether all of them are appropriate, or whether some should be rejected. If it is in the interest of the designer to prove that a design solution is safe, aiming at meeting minimum standards, rather than managing the fire risks appropriately, then there is a risk that poor solutions will accepted based on inadequate analysis. The level of fire safety will then be too low. The quality of the verification is not only dependent on the method of evaluation or the protection system being verified, but on how the designer chooses and applies the models. The conditions for verification change from one project to another, and what is suitable for one case may give misleading results in another.

Some of the most serious flaws identified in the study of fire protection documentation described in Section 4.2 are summarized below.

- Parallel systems with built-in resiliency were replaced by more vulnerable single-chain safety components, without considering the consequences of failure.
- Safety measures were studied in isolation, only addressing non-compliances, and therefore little or no attention was devoted to the fire protection system as an integrated system.
- Identification of *what* requires verification, i.e. which safety aspects must be addressed, is often performed in an ad hoc manner or totally forgotten. All emphasis is put on *how* to verify the design, i.e. the appropriate complexity of the model.
- The analysis of how the safety is affected by technical trade-offs is in many cases so poor that it is not clear what effects the change has had on the fire safety or protection of the building.
- Inappropriate verification methods were used and no proper risk assessment was conducted, e.g. single scenarios were used for comparisons in relative analysis with no motivation of why the scenario was considered sufficient to evaluate the total effect on safety.
- Some designers appear to be unaware that different demands apply for verification and review, depending on whether the prescriptive or the fire safety engineering design method is applied.
- Verification analysis of design solutions is sometimes not conservative as a consequence of oversimplification, bold assumptions and a lack of understanding.
- It appears that designers are eager to adopt the benefits of fire safety engineering, but are reluctant to take on the extra workload and engineering responsibilities.
- In some cases, the budget for the project governs the scope and the level of detail of the verification, instead of the actual need for verification of the specific design. This need is largely dictated by the solution proposed by the designer, which was not available when the budget for fire safety was decided.

Inadequate verification means that the demands in *BBR* will not be fulfilled and that solutions leading to inadequate protection will not be revealed. If designers regard verification only as an academic exercise, and rely solely on their instincts when determining the appropriateness of a design solution, the societal risk control intended in *BBR* will not be achieved.

The study of the fire protection documentation also showed that serious events are not considered in verification, for example, if a system fails or if a serious fire breaks out. Despite the fact that it is impossible to completely prevent the consequences of such events, measures can be taken to limit the damage. Not considering such events at all seems counter intuitive from a risk management perspective. Protection against serious accidents must be included as part of a building's total fire protection, despite which design method is used. The design of such protection is not dealt with explicitly in today's building legislation. If the contribution to the risk from these types of scenarios is not included in verification, protection against serious accidents will be undermined at the same rate as the use of analytic design. It is a sobering fact that society has no way of knowing whether this is happening or not.

6.3.2 Problems associated with elements of the verification procedure

The problems and shortcomings presented in Section 6.3.1 were identified by studying how the possibility of changing traditional fire protection has been used in practice when the analytic design method was applied. Some of the problems associated with this design method and the consequences of these problems in safety control are discussed in more detail below.

6.3.2.1 Hazard identification

In fire risk assessment, the choice of risk analysis method, criteria in terms of threshold for critical conditions, input data, calculation models, etc. are often of great concern for all involved parties. Little or no attention is paid during the design process to the first and most important phase in the risk assessment process, i.e. hazard identification or, What has to be analysed in order to prove that the safety of the design is equivalent, i.e. sufficient?

This phase is the most important part of risk assessment (Haimes et al., 2002) as the scope of the analysis is determined, which indirectly influences the outcome of the analysis. If hazard identification is not carried out properly then verification will miss some of the relevant aspects of fire safety in the building and several important scenarios which could cause the design to fail may be overlooked. Shortcomings in the choice of scenarios are one of the most serious threats to the quality of risk assessment when used for safety evaluation purposes (Hall, 1999). As a result, the *verified as equivalent* design might not meet the demands laid out in the building regulations, and it is possible that the level of fire safety will be inadequate, but will remain unnoticed in the design solutions. If such mistakes occur, they should at least be identified in the design review, which must form an integral part of all design projects.

6.3.2.2 Serious scenarios

One consequence of using inadequate or inappropriate risk analysis in verification is that the protection against serious accidents can be reduced without this being noticed. Protection against serious fires was often completely forgotten or neglected in the verification of that the safety objectives were met in the cases studied. In this context, protection against serious events concerns the ability of the building to resist the consequences of serious fires, i.e. a fire greater than those normally used for design, or a fire in a particularly unfavourable location. Examples of this are fires that start in an adjacent room and which grow before being discovered (e.g. fire type 2 in Section 4.4.2). Such a fire can result in a ventilation controlled fire (potentially vitiated conditions) where the yield of species (i.e. combustion products), toxicity, visibility, rate of heat release, risk for flash over etc. can be quite different compared to a well-ventilated fire. Another situation when the consequences can be serious is when one or several fire protection systems do not work as they are intended to, see Figure 48.

In fire safety design it is often considered adequate to perform calculations for one design scenario, while in the design of load-bearing structures several load cases are used (further developed in Section 6.4.3), and the uncertainties associated with each case are taken into consideration. If only a single scenario is considered in the assessment of fire risk it will not be possible to reveal an increase in risk resulting from increased risk in any other scenario. When analytic design is used changes to the fire protection system derived with the prescriptive method can have large impact on the scenarios enclosed in the ellipse in Figure 48. Trying to evaluate whether the risk is acceptable or not based on scenarios that do not involve any risk, i.e. the contribution to the risk is zero, is meaningless. The scenarios contributing to the total risk must be considered in order to obtain an estimate of the total risk.

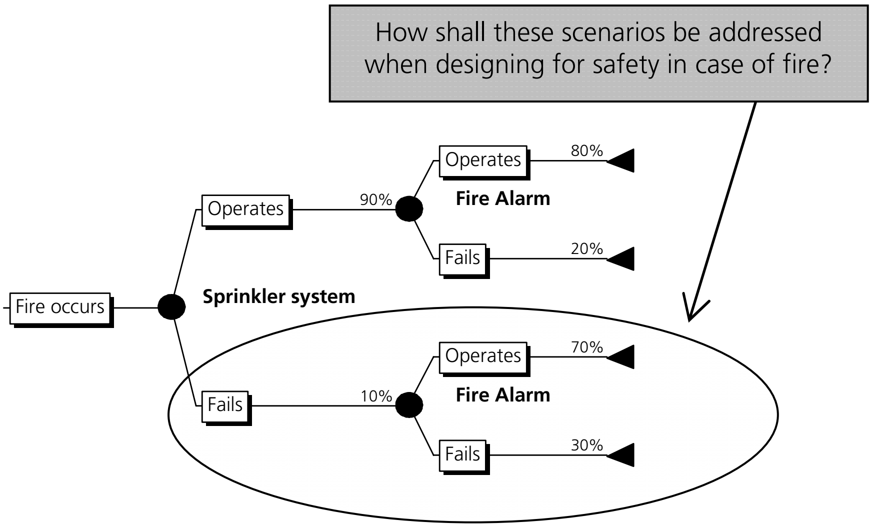


Figure 48. Scenarios seldom considered in analytic design.

When the prescriptive design method is used, the protection will provide a certain protective effect in all scenarios, even if the consequences are not zero. It does not seem reasonable to expect society to accept an uncontrolled reduction in fire protection in these scenarios, while the solution is still regarded as affording sufficient safety. When analytic design is used in the way it is today, there will be an imminent risk that fire protection in the case of serious accidents will be overlooked.

6.3.2.3 Choice of single design scenarios

In an effort to find specific criteria with which to compare solutions in order to prove that the total fire protection of the building has not become worse than if prescriptive design had been used, the demands laid out in *BBR* 5:31 and *BBR* 5:36 are often used as the starting point.

BBR 5:31 General
"Buildings shall be designed so that satisfactory escape can be effected in the event of fire."

BBR 5:36 Design conditions
"In design with respect to the safety of escape, the conditions in the building shall not become such that the limiting values for critical conditions are exceeded during the time needed for escape."

These demands are in general interpreted as meaning that a limit-state must not be exceeded. The limit-state for evacuation safety is defined as a time margin, i.e. the difference between the time before critical conditions are reached, and the evacuation time when this interpretation of *BBR* 5:31 is used. Verification is performed by analysing the time margin for a design scenario. If the time margin is positive, the solution is regarded as being sufficiently safe.

One advantage of this method is that it is specific, and easy to understand, but there are several problems. One of the most serious is that it is not clear which scenario should be used as the design scenario. There are very many possible fire scenarios that can occur in a building. Should all scenarios be investigated, or just one representative one, and how should this one be chosen? Since the number of possible scenarios is more or less unlimited a complete scenario analysis is out of the question. However a single scenario (or a few) constitutes a very limited representation of the complete set of scenarios, i.e. the total risk.

In scenarios where one or more protection systems fail, it can be difficult to evacuate the building before critical conditions occur. If such scenarios are used to verify a solution in relation to the time margin, then few or no designs will be acceptable. Prescriptive designs would not pass such a test either, which indicates that it is unreasonable to demand that everyone should be able to escape before critical conditions occur in every scenario.

In order to circumvent this problem while still using the established method attempts have been made to use conditions that will cause injury or fatality in order to define a limit-state for slightly more serious scenarios than the ones normally analysed. In practice, this means that more serious consequences are accepted in the more serious scenarios since many people may be affected by critical conditions for a long time before anyone dies. An alternative method that gives the same result is allowing a certain negative time margin for these scenarios, but still measuring the consequences at critical conditions. The question still remains: *For which scenarios is this valid?*

The performance requirement in *BBR* 5:36 is more of a political description of the aim of fire safety, than the demands on the performance which can be verified. The demand may reflect the desired performance or the level of fire protection when all systems work as they should, but is inadequate as a design criterion as a number of different scenarios may arise. It is not clear which level of performance of the fire protection system can reasonably be demanded when one or more systems fail. There is no guidance on how to determine the adequate level of protection in these scenarios.

The method of using limit-state functions was developed for the design of load-bearing structures, but the concepts have been uncritically transformed to the design of evacuation safety. In order to investigate whether it is actually possible to apply this method in assessing fire risk, a detailed analysis was performed, and is presented in Section 6.4.3.

6.3.2.4 Arbitrary choice of the risk measure in risk comparison

Another problem associated with defining the consequences of scenarios using a time margin is that it is difficult to determine the number of people affected. If the time margin in a scenario is -10 seconds, this may mean that one person had to walk a long way to the exit, or equally that 10 people will not have time to evacuate the building. Whether a negative time margin of 10 seconds is considered long or not depends entirely on the course of evacuation. In a comparison between different designs where the course of evacuation varies, the time margin may thus not be a suitable risk measure. Neither is it probably suitable to express general acceptance criteria or safety margins in terms of this measure. In most cases it is better to define the consequence endpoint as the number of people not having time to leave the building before critical conditions occur, in order to avoid this problem.

A suitable acceptance criterion, e.g. critical conditions, is actually not based on what people can withstand. The purpose of the acceptance criterion is to be able to evaluate if a design offers an acceptable level of safety by evaluating the conditions in the design with a certain method. In order to do so, the acceptance criterion must be derived and connected to a design method, assessment of uncertainties in the calculations, and selection of values of input data and other variables. The safety achieved when verification has proven a design acceptable is a combination of the criterion used, the severity of the scenario tested and how the uncertain input variables were selected. If the criterion and fire scenario investigated are not well determined, the results of the verification will be very uncertain. Giving an acceptance criterion without referring to the design method leads to a false impression that the required level of safety has been achieved.

6.3.3 Lack of requirements regarding competence of analysts

In Sweden no requirements are made regarding formal qualifications or experience in designing fire protection systems, in contrast to other countries, for example, the USA and the UK. In these two countries a system based on certification or licensing is employed. Building legislation demands that an engineer has to be licensed in the relevant area. This means that fire safety engineers must able to demonstrate their ability in written examinations and continual training in order to retain the right to practice.

No such demands are made in Swedish legislation. *Boverket* has issued general recommendations on the certification of independent expert (third party controllers) within the field of fire safety (*Boverket*, 1996), but no accredited certifying body has yet been established. No expressed demands are made regarding certification of independent reviewers in any regulations, and little interest has been shown by developers and other parties involved. Professional societies representing those practicing the field of fire safety engineering offer certification on a voluntary basis, but the demand is almost non-existent in Sweden. Both in the private and public sectors engineering students that haven't completed their education and received their degree are employed.

Although no formal demands are made regarding competence, it should be in the interest of building committees to ensure that fire safety designers have the necessary qualifications, through training and experience, when the level of design review is determined.

6.3.4 Design review – the problem with changeover

All the fire protection documentation that was scrutinized (Section 4.2) and in which the flaws presented in Section 6.3.1 were discovered, had passed both internal review at the engineering companies and general quality control performed by the building committee. The fact that the flaws were not discovered in the self-implemented control of the designer, nor in any other possible action that could have been taken during the construction process, is a problem in itself. This can not simply be explained by engineers not living up to their responsibility, but rather a more fundamental lack of structure regarding how verification and review are carried out when fire safety engineering is practiced. It is also possible, but not likely, that the identified flaws were not even regarded as problems by the practitioner.

One possible explanation is that the tools for verification and review have not been subjected to the same degree of development as design tools, e.g. CFD models and risk analysis methods. At the same time, sizable trade-offs are becoming more and more common. More complex and innovative buildings are being designed, and the new design tools are leading the way towards significant changes in traditional fire safety strategies. The building regulations allow extensive changes to the traditional fire protection measures. Increasing changes are constantly being made to traditional solutions and the limits of acceptability are being tested in pursuit of lower building costs.

Activities are ongoing to structure the review process of fire safety engineering solutions (SFPE, 2002a), but there is still a lack of tools to determine the appropriate level of review. Unfortunately, the tools available are sometimes used in the wrong way or not used at all. According to interviews made during the study of Swedish fire protection documentation Sweden it was obvious that third-party review is unfortunately not being performed on a regular basis.

Is the lack of tools to determine the appropriate level of review only a problem in Sweden? The development of the fire safety engineering concept is global and is characterized by international cooperation and exchange of ideas. The similarities in the fire safety engineering design concept used in Sweden and other countries are many, even if the codes and procedures are not identical. Although no detailed analysis has been made of fire protection documentation from other countries, twenty-five case studies that have been presented at international conferences (SFPE, 1996, 1998, 2000b, 2002b, 2004) have been briefly investigated. The problems identified and presented in Sections 6.3.1 to 6.3.3 are relevant in several of these, and the similarities between the fire safety engineering design concept used in Sweden and other countries are many, although the codes and procedures are not identical. Many of the flaws presented above have been recognized in designs in other countries (Babrauskas, 1998; Fleming, 1996; Loveridge & Lundqvist, 2002; Marchant, 2000; Ulfsnes & Danielsen, 2004), which supports the idea that the problem is not unique in Sweden.

One difficulty that can arise when regulations are changed from being prescriptive to addressing *safety procedures & safety case* (e.g. directed towards quality control of design), is that the person who checks compliance is the same as the person who previously carried out the technical control (Hopkins & Hale, 2002). This person may have little experience in the field of management, and could find it difficult to make relevant demands in this field. Furthermore, there is a risk that the building officials will not be able to maintain their level of technical competence. Alternatives to reviewers or inspectors employed by authorities to assess compliance with rules are self regulation, perhaps including certification, and independent third-party control. This problem has become very obvious in the construction process. In most countries, the building officials determining the need for review have had neither significant education nor training in advanced fire safety engineering analysis, or training in systematic approaches to evaluate designer's quality control systems after the introduction of the performance-based building regulations. The competence of the building committee determining the need for control will unavoidably vary between different communities. In small communities where the number of staff is limited, a lower degree of competence can be expected. It is unrealistic to expect a building official to master all aspects of fire safety engineering. As a consequence, and since analytic design can hardly be geographically restricted in countries with performance-based codes, the person who decides the suitable level of review often has lower qualifications than the designer. Therefore the building official must be equipped with simple tools to be able to judge which types of designs need a high or a low level of review, without being a trained professional in fire safety engineering. Depending on the size of the trade-off in terms of modifications of a prescriptive design and the potential of harm (hazard), different levels of review will be needed. A small modification of a prescriptive design often has little impact on the safety, and the need for review is therefore low. However, there are several difficulties associated with analysing requirements when a design is reviewed.

The building committee's decision regarding the level of review can not be based on the verification analysis carried out by the designer. Critical assumptions and simplifications made by the designer may contain errors, leading to a poor decision on the part of the reviewer. When the need for verification is determined by the designer, subjective judgment is inevitably introduced and the potential bias associated with the person performing the identification must be addressed. The designer's judgment can be affected by demands other than thorough verification, e.g. limited time or budget, or demands for cost-cutting etc. A designer-induced bias can affect the scope of the verification, i.e. the completeness, and thereby threaten the quality of evaluation of trial designs. This is one reason why review of the verification is necessary and the level of review must be determined by an independent body, e.g. the building committee. At the same time, it is inappropriate to perform an extensive analysis in order to determine the need for review for each project, since the resources available for review are limited. Design review is important but has to be efficient and focused on the appropriate projects. Rigorous review can result in unnecessarily costly delays in obtaining the approval required to continue in the design process. This indicates the need for the development of additional tools in the design process, i.e. simple tools to determine the appropriate level of review, to ensure the quality of fire safety design.

In addition to the lack of tools there are some moral concerns with the Swedish review system. One moral dilemma is that the third-party reviewers receive their fee from the developer and it can be questioned how impartial the third-party reviewer then really is. Observations supporting the fact that this is a problem have been made during the study and while interviewing designers and building committee personnel, even if a systematic investigation has not been conducted. In some projects the designer and the third-party reviewer team up, since their roles may be reversed in the next project. It happens occasionally that a developer contacts several potential third-party reviewers and asks for their opinion and analysis before the suggestion of the independent third-party reviewer is submitted to the building committee. The selection of reviewer is then obviously biased towards the reviewer's response to the request rather then the reviewer's competence. The developer can "shop around" in order to be certain of getting a third-party reviewer who supports his or her solution. This kind of behaviour clearly violates generally agreed codes of ethics in the area, e.g. the Canon of Ethics for Fire Protection Engineers adopted by the Society of Fire Protection Engineering (SFPE), but can be convenient and no repercussions are expected.

6.3.5 Local adaptation of procedures

The designer's performance and the quality of the design depend on the reaction of the building committee. In order not to cause delays in the design process, it is sometimes necessary for the designer to "conform to the system". As a result of this, there will be local differences in how the construction process actually works, and how building regulations are interpreted. An example is when local demands are stated, that are not called for in building legislation. This has been noted by *Boverket*, but is difficult to prevent. It is often more efficient (i.e. easier and cheaper) for the owner and designer to accommodate such local demands than to try to apply the same approach, regardless of where in the country the project is taking place. This is very evident if there is a risk of the project being involved in a legal process which is likely to delay the building project.

One of the aims of introducing building legislation was to do away with local variations, but these still exist to varying degrees. One reason for this may be that there is a certain vacuum between practical measures (direct risk control) and legislation, i.e. the regulatory national authority (i.e.

Boverket) has not interpreted the legislation, provided examples nor made recommendations regarding how compliance ought to be assessed. Local actors are thus more or less forced to devise their own guidelines in order for the design not to be perceived as too arbitrary. This is a well-known dilemma in safety legislation, i.e. there is a conflict between the formulation of goals allowing a high degree of flexibility in a system and giving guidelines and instructions, as the latter are perceived as making the rules more prescriptive (Hale, 2001).

6.4 Detailed quantitative and qualitative analysis of specific identified problems

Some of the major problems presented in the previous section (Section 6.3) have been investigated further. One of these is inadequate scenario identification, i.e. hazard identification, in the risk analysis used in verification analysis.

Several papers and reports have been published on how the computational tools used in engineering design can be verified (Beller, 2001; Hurley & Madrzykowski, 2002; Lundin, 1999), which is crucial in establishing a sound technical basis for verification. But it is also necessary to address trial design evaluation on a more general and holistic level, since serious weaknesses in hazard identification (e.g. scenario identification) have been revealed, see Section 6.3.1 or Lundin (2001, 2005).

In the following Sections 6.4.1 and 6.4.2 two underlying problems leading to inadequate hazard identification are analysed and synthesized. The task of verification is discussed based on the following postulations:

- interdependencies within the total system of fire protection require a system approach (Section 6.4.1), and
- the logical structure of the regulatory system is neither transparent nor fully understood by all actors involved in the construction process (Section 6.4.2).

In addition to the difficulties associated with scenario identification, the suitability of using design methodology taken from structural engineering is also analysed (Section 6.4.3). The effects of arbitrarily selecting input data and the risk measure used in the verification calculations are studied in Section 6.4.4. Finally, conclusions about incorporating major disasters (serious scenarios) in the risk analysis process are summarized in Section 6.4.5.

6.4.1 Interdependencies within the total system of fire protection require a system approach

When analysing the effects of trade-offs on the fire protection system, safety measures removed or added cannot be studied in isolation because of interdependencies. It is necessary to adopt a system approach to identify the function and purpose of each safety measure, in order to re-design the system so that the performance of the whole system is adequate. When trade-offs are evaluated the analysis can not be limited to covering only non-compliances with the prescriptive solution, since the modification may affect the rest of the system.

Interdependencies in complex systems are not easily identified, but their consideration in safety design has been proven to be crucial (Kaplan et al., 2001), for example when evaluating vulnerability. The ability to model the intricate relation among various sub-systems is also a necessity when evaluating the impact of changes of a complex system. An interdependent fire protection system consists of sub-systems that directly affect the course of events or conditions in the building, e.g. how the fire and smoke spread, but at the same time their effectiveness depends on how the conditions develop. For example, the limitation of fire size due to suppression systems might decrease the amount of smoke generated, but at the same time prolong the detection time at locations remote from the fire. It may not be evident whether the net outcome is positive or negative from a safety perspective in a complex building.

Obtaining an overview of how the whole fire protection system fits together in the building is a major challenge to the designer. Attempts have been made to visualize the complex relationships between different sub-systems, e.g. in the Global Information Bus (ISO, 1998b), but these have so far been of little practical use.

One starting point is to consider the different types of safety measures required in the building regulations. These safety measures can be divided into three different types, according to their risk-reducing effects:

- those that reduce or eliminate the hazard or risk source, i.e. the probability of fire initiation,

- those that reduce or eliminate exposure, i.e. fire development and fire and smoke spread, and
- those that prevent hazardous effects on the objects that are to be safeguarded (e.g. occupants and load-bearing structures), i.e. accumulation of heat, smoke and toxic products or products causing non-thermal damage.

The different types of safety measures can be seen as multiple barriers which are combined to achieve the required performance of the fire protection system.

6.4.2 The logical structure of the prescriptive regulatory system is not transparent

The structure of the performance-based regulatory system is more or less the same in all countries that have adopted this regulatory regime. The common overall objective is to safeguard society's fire safety goals in buildings, even if the safety level is not necessarily the same. The model proposed by the Nordic Committee on Building Regulations (NKB, 1978) is often used to illustrate the hierarchal structure of the regulatory system (see Section 2.2), where several levels correspond to different types of regulations. In Figure 49 the levels in the NKB model have been transformed into an idealized structure illustrating the organisation of the regulatory system. In this structure the top level can be broken down into independent demands on the lower levels.

In reality, the safety goals, performance requirements and mandatory provisions leading to acceptable solutions are not arranged in a strict hierarchy. Many safety measures are part of an integrated safety solution which can have multiple purposes and contribute to fulfilling several functional requirements. An example is escape routes, which serve both as a way out for occupants, and as entrances for the fire and rescue service. This leads to the true structure of the cause-effect relation between the safety measures, the performance requirements, and the technical requirements not being fully transparent, i.e. the rationale behind the safety measures is not always fully known or understood. This result is understandable considering the evolution of, and influences on, the regulatory system. Traditionally, the acceptable level of safety has been defined by detailed demands in terms of acceptable solutions and *deemed-to-satisfy* provisions (i.e. the prescriptive method). These demands reflect building tradition and have been developed over many years, driven by public perception of accidents that have happened, and can be seen as an historical patchwork (Babrauskas, 1998).

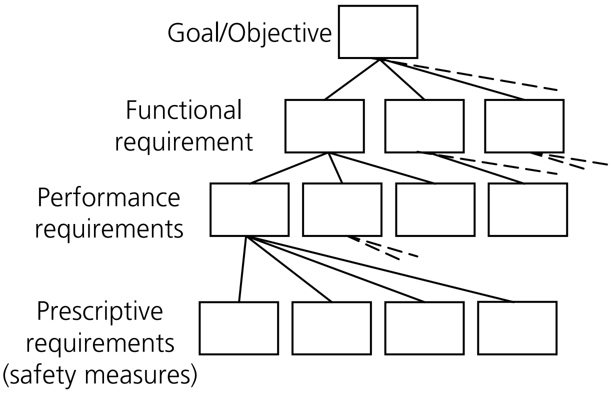


Figure 49. The idealized structure of the performance-based regulatory system.

The discrepancy between the formal regulatory system (depicted in Figure 49) and the "actual" safety achieved by the fire protection system (shown schematically in Figure 50) can make it difficult to understand how a trade-off affects the safety.

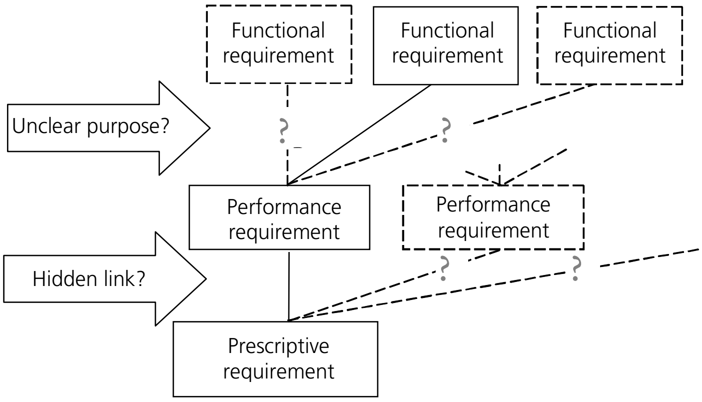


Figure 50. Unclear purposes and hidden links can cause problems for the designer when trying to structure the verification needs.

If the formal regulatory system is used to determine what should be verified, it may be difficult to identify which functional requirements and performance requirements are actually affected. There also seem to be different opinions between the regulators and some designers in Sweden regarding which functional requirements are covered in the code and their purpose. According to the results of a questionnaire used in an EU-project BENEFEU such differences exist, for example, regarding the purpose of requiring fire protection of load-bearing structures in the building regulations (Warrington Fire Research Group, 2002). If such fundamental issues are not communicated between or perceived by the actors involved in the construction process, inadequate verification can be expected.

In the Scandinavian countries the performance requirements in the building regulations cover a number of functional requirements originating from the interpretative document, Safety in Case of Fire, issued by the European Union (EU, 1990). These were introduced "on top of" the prescriptive code before the performance-based regulations were introduced. Their purpose is not to harmonize the building regulations in the European Union, but rather to define the safety objective in the context where building products are used, i.e. for construction works.

In some other countries, the USA, for example, the regulatory system is arranged in a more transparent way than in Sweden. A similar structure to the NKB model is used, but each functional requirement is covered by a single code, e.g. there are separate codes for the safety of those in the building and the safety of the fire fighters. Since both codes have to be adhered to explicitly in the design, the risk of overlooking multiple purposes of modified measures is smaller.

6.4.3 Applying principles from design of load-bearing structures

The lack of a general, accepted method for the design of evacuation safety has led to the application of principles and approaches from other areas. This section considers certain methodological and evaluation problems that arise when principles intended for load-bearing structures are applied in the design of evacuation safety in case of fire.

6.4.3.1 Brief overview of the design principles for load-bearing structures

It should be stressed once again that the design of load-bearing structures is a mature engineering area, in which the methods are related to underlying principles leading to risk control (see also Section 3.1). The main principles and the simplified method prevalent in the field are presented below and based on the Swedish design regulations (*BKR*, 2003). For a more detailed description of design methods for load-bearing structures, the reader is referred to standard textbooks in the area (e.g. Ang & Tang, 1975; Thoft-Christensen & Baker, 1982).

Figure 51 shows a greatly simplified illustration of the risk associated with collapse of load-bearing structures. Detailed descriptions of all types of failures that may occur are not presented here (e.g. material failure, instability, tilting, uplift, sliding and accidental actions), but these must be considered by the designer. The illustration should be regarded from the perspective of how the analytic design of load-bearing structures is related to risk control.

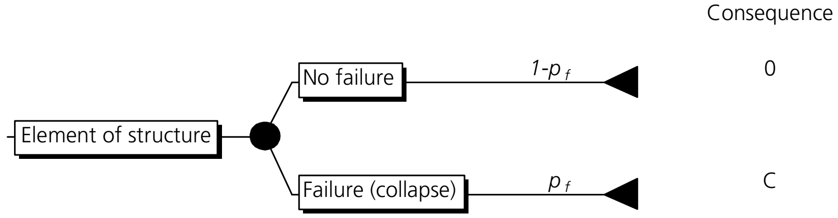


Figure 51. A greatly simplified illustration of the risk associated with the failure of an element of structure.

If failure occurs, consequences can be expected in a building in terms of injuries, fatalities and economic loss, which are denoted C. The probability of failure of an element of structure, e.g. a column or a beam, is denoted p_f.

The design of load-bearing structures, regarding health and safety, is based on collapse or other types of structural failure, i.e. the ultimate limit-state. Failure occurs when the load exceeds the load-bearing capacity, which can be expressed as a limit-state function, in which the probability of failure is defined by $p_f = P(R_s < S_s)$. The variables R_s and S_s are stochastic and represent the resistance (i.e. load-bearing capacity) and the action effects (e.g. loads). Consideration also normally has to be taken to the serviceability limit-state, i.e. deformation which may affect the appearance, comfort or effective use of the building due to, for example, vibrations or cracking. The later requirements are normally stipulated by the building owner and will not be considered further.

The risk associated with failure is controlled by allowing a maximum level of damage upon collapse of an element of the structure, C_{max}, together with the maximum allowed probability of failure, $p_{f\,max}$. This means the indirect definition of the maximum permissible risk (i.e. acceptable risk). Furthermore, the allowed probability of failure and the extent of personal injury resulting from that failure are related through three safety classes, defined in the regulations (*BKR*, 2003), where the probability of failure is given for each class in the form of a safety index, β, related to a reference period of one year. This safety index can be transformed into p_f using the normal distribution, $p_f = \phi_N(\beta)$. The division of structural elements into safety classes (also denoted consequence classes) is based on the consequences in the case of failure. If failure leads to serious consequences a lower probability of failure will be acceptable, and vice versa. This indicates that consideration is taken of the total risk associated with failure, i.e. both the consequences and the probability of failure.

This approach means that the designer does not explicitly analyse the consequences once failure has occurred. This may seem strange as risk has previously been defined as a combination of probability and consequence. The reason is that in the design procedures for load-bearing structures it is sufficient to define the consequence as the collapse of the element or not, i.e. it can only have two values. In the design regulations it is stipulated that in the case of failure, the largest acceptable area of primary damage is 150 m^2 (Albertsson et al., 1982; *BKR*, 2003). If the damage is greater, there is a risk of progressive collapse, which is not acceptable under any circumstances. There are specific design regulations to prevent this. By applying this procedure the risk can be controlled by designing an element of structure with analytical methods such that $p_{f\,max}$ is not exceeded. In such a case the contribution to the risk from failure may not exceed the acceptable risk, i.e. $p_{f\,max} \cdot C_{max}$, where C_{max} is equivalent to the maximal damage if 150 m^2 is affected by the collapse. An acceptable risk, applied in the design of load-bearing structures, has thereby been defined without giving the explicit number of fatalities, and is probably as good an estimate of what is acceptable to society as damage in terms of a certain number of injuries or fatalities. Risk control is attained.

By selecting the safety class for an element of structure the acceptable probability of failure will be determined, $p_{f\,max}$. The requirement on the analytic design method is to ensure that the element of a structure will not exceed this target probability of failure. A logical result of the ultimate limit-state is that a stronger beam (or column) will provide increased load-bearing capacity, and thus a lower probability of failure. The aim of the design exercise is therefore to design an element of structure with sufficient strength so that the target probability of failure is not exceeded. The probability of failure, p_f, can be determined by probabilistic reliability analysis, which is normally very complicated and extensive. A large number of uncertain variables are included in such limit-state functions and the competence and information required makes it impractical to design many types of structures in this way.

To facilitate design, a simplified deterministic method has been developed, the so-called partial coefficient method, which is described, for example, in the design regulations (*BKR*, 2003). This method is based on verification by the designer that a building has sufficient load-bearing capacity in a number of load cases. A load case defines the loads to be considered and how different loads are to be combined in the design calculations. The designer has to verify that the element of a structure has sufficient load-bearing capacity for all load cases specified in this method. Examples of loads that have to be considered in different ways are permanent, variable and accidental loads, both in normal use of the building and if fire occurs.

When the loads are combined, the maximum value of each specific load is not used at the same time due to several reasons. For some of the loads the maximum values can not co-exist, e.g. loads due to thermal expansion and snow, and for some loads the probability of two or more occurring simultaneously is so low that such a case is considered part of the acceptable risk. For example, very high wind and snow loads are assumed not to coincide. Another example is that fire and accidental loads, e.g. the building being hit by a truck, are assumed not to occur at the same time. If such load combinations were to occur at the same time as the load-bearing capacity is low it is likely that the element of structure would collapse. These very rare situations constitute part of the acceptable risk, since they represent the rare combinations of events that can actually lead to failure, i.e. they constitute p_f. The design method is designed and calibrated such that the sum of the cases where the loads exceed the strength does not exceed the target probability of failure. Even if failure occurs due to unlikely load combinations, the consequence will still not exceed C_{max} and the risk is deemed acceptable according to the design methodology. Neither is the size of C_{max} affected by the specific design solution for a building component.

In order for the design method to fulfil its purpose, not only the load cases are specified, but also a number of key components in terms of the design equations for strength calculations, the input data in terms of characteristic values and partial coefficients and the acceptance criterion. The outcome of the design method depends on these key components being calibrated correctly, which is the extensive process in which the load cases were defined, the input data determined, etc. Therefore, these values can not be chosen arbitrarily by the designer. The method must be used in the prescribed way, or the use of an extensive reliability analysis in which all uncertainties are considered will be necessary.

In the verification of evacuation safety, parallels are often drawn with both the design principles and method described above, without taking the underlying differences into consideration. Quite often, parts of the concept are used without recognizing that the key components in the simplified method, i.e. load cases, input data and criteria, are the result of extensive calibration with reliability analysis. This is problematic as it leads to serious scientific shortcomings in risk control in the way the method is applied in fire safety engineering. Some of these problems and their consequences are discussed in the next sub-sections.

6.4.3.2 Interpretation of performance requirements for evacuation safety in BBR

As no information is given on how *BBR* 5:11 is to be interpreted or expressed in connection with design calculations, Eq. (20) is often applied as a design expression. There are, however, a number of problems associated with this interpretation, which have been addressed earlier in Section 6.3.2.3 but are discussed in greater detail in this section.

$$\Delta t = t_{crit} - t_{esc} \tag{20}$$

Δt = time margin
t_{crit} = time to critical conditions
t_{esc} = escape time

The limit-state $\Delta t > 0$ is used as the design criterion in the analysis of a single scenario to determine whether the level of safety is acceptable or not. The input variables are sometimes arbitrarily chosen without knowledge of their uncertainty. This makes it impossible for the designer to determine the reliability in the results from the chosen input data.

If uncertainties in the limit-state function $\Delta t > 0$ are taken into consideration the design condition is defined as the probability of the limit-state not being fulfilled, i.e. $P\ (\Delta t<0)$. This means that it is accepted that there will be a certain probability that the time allowed for evacuation in a certain scenario will not be sufficient, in much the same way as it is accepted that there will be a small probability that a load-bearing structure will collapse. In contrast to the design of load-bearing structures, this approach does not mean that the complete fire risk is controlled in the design of evacuation safety. Some of the reasons for this are presented in Sections 6.4.3.3 to 6.4.3.5.

6.4.3.3 Defining the consequences with a limit-state function

Assuming that an element of structure fails, the limit on the area affected by the primary failure is 150 m^2 (see Section 6.4.3.1). In the case of fire, the situation is different. Using the time margin as the limit-state works well in cases where it is reasonable to demand that all the occupants of a building be able to escape, but it gives a poor measure of the consequences in cases where everyone does not manage to escape. Should this be taken into consideration? Are there cases in which it must be accepted that one or more people will be affected by critical conditions? The answer to both questions is yes.

A level of fire safety that ensures that no one is exposed to critical conditions, regardless of the scenario, is too costly, and places unreasonably strict limitations on the design and use of the building. It does mean, however, that it is necessary to limit the damage in cases where one or more people do not have time to evacuate the building before critical conditions occur. If the time taken to reach critical conditions is shorter than the evacuation time, then it is not the difference in time that is of interest, but the number of people affected (as indicated in Section 6.3.2.4). For example, 2 minutes too few for evacuation will lead to different numbers of people being affected depending on the building and the course of evacuation. In order to assess the contribution to the risk from a scenario, it is useful to study how many people will be affected, as the scenario will only constitute a risk if someone is exposed to critical conditions. Merely determining the difference in time is thus, in many cases, not adequate to capture how the total risk is affected and therefore not sufficient for the purpose of risk comparisons when the course of evacuation differs between two designs. This means that the interpretation of the performance demand in *BBR* 5:36 (i.e. $\Delta t > 0$) often used in verification should be questioned.

6.4.3.4 Using one scenario to evaluate the total risk

The reason why the total risk cannot be measured by studying the contribution from one scenario is that the relation between this risk and the total risk from all scenarios is not sufficiently strong. The reliability, and thus the probability of the various scenarios, varies for different types of fire protection systems. Examples of factors that affect this are quality, operation & maintenance plans and correct design. The effect on the consequences of whether a fire safety protection system works or not depends on how the system affects the fire and/or the evacuation, and is expected to vary considerably between different designs. There is no support for the hypothesis that there is a predefined relation between the consequences of various scenarios, e.g. that a single-source failure is equivalent to 1/10 of the consequences in a worst-case scenario. Nevertheless, the consequence of how the selection of design scenarios were justified (or the lack of justification) in the fire protection documentation studied (see Section 4.2) implicitly supports this hypothesis.

Eq. (21) gives the expression for calculating the mean risk in a simple example where there are four possible scenarios arising from a fire.

$$E(R) = \sum_{i=1}^{4} \left(p_i \cdot c_i \right) = p_1 \cdot c_1 + p_2 \cdot c_2 + p_3 \cdot c_3 + p_4 \cdot c_4 \qquad (21)$$

It is reasonable to assume that c_1, c_2, c_3 and c_4 to a large extent weakly correlated as they represent the consequences of completely different scenarios. The differences between these are, for example, whether or not various protection systems work or not. It is not possible to estimate the total risk based only the consequences from a single scenario, e.g. c_3 (see Eq. (22), or to limit the total risk by determining an acceptance criterion for evaluating this scenario.

$$f(c_3) \approx E(R) \qquad (22)$$

This might seem self evident, but in the fire protection documentation studied scenarios were selected and neglected without motivation. One might sometimes suspect that the selection of scenarios is affected by the desired outcome of the verification exercise.

6.4.3.5 Studying a specific fraction of the scenarios

In order to reduce the time required for verification it is necessary to reduce the number of scenarios that are analysed (since the number of possible scenarios is unlimited). However, verification will be less reliable if it is performed in such a way that the fire safety is not properly analysed. Various kinds of inadequate suggestions have been proposed. One such suggestion is to base a decision on the adequacy of fire safety by determining the risk from a specific fraction of the total number of scenarios. By sorting the scenarios according to their severity, the fire protection systems could be designed for the scenario corresponding to the required level of safety. The origin of this suggestion is unclear, but it may well be based on the fact that a certain probability of collapse is accepted for a load case in the design of load-bearing structures. A risky interpretation of this may mean that if the fire safety of a building is evaluated for 95% of all the scenarios then the safety is considered to be acceptable.

This interpretation is reprehensible and unsound engineering practice for at least two reasons. Firstly, it is by no means easy to identify a single scenario that represents 95% of all the possible scenarios. In the modelling of fire risk according to the methodology presented in Section 4.3, the structure of the event tree will vary from project to project, depending on the protection system used and what affects the course of events. The structure of the scenario varies from one building to another. The other reason, which is the most important in dismissing the suggestion, is that even if a scenario that represents a certain fraction of all scenarios can be identified, it will give no idea of the magnitude of the total risk. If a scenario represents 95% of all the possible scenarios, it is still difficult to determine how large a part of the total risk is represented by the remaining 5% of the scenarios. The magnitude of the consequences of these scenarios is unknown, and varies depending on a number of variables. It is clear that it is important whether the consequence is 1, 10 or 1000 injuries or fatalities, if the safety is to be considered as acceptable or not. In the case of load-bearing structures the consequences are the same for different scenarios, so the risk can be controlled by designing the structure based on a certain fraction of the scenarios. The probability of several accidental loads occurring at the same time can be calculated. As the consequences are known the magnitude of the risk contribution is controlled, and it is possible to make a decision as to whether this load case is acceptable and not necessary to consider in the verification. In the risk analysis performed when verifying evacuation safety the consequences vary between the different scenarios, and some of the scenarios cannot be ignored just because the probability of them occurring is small. It is necessary to analyse the magnitude of the consequences before it can be stated whether the contribution to the risk from a particular scenario is small or large, i.e. is acceptable or not.

6.4.4 The importance of the choice of input data and risk measure

A common factor in several of the problems noted is the great freedom of choice of the designer in the verification process. In order to study the effect of this, a quantitative analysis has been performed on the importance of the choice of input data on the calculated risk, and the importance of the choice of risk measure in representing how the total safety is affected when input data is varied. An overview of this study is presented in Section 6.4.4.1, followed by a summary of the results in Section 6.4.4.2. Thereafter, the impact of the variation in input variables on the output is discussed, and the appropriateness of using scenario-based risk measures and the pros and cons of the mean risk and risk profile are evaluated (see Sections 6.4.4.3 to 6.4.4.5). This section concludes with some final comments on the analysis in Section 6.4.4.6.

6.4.4.1 Overview of the sensitivity analysis

The analysis is based on the example called *the base case* (the risk analysis method, input data and variation intervals are presented in Section 4.4 and Appendix C), and consists of a comprehensive sensitivity analysis where the input data are varied systematically, and several risk measures are calculated for each combination of input variables. The premise is an assembly hall where the fire starts in an adjacent room.

Each input variable is denoted with a variable index, e.g. see Figure 52. A short explanation of the indices is given beside the figures in which the results are shown, and a complete explanation of all indices and variables is given in Appendix C. The variables can be grouped according to the type of uncertainty they represent. This has been explained previously in Section 4.3.5, and is summarized below:

- variables in group 1 (natural uncertainty and knowledge uncertainty for a specific building),
- variables in group 2 (uncertainties associated with variables defining a class of buildings, i.e. affected by design decisions),

- variables that represent protections systems probability of failure, and
- assumptions used in calculations (e.g. type of fuel and choice of critical conditions).

The following measures of risk were studied in the sensitivity analysis, and a more detailed description of these risk measures can be found in Section 4.4.3;

- the consequences when all systems work ($C_{all\ work}$),
- the maximum consequence when a single protection system fails, i.e. maximum single-source failure ($C_{max\ ssf}$),
- the consequences of the worst-case scenario ($C_{worst\ case}$),
- the mean risk (R_{mean}),
- the individual risk (P_{ind}), and
- the individual risk to the most exposed individual in the building (P_{worst}).

”No design effect” in Tables C1 and C2 in Appendix C means that no consideration has been taken of how the change in the variable affects other variables in prescriptive design method. This means, for example, that the width of the exit is not changed when the variable describing the number of occupants (variable 2_5) is changed. A greater number of people may be present in the building than the number for which it was designed, and it is of interest to study how this affects the risk. The two cases when ensuing effects are considered and when they are not were studied for several variables. In this way it is possible to study the importance of whether the design conditions and design values in prescriptive design are adhered to or not.

The detection time is affected by which technical systems function correctly. In the sensitivity analysis it is assumed that there is a delay of 45 seconds between automatic detection and manual detection. This delay reflects the time taken for people to detect smoke, decide to activate the evacuation alarm, find the manual activation button and press it. The delay when the evacuation alarm does not work is assumed to be only slightly longer, another 15 seconds, as the person is expected to initiate evacuation directly after trying to activate the alarm, and will be noticed by other people in the assembly hall. The detection time is calculated using Eqs. (23) and (24).

$$t_{d\_man} = t_{d\_aut} + 45 \tag{23}$$

$$t_{d\_noal} = t_{d\_man} + 15 \tag{24}$$

t_{d_aut} = detection time when the automatic detector works (smoke detector) [s]
t_{d_man} = detection time in the case of manual detection (pressing the button) [s]
t_{d_noal} = detection time when the alarm does not work (a person initiates evacuation) [s]

The ceiling height is assumed not to have any significant effect on the detection time. Even in the case of high ceilings, detection is rapid as people in the building notice the fire quickly.

6.4.4.2 Results from the sensitivity analysis

The results of the sensitivity analysis are presented in Figures 52-57, which show the interval of variation of a risk measure when the input variables are varied separately. This interval is defined as the highest and lowest value of a risk measure obtained by varying each input variable in the sensitivity analysis. The complete set of output from the analysis is given in Appendix G, where each risk measure is plotted as a function of each input variable. The measure *risk profile* is not reported due to practical reasons concerning risk evaluation (developed in Section 6.4.4.5) and reasons of space limitations.

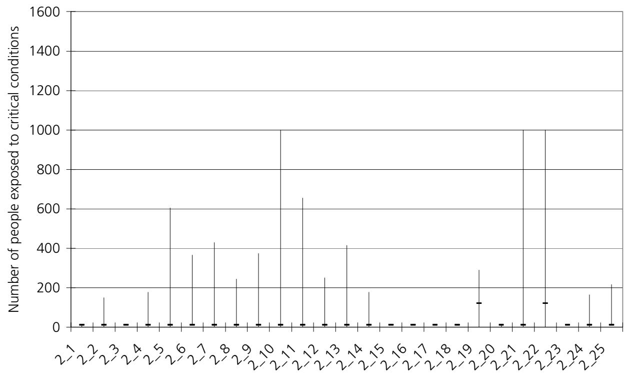


Figure 52. Interval of variation for the risk measure "consequences when all systems function", $C_{all\ work}$.

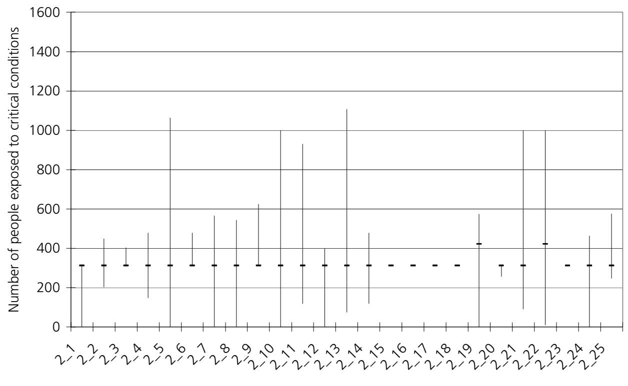


Figure 53. Interval of variation for the risk measure "the maximum consequence when a single protection system fails", $C_{max\ ssf}$.

VARIABLES

Group 1

2_1 Q
2_2 t_{d_aut}
2_3 t_{d_man}
2_4 t_{pre_alarm}
2_5 N
2_6 F_{ME}
2_7 f_{UK}
2_8 f_K

Group 2

2_9 w
2_10 A
2_11 h
2_12 A, N, w
2_13 N, w
2_14 w_{1a}

Reliability

2_15 p_{f_evac}
2_16 p_{f_aut}
2_17 p_{f_man}
2_18 p_{f_exit}

Assumptions

2_19 Q_{wv}
2_20 Fuel type
2_21 Crit. cond.
2_22 Crit. cond. (wv)
2_23 ΔH_c
2_24 χ_{rad}
2_25 ρ_{design}

The variables are defined in Appendix C.

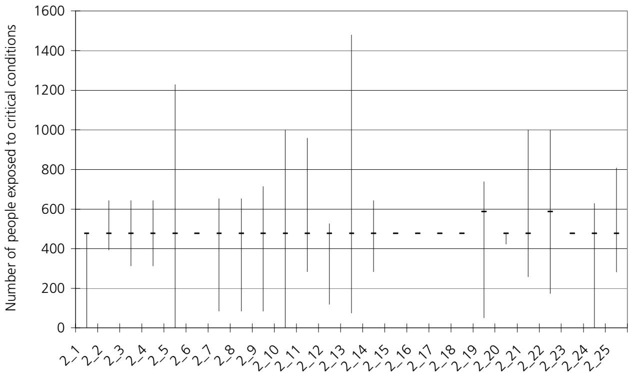


Figure 54. *Interval of variation for the risk measure "worst-case scenario", $C_{worst\ case}$.*

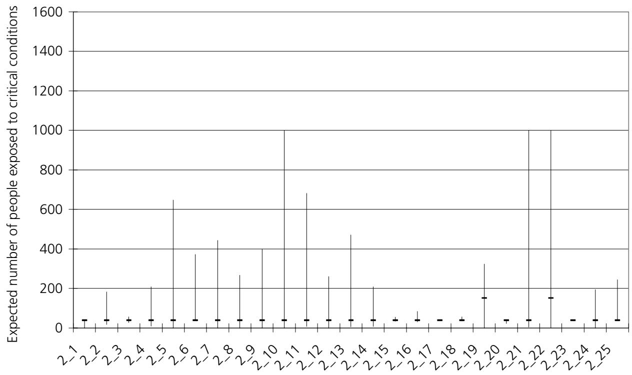


Figure 55. *Interval of variation for the risk measure "mean risk", i.e. the expected number of people being exposed to critical conditions, for each fire, R_{mean}.*

VARIABLES

Group 1

2_1 Q
2_2 t_{d_aut}
2_3 t_{d_man}
2_4 t_{pre_alarm}
2_5 N
2_6 F_{ME}
2_7 f_{UK}
2_8 f_K

Group 2

2_9 w
2_10 A
2_11 h
2_12 A, N, w
2_13 N, w
2_14 w_{1a}

Reliability

2_15 p_{f_evac}
2_16 p_{f_aut}
2_17 p_{f_man}
2_18 p_{f_exit}

Assumptions

2_19 Q_{wv}
2_20 Fuel type
2_21 Crit. cond.
2_22 Crit. cond. (wv)
2_23 ΔH_c
2_24 χ_{rad}
2_25 ρ_{design}

The variables are defined in Appendix C.

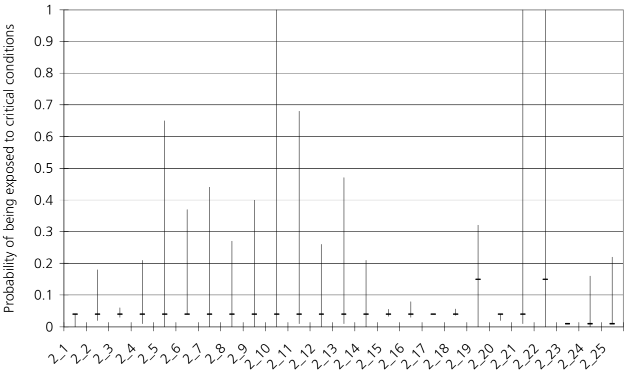


Figure 56. Interval of variation for the risk measure "individual risk", P_{ind}.

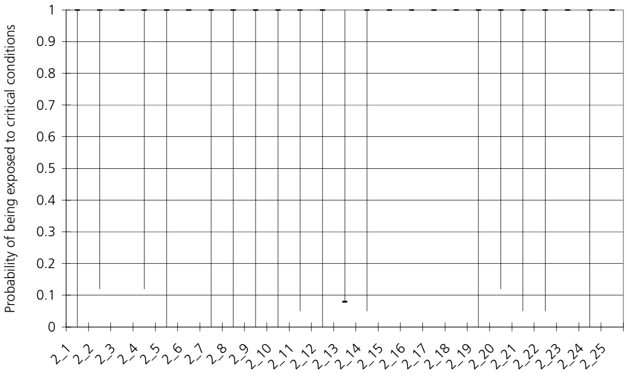


Figure 57. Interval of variation for the risk measure "the risk to the most exposed individual", P_{worst}.

VARIABLES

Group 1

2_1 Q
2_2 t_{d_aut}
2_3 t_{d_man}
2_4 t_{pre_alarm}
2_5 N
2_6 F_{ME}
2_7 f_{UK}
2_8 f_K

Group 2

2_9 w
2_10 A
2_11 h
2_12 A, N, w
2_13 N, w
2_14 w_{1a}

Reliability

2_15 p_{f_evac}
2_16 p_{f_aut}
2_17 p_{f_man}
2_18 p_{f_exit}

Assumptions

2_19 Q_{wv}
2_20 Fuel type
2_21 Crit. cond.
2_22 Crit. cond. (wv)
2_23 ΔH_c
2_24 χ_{rad}
2_25 ρ_{design}

The variables are defined in Appendix C.

The value of the risk measure of the base case is indicated in the variation intervals by a heavy dash, i.e. all variables have this value as a reference value. The reason why these two reference values are different for the variables with indices 2_19 and 2_22 compared to the other variables is because the fire is assumed to be well-ventilated for these two cases. The fire development, and thus the consequences, is affected by the ventilation conditions, which means that the reference values will be affected due to this assumption even if all other variables are the same. A more detailed description of the effects of the ventilation conditions on the fire is given in Appendix A.

6.4.4.3 Analysis of the impact of the sensitivity in the risk calculations

In the calculation of the mean risk, information on the probability and consequences of all scenarios, which can be found in the event tree (see Figure 25), was used, while several of the other risk measures only represent parts of the total risk, e.g. the consequences in a single scenario. The analysis showed that several of the variables of group 1 had considerable effects on the risk measures. This means that the uncertainty that arises from the natural variation of some variables can lead to considerable variation in the level of risk in a building. Other conclusions that can be drawn are that the designer's deterministically chosen values of the variables in the range studied have a significant effect on the calculated risk. Changes in a prescriptive design are likely to affect several of the variables in group 2 studied in the sensitivity analysis. Both the level of risk and the variation in the level of risk can thus increase considerably if the effects of changes are not dealt with correctly to ensure that the level of safety is maintained. Detailed conclusions from the sensitivity analysis used to define the uncertainty analysis are presented in Appendix C.

6.4.4.4 Analysis of the appropriateness of scenario-based risk measures

The choice of risk measure in safety verification is of great importance as differences between proposed designs can affect the risk measures to varying degrees. The sensitivity analysis shows that several of the variables affect more than one scenario in the event tree. It is difficult to discern a clear trend regarding the variations in the scenario-based risk measures, both between the measures and in relation to the mean risk. In order to assess the suitability of each risk measure as a measure of how the total risk changes, a comparison was made with the mean risk. By studying the results from the sensitivity analysis it is possible to see how well the risk measures based on a single scenario reflect the variation in a risk measure representing information based on all scenarios, e.g. the mean risk. This can be of great importance if the risk measure is used as the basis for risk ranking in verification. If the use of a scenario-based risk measure results in a different ranking of two solutions compared with the case when the mean risk is used, this approach to verification must be considered inadequate.

Indications that the scenario-based risk measures can lead to doubtful ranking were found in an analysis of the different scenario-based risk measures in the results from the sensitivity analysis in Figures 52-57. Examples are presented below:

- The mean risk varies, but there is no variation in the scenario-based risk measure. Example: compare R_{mean} with $C_{all\ work}$ for variables 2_1 and 2_3.
- The mean risk is changed from the initial value (i.e. the base case) in one direction (i.e. either increases or decreases) while the scenario-based measure both increases and decreases. Example: compare R_{mean} with $C_{worst\ case}$ and $C_{max\ ssf}$ for variable 2_25.
- The mean risk both increases and decreases compared with the initial value, while the scenario-based risk measure changes in only one direction (i.e. only either increases or decreases). Example: compare R_{mean} with $C_{all\ work}$ for variables 2_1 to 2_5.
- The increase and decrease in the mean risk and the scenario-based risk measure are of different sizes, i.e. the mean risk shows a large increase and small decrease while the scenario-based measure shows a small increase and a large decrease, or vice versa. Example: compare R_{mean} and $C_{worst\ case}$ for variable 2_13, which seem to apply to most of the variables for both $C_{worst\ case}$ and $C_{max\ ssf}$. The imbalance in the variation is caused to some extent by the fact that R_{mean} is low for the base case, and only a limited decrease is possible.

The problems presented above are related to risk ranking of single variables. In fire safety design it is quite common that differences between solutions that are to be compared affect more than one variable. Additional problems occur when risk ranking is based on a scenario-based risk measure if several variables are affected. Considerable differences in the relation between the mean risk and the scenario-based risk measures for the different variables constitute such a problem. In such cases, variables with low correlation to the mean risk may indicate a high variation in the scenario-based risk measure, and vice versa. As a consequence, changes in less important variables may have considerable impact on the risk measure, while important variables show less impact. From a theoretical standpoint this can be dealt with by assigning weights linked to the different variables to the risk measures. However, this kind of meta model generally has a very limited area of applicability, and therefore does not provide a practical solution. Even if such a weighting model could be designed, other difficulties arise. An example is if the variation pattern of the variables is different for a scenario-based risk measure compared to the mean risk, e.g. when the variable that varies the most changes (cf. R_{mean} with $C_{worst\ case}$ and $C_{max\ ssf}$ presented in Figures 53-55).

It should be noted that the single observation made above is affected by the definition of the intervals for the variables when performing the sensitivity analysis. The relations between input variables and the different risk measures are seldom linear, which makes it difficult to predict how the measures will change if the interval is modified. This in itself calls for caution in using the scenario-based risk measures for ranking, since it is almost impossible to discern when the validity of the approach changes.

It was pointed out in Section 6.4.3.3 that the relation between single scenarios and the total risk is dependent on the safety systems included in the solution. As a consequence, if a relation between a scenario-based risk measure and the total risk can be established, it is certainly only valid for that specific building, with that specific safety system.

It is an indisputable conclusion that it is necessary to use a more comprehensive measure than the consequences of a single scenario in order to describe and evaluate risk when solutions are compared (e.g. in trial evaluation). A suitable risk measure must strive to represent all the scenarios that are affected by a change in the fire safety protection as a result of using analytic design. If the consequences of a single scenario are to be used to represent the total risk, it is necessary to *show clearly* how changes in the fire protection affect this scenario only. Such an analysis must be made for each specific case to motivate the use of scenario-based risk measures for risk ranking. To facilitate such an analysis the model presented in Figure 17 can be used to structure the scenarios.

There is no need to investigate whether the observations described apply to all types of buildings. It is sufficient to conclude that scenario-based risk ranking is inappropriate in many cases and its use must be questioned, if its relevancy is not proved valid in a specific case. The suspicion that it is inappropriate to describe the total risk using single scenarios is strengthened (if not over-analysed). However, risk ranking based on single scenarios was the most commonly used approach in analytic design in the cases studied, so alternative approaches must be promoted. A natural choice seems to be between the mean risk and the risk profile.

6.4.4.5 Pros and cons of the mean risk and the risk profile

The risk profile is a risk measure which has been introduced in Section 4.3.3. A proposal of criterion for acceptability of fire risk in buildings linked to risk profiles was suggested as early as in the middle of the 1980s by Rasbash (1984/85), but has not nearly gained the same ground as in for example land-use planning (Ale, 2005) where this type of criterion is a key to societal risk control.

An advantage of the risk profile over the mean risk is that it shows the spread in consequences for the scenarios studied, while the mean risk is a single value and represents an average of the possible consequences. As mentioned in Section 5.3.5 society often deems severe consequences (catastrophes) to be disproportionately worse than indicated by the mean risk. This means that the magnitude of the contribution to the total risk from different scenarios is not proportional to the product of probability and consequence. This in turn also means that the increase in risk is not linear with the increase in the consequences of a scenario, assuming that the probability is unchanged. The increase in risk with consequence is instead exponential. An aversion to severe consequences can be seen in the slope of the acceptance criterion in an *f(N)* diagram, e.g. the risk criterion used in the Netherlands where the slope equals -2 (Vrijling et al., 1995). Although the mean risk does not explicitly take into consideration the distribution of the consequences, it is still possible to account for the fact that severe consequences are perceived as disproportionately more severe than less serious ones. One way in which to impose a "penalty" on scenarios with severe consequences is to use so-called utility functions. It is often difficult to determine in quantitative terms how much serious consequences should be weighted in relation to less serious ones (e.g the risk attitude), but there are a number of approaches available for investigating this (see Section 5.5.4). No general survey of this kind has been made previously for fire safety design, but it may be of interest. The method of risk calculation (see Section 4.3) that has been used to analyse the class of buildings was developed in order to study the effects of using utility theories on risk levels. However, at the present time, there is a lack of information on which attitude to risk is suitable for this kind of analysis. It has therefore been assumed that society has a neutral attitude to risk in the calculations in this study.

Although there are some advantages associated with risk profiles, results of earlier research show several problems in their use in the assessment of risk (Evans & Verlander, 1997) and this concept is seldom used in practical design applications. Examples of unsolved problems are:

- To what should the acceptance criteria be related in design?
- Does the criterion represent the acceptable risk for a whole building?

In the analysis presented in this thesis, the fact that fires occur with different frequencies in different types of buildings was ignored (see (see Figure 21). Furthermore, the probability of a fire occurring is affected by the size of the building (Rahikainen & Keski-Rahkonen, 2004; Rutstein, 1979).

An alternative is to express the risk profile as an acceptance criterion per fire compartment, but this would result in an increase in the total risk being allowed in a building simply if it were divided into more fire compartments. If an acceptable level is determined for a fire compartment of a certain maximum area, a greater area can be acceptable in an alternative design if the level of risk is maintained by introducing one or more risk-reducing measures. The problem with this approach is that restrictions on areas have been removed from prescriptive design when *BBR* was introduced and it would thus cause confusion if they were introduced only in the analytic design method.

Can acceptance criteria be related to single scenarios, for example by specifying a maximum risk contribution? Using single scenarios to represent the total risk is problematic; as is discussed in Section 6.4.3.4. Furthermore, it is always possible to divide the scenario into smaller scenarios thus reducing the probability, thereby reducing the contribution to the total risk from a single scenario. An alternative method may be to consider the frequency of fire in the comparison of risks using risk profiles. The disadvantage of this method is the lack of knowledge on fire frequencies for various kinds of buildings, and on how they are affected by variables such as area, operation & maintenance, etc. There is also a risk that the extent of the analysis will be unrealistically large if the ambition is to include all potential scenarios in the whole building. Despite the presence of several problems, identifying and standardizing scenarios for verification is an approach that should be investigated further. The future development of this approach is discussed in Section 5.5.3.

Another method-related problem in giving an acceptance criterion as a line to which the risk profile is compared is that this may lead to doubtful ranking of solutions in some cases, since a solution is failed if the risk profile crosses the acceptance criterion. An example is presented in Figures 58 and 59. Expressing the acceptance criterion as a line in the diagrams will lead to the solution in Figure 58 being preferred over the one in Figure 59 which is failed, despite the fact that the first solution has a higher mean risk and greater maximum consequences than the second.

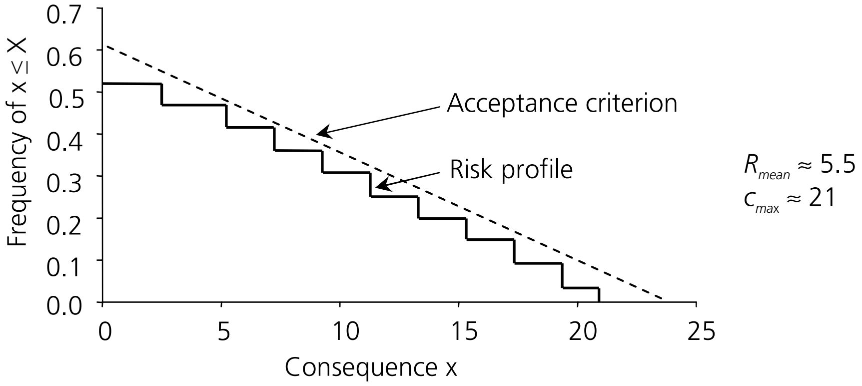


Figure 58. An example of a solution that is acceptable.

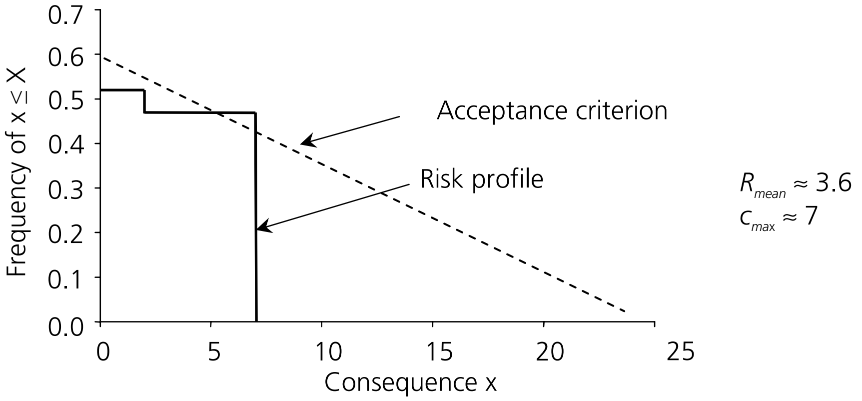


Figure 59. An example of a solution that is not acceptable.

An advantage of the mean risk over risk profiles is that it is simpler to communicate and understand. The concept is common in areas other than fire safety engineering, although the risk levels are not directly comparable between different areas. Another advantage of the mean risk is that it is easier to calculate and analyse than the risk profile. The risk profile contains more information and there are established methods for carrying out uncertainty analysis of risk profiles (Frantzich, 1998). Unfortunately, the results have proven to be difficult to interpret and cumbersome to manage, which greatly limits their practical use.

Neither the mean risk nor the risk profile shows how the risk is distributed among the people in the building. If one individual is exposed to a very high risk, e.g. in a certain part of the building, it will not be clear if the risk to the others is low. Societal risk and individual risk should thus be used as complements to each other as they represent two different perspectives (earlier suggested in Section 4.3.3.3). This distinction is seldom made in the evaluation of fire risks, but bearing in mind the problems mentioned above, there is reason for introducing these risk measures. Both the mean risk and risk profiles have their strong and weak points, and it is not uncontroversial whether one or both of these risk measures should be used.

6.4.4.6 Comments on the sensitivity analysis

The sensitivity analysis shows that there is a considerable difference between how much the input variables affect the variation in the different risk measures studied. In order to determine whether the effect on the risk measure is small or large, the variation must be seen in relation to how much the total risk is expected to vary. The total risk is calculated as the risk assuming a fire occurs, multiplied by the frequency of fire. Of the variables studied, it is expected that the area, for example, will affect the frequency of fire. It is reasonable to assume that fires will occur more frequently in a larger building than in a small one where the activities are the same.

In this thesis no detailed analysis of fire frequency is carried out, but a rough estimate based on the work of Rutstein (1979) shows that the frequency of fire varies almost linearly with the area for the type of building considered here, which is also supported by Rahikainen and Keski-Rahkonen (2004). The frequency of fire for a building with an area of 2000 m^2 is expected to be about ten times higher than for a building of 200 m^2, which corresponds to the interval over which the area is varied in the sensitivity and the uncertainty analyses (see this section and Section 5.4.1). The estimate of fire frequency is very rough as Rutstein's data were collected during the middle of the 1970s, and even then were considered to be uncertain. However, they provide some indication of the magnitude and variation. It can be seen from Figure 57 that for some parameters the mean risk varies by a factor of 50 compared with the reference value. This gives an indication that the variation is important, and not negligible in relation to the uncertainty in the fire frequency. In order to improve the picture of the variation in the total risk, it is necessary to perform a more accurate study on the factors apart from area that affect the frequency of fire, e.g. the kind of activities, the age of the building and the quality and execution of operation & maintenance plans.

As a conclusion the results indicate that the high degree of freedom of the designer can lead to considerable variation in the conditions for determining whether a solution is acceptable or not. This means that societal risk control is seriously threatened. As it will be difficult to review whether the regulations are being adhered to, it cannot, at present, be ensured that inadequate solutions will be revealed. It must be made easier to identify unsuitable solutions. If an arbitrary approach is used for verification this could lead to considerable national variation in actual safety, which is in direct conflict with one of the most important reasons for introducing the new building regulations. There is thus great need for clarification of the regulations and formulation of regulations in such a way that they can be verified and the degree of freedom of the designer reduced. Specific suggestions are presented in Chapter 9.

6.4.5 Risk contribution from serious scenarios

A serious scenario is defined as one that leads to a large number of fatalities. Apart from the fact that when using prescriptive design the risk varies unacceptably, it was found in both the sensitivity analysis and the uncertainty analysis (Section 5.4.1) that the contribution to the total risk from scenarios that can be classified as serious cannot be neglected in verification. The sensitivity analysis shows that the effects of different variables differ considerably depending on which scenario is studied. The number of people in the building and the corresponding exit width according to prescriptive design (variable 2_13) has very little effect on the consequences of the scenario when all the systems function (see Figure 52), but a very large effect on the consequences when all system fails, i.e. the worst-case scenario (see Figure 54). This is also the case for several other variables, e.g. the occupant flow through escape routes.

Fires starting in adjacent rooms have, on many occasions, claimed many victims. This conclusion is supported by both the risk analysis and actual fires (SHK, 2001). Statistics show that during the past 30 years several accidents have occurred leading to severe consequences. Table 14 lists a number of those in which fatalities occurred in assembly halls. Several of the most serious fires had the following points in common.

- The fire started in an unoccupied, adjacent room.
- The fire grew large in this room, which either lacked detection or extinguishing systems, or they failed to operate.
- When the initial fire had broken through the fire safety barrier or other compartmentalization, or when a door was opened, the spread of smoke to the main room took place very rapidly. The progress of the fire was, in many cases, aided by combustible surface materials.
- One or several escape routes were inadequate, locked or blocked, either by contents in the building or by smoke early in the fire development.

Too far-reaching conclusions must not be drawn from these events. All the underlying causes are not known, neither has the condition of the fire protection system before the fire been analysed. In many other cases, the fire protection has worked as it should in this kind of building, but the fact still remains that the catastrophes in Table 14 represent scenarios where not all the fire protection measures worked as intended. The course of events thus led to more serious situations than would normally be studied in verification. If such scenarios are not included in verification, it is likely that protection against serious fires will deteriorate when analytic design is applied relative to when prescriptive design is used. Some level of protection against catastrophic fires is inherent in the prescriptive design method (see Section 6.3.2.2), which is not necessarily the case for analytic design method.

Table 14. Serious fires in assembly halls leading to fatalities over the past 30 years (NFPA, 2004a; SHK, 2001; Times, 2005).

Year	**Place**	**Number of fatalities**
2005	Theatre Cultural Palace, Beni Suef, Egypt	42
2004	Cromagnon Republic club, Buenos Aires, Argentina	180
2003	E2 Night Club, Chicago, USA	21
2003	The Station Nightclub, West Warwick, USA	100
2002	Saigon Int. Trade Center, Ho Chi Minh City, Vietnam	61
2002	La Goajira Nightclub, Caracas, Venezuela	47
2002	Night Club, Lima, Peru	25
2002	Saigon International Trade Center Restaurant, Vietnam	33
2001	Mah-Jongg Club, Tokyo, Japan	44
2001	Little Heaven café, Volendam, Netherlands	10
2000	Discotheque, Luoyang, China	309
2000	Lobohombo nightclub, Mexico City, Mexico	20
2000	Cinema, Jiaozuo, China	74
1998	The Macedonian Society, Göteborg, Sweden	63
1996	Rhein – Ruhr Airport Dusseldorf, Germany	16
1996	Ozone Disco Club, Quezon City, Philippines	160
1995	Weierkang Club, Taichung, Taiwan	64
1995	Karaoke Club, Urumqi, Xinjiang province, China	51
1994	Zwitel Hotel, Antwerp, Belgium	15
1994	Nightclub, Fuxin, China	234
1990	Happy Land Social Club, New York, USA	87
1990	Discotheque Flying, Zaragoza, Spain	43
1983	Discotheque Alcalá, Madrid, Spain	81
1981	Discotheque, Stardust Club, Dublin, Ireland	48
1978	Discotheque Stadt, Borås, Sweden	20
1977	Beverly Hills Supper Club, Kentucky, USA	165
1976	Club Puerto Rico, New York, USA	25

The risk contribution from fire type 2 (defined in Section 4.4.2) is deemed to be so high that this type of fire cannot be neglected in verification, despite the fact that the probability of fires of type 1 and type 2 has not been investigated in detail in this work. A simple solution to the problem is to use somewhat more serious scenarios (e.g. fires of type 2) as points of reference in risk comparisons (see Section 6.4.4.6). There is no reason to demand increased protection against serious scenarios for the class of building discussed here, on the other hand, nothing indicates that this protection is not necessary and can be reduced. Therefore, in order to verify that the protection afforded using analytic design is as good as, or better than, that with prescriptive design, it is necessary that the protection against catastrophic fires must be included in the verification.

6.5 Solutions and need for development

In an attempt to highlight some of the quality concerns presented in the previous sections (Sections 6.3 and 6.4) a number of tools were developed in order to assist the designer in determining the need for verification in a systematic way when analytic design is used (Section 6.5.1). Today, there is no general method of verification as needs vary greatly from case to case, depending on the building, the way in which the designer chooses to implement fire protection, and the effect this has on the total safety. In order to approach the problems of verification in a systematic way, these tools can be regarded as components in a process of verification. Section 6.5.2 presents an outline of how such a procedure may be carried out, based on several of the tools and methods presented in this thesis. Finally, a proposal is made regarding a simple tool that can be used to identify projects where the need for verification is high, so that the appropriate need for design review can be determined by building officials (Section 6.5.3).

6.5.1 Tools to identify verification requirements

It has been concluded by Kaplan et al. (2001) that it may be impractical to represent all aspects of a large-scale system by a single model when performing risk assessment. This is probably also true when evaluating fire safety designs with risk assessment. A single model rarely covers multiple objectives and the different phases of fire development, and can rarely be used to analyse all the relevant fire and/or smoke spread routes in a building (see the ISO-document Fire Safety Engineering – Part 6: Structural response and fire spread beyond the enclosure of origin (ISO, 1998b) for major examples). Furthermore, it is imperative to consider multifarious aspects of the protection system when evaluating equivalent safety. At the same time, it may be difficult to avoid overlap between different models when analysing the safety aspects of a system. However, a modest amount of overlap can be tolerated, in order to reduce the likelihood of important aspects being overlooked (Kaplan et al., 2001). Therefore two additional supplementary matrix tools are suggested in Sections 6.5.1.1 to 6.5.2.1, which highlight different aspects of the effects of trade-offs on fire safety, in addition to the matrix presented in Section 5.5.5.

The tools are not verification methods in themselves. By using the tools the designer can obtain input to determine the magnitude of the trade-off and *what* the verification analysis must cover, by obtaining knowledge on how the fire protection system will be affected. It is not claimed that these tools are complete, and they can not be used to obtain a "go/no-go" decision in trial evaluation, which may limit their practical use. These tools should be seen as support in systematic hazard identification to define the relevant scope of the verification analysis and to detect potential flaws in solutions. This will indicate where further risk analysis is needed in order to verify that the level of safety is acceptable and the appropriate scope and objective of such analysis. The tools provide an overview of the verification problem, and it might be necessary to develop more complex tools for specific purposes. The tools are listed below and described in the following sections.

- *A tool to analyse the structure of the fire protection system in the building (Section 6.5.1.1).* This is a tool to identify which part of the fire safety strategy is affected by a trade-off. This is done by analysing the structure of the total fire protection system in the building and the impact when the system is changed.

- *A tool to analyse the purpose of the performance requirements (Section 6.5.1.2).* In building legislation and building regulations the purpose must be well understood to ensure that the demands of society in terms of fire safety are fulfilled. If several functional requirements are affected by the trade-off, several analyses may be needed, and different design scenarios and acceptance criteria may be required. This tool is used to establish the various cause-effect relations between each safety measure and the demands in the building regulations.

These matrix tools will be applied to a real world example in which a simple trade-off is made for illustrative purposes. The prescriptive design is used as a reference case to define the acceptable level of risk according to the building regulations. A brief description of the example is given below.

A developer has been engaged to remodel an industrial building with few occupants and low fire load into a three-story office building. The original load-bearing structure was made of unprotected steel, which was not controversial since the structural requirement for the original type of building was low and the probability of a fully developed fire was also low. The owner of the building intends to make extensive changes to the layout by adding two floors. The architect wants to retain the unprotected steel beams in the roof, see Figure 60. According to the requirements of the Swedish Building Regulations (*BBR*, 2002) the demand for fire resistance in three-story office buildings is 60 minutes, according to the ISO-curve (1975) or complete burnout. The unprotected steel does not meet these requirements but, as mentioned earlier, was sufficient for the original premises.

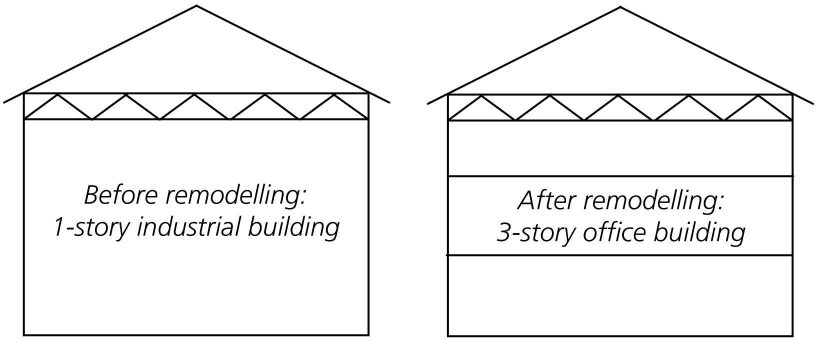


Figure 60. Layout before and after the remodelling of the industrial building.

A fire protection engineer is hired as a sub-designer to prove that a sufficient safety level can be achieved without protecting the load-bearing system if an evacuation alarm with smoke detectors is installed. The designer's verification is carried out with enclosure fire dynamics calculations and simulation of the evacuation time, limited to pre-flashover conditions in the fire room. The time to reach critical conditions is compared with the evacuation time, and it can be shown that the employees can leave the building before critical conditions occur. The smoke temperature is calculated to show that the load-bearing capacity of the steel beams is sufficient, at least for the period of time required for evacuation. According to the fire protection documentation this is sufficient to prove that the level of fire safety has not been reduced. Equivalent safety has been established, or has it?

The verification procedure described above has several weak points. The designer's analysis is limited to pre-flashover conditions but, according to the performance requirements in the building regulations it is clear that the structure must withstand both a post-flashover fire and a localized fire. No arguments are presented that a fully developed fire would not occur in this type of building, which could be used to question the relevance of designing for a fully developed fire. One important purpose of the requirement on the load-bearing capacity is to ensure the safety of the members of the fire and rescue service, since they assist in evacuation and must be able to extinguish or control the fire. No effort was made to verify that this feature of the fire protection system was not reduced when the trade-off was made. In this case, the trade-off affected several safety goals, but only the impact on technical requirement was analysed. The result of this was serious since the safety of the members of the fire and rescue service was clearly reduced.

6.5.1.1 A tool to analyse the structure of the fire protection system

In order to analyse the impact of a trade-off on the fire protection system a number of important questions must be asked. Examples are:

- What type of risk did the measure aim to reduce or eliminate, and how?
- What was the aim of the measure, and was this achieved in combination with other measures?

Here a tool is presented that could be used to design cases like the one described in the Section 6.5.1. The application of the tool to the remodelled industrial building is exemplified in Table 15. The purpose of this matrix tool is to visualize the type of risk-reducing measures that have been removed or added as a result of the trade-off. The designer starts by defining which safety measures are required according to the prescriptive method. This solution is then compared with the solution suggested by the designer to identify non-compliances and trade-offs. The matrix consists of a number of columns for measures added and for measures removed. Each column has an index. The number of columns is defined by the number of measures added and removed. The type of protection provided by the measure is indicated in the appropriate row in the column corresponding to the measure's index.

Table 15. A tool to identify the effects of trade-offs on the structure of the fire protection system when a solution is compared to the prescriptive requirements.

Type of safety measure	**Purpose of the fire safety measure (linked to performance requirements in *BBR*)** Index no.	**Trade-off**					
		Added measure			Removed measure		
		A_1	A_2	…	R_1	R_2	…
Hazard mitigation	Protection against the outbreak of fire						
Exposure reduction	Protection against the spread of fire inside a fire compartment						
	Protection against the spread of fire and smoke between fire compartments						
	Protection against the spread of fire between buildings						
	Fire fighting facilities						
Effect reduction	Escape in the event of fire (escape-supporting systems)	+[1]					
	Load-bearing capacity in the event of fire				–[2]		

Added or improved measure: A_1 = smoke detectors and evacuation alarm
Removed or reduced measure: R_1 = load-bearing capacity

Comments:

[1] An evacuation alarm with smoke detectors (A_1) will result in earlier detection by the occupants and presumably a shorter time for them to leave the building.

[2] The unprotected steel will result in reduced fire resistance of the load-bearing system (R_1) compared with the legal requirements. The trade-off will have no other obvious effect on any other type of risk-reducing measure.

The information in the matrix will not give an automatic pass or fail answer, but several conclusions can be drawn. By regarding the vertical spread in the position of the + and – signs it is easy to determine whether the trade-off affects one or several types of safety measures. If the spread is significant, the original safety measure is likely to have been replaced by another type of risk-reducing measure; hazard mitigation, exposure reduction or effect reduction. This calls for an extensive analysis, since the structure of the protection system has been modified. It is necessary to check that the new safety measure provides protection for all the safety objectives covered by that removed. For example, if compartmentation, which prevents fire and smoke from spreading, is replaced by an evacuation alarm, several design objectives which *were* addressed may no longer be addressed, e.g. the protection of a load-bearing system or the safety of the fire and rescue service personnel. If the measure replaced formed an integral part of the protection system and contributed to the protection of several safety objectives, extensive verification is necessary to ensure that the new measure can provide the same performance from a system point of view.

If there is imbalance between the total number of + and – signs in the vertical direction the numbers of independent barriers, i.e. the defence in depth, is likely to be reduced. The fire protection required by the prescriptive method is generally designed with defence in depth in mind, which results in a combination of measures aimed at hazard mitigation, exposure and effect reduction. A vertical spread in the signs also indicates that it is important to check whether measures with multiple purposes have been removed without adequate compensation.

If there is imbalance between the total number of pluses and minuses in the horizontal direction or in the horizontal and vertical directions, great care must be taken. This is an indication that the protection relies on a smaller number of safety measures, and that the risk of common-cause failure has increased. Each single reduction may appear negligible, but together, they can have serious implications on safety. For example, installing a sprinkler system is sometimes used to reduce the protection of a number of independent safety measures, e.g. the ventilation system, lower rated surface material, reduced compartmentation, longer travel distances to escape routes, etc. Each of the replacements may be considered appropriate when studied in isolation, but the total effect must be evaluated. What would happen if the sprinkler did not work? Is this acceptable or not? These questions can not be neglected if risk control is to be ensured.

The outcome of the verification analysis is very sensitive to the selection of scenarios and the scope and complexity of the analysis. In practice the magnitude of these issues varies from project to project and probably occurs because ad hoc methods rather than standard methods are used to make choices about which hazards and scenarios are worthy of consideration in the verification.

6.5.1.2 A tool to analyse the purpose of the performance requirements

Another important aspect in identifying verification requirements is that the purpose of the performance requirement affected by the trade-off is well understood, otherwise it is difficult to choose models and criteria that measure the effect on the safety appropriately.

A tool with this purpose is presented as a matrix in Table 16. The tool can be used to assist the designer in identifying the impact of the trade-off on the safety goals represented by the functional requirements. The aim of this tool is to elucidate whether the added and removed measures have effects on several functional requirements, which is an indication of multiple purposes of a performance requirement.

The tool has been applied to the example described in the beginning of Section 6.5.1. This tool is used in a similar way to the matrix tool presented in Section 6.5.1.1, but no trade-offs between the different functional requirements are allowed. If a minus sign appears without any plus sign for a functional requirement this must be interpreted as a warning. Then it is possible that the safety effect of the measure removed has not been adequately compensated for. If the plus and minus signs imply that both reduction and compensation have taken place, verification should be focused on showing that the replacement measures are sufficient to ensure the same safety level as before.

There is an obvious need to verify that the positive effect on egress safety due to the evacuation alarm compensates for the reduced safety due to the reduced load-bearing capacity. A quantitative analysis of the egress time and time to collapse is suitable for such a comparison. The tool shows that the reduced load-bearing capacity will lead to reduced safety of fire and rescue service personnel without any compensation from the added safety measure. The need for safety of the fire and rescue service is not reduced by the trade-off. Verification of the overall safety must include an extensive analysis of the consequences of this aspect of the trade-off. It is likely that other safety measures may be required to safeguard fire and rescue service personnel.

Table 16. A tool to investigate the effect of removed and added safety measures on the functional requirements.

Functional requirements / statements (*BVF*, 1994)	**Trade-off**					
	Added measure			Removed measure		
Index no.	A_1	A_2	…	R_1	R_2	…
The load-bearing capacity in the case of fire is endured for a certain period of time				–[2]		
The outbreak and spread of fire and smoke within the building is limited	(+)					
Fire spread to adjoining buildings is limited				(–)		
People in the building can escape from the building or be rescued in some other way	+[1]			–[3]		
Consideration is given to the safety of the personnel of the fire and rescue service				–[4]		

Added or improved measure: A_1 = smoke detectors and evacuation alarm
Removed or reduced measure: R_1 = load-bearing capacity

Comments:

[1] Since the smoke detectors and evacuation alarm (A_1) will shorten the time required for the occupants to leave the building, these will have a positive effect on the safety of the occupants.

[2] The load-bearing capacity will be reduced (R_1) since the beams are made of unprotected steel.

[3] Due to the reduced load-bearing capacity (R_1), falling construction elements can threaten the occupants during evacuation.

[4] The safety of fire and rescue service personnel is reduced (R_1).

It must be stressed that Tables 15 and 16 are not risk analyses in themselves, but rather tools to analyse the extent and objectives of the risk analyses. A destructive building fire developing from ignition to building collapse represents a complex sequence of events. When modelled by an event tree, the final impact of adding or removing a protection component will depend on when in the chain of events the component is expected to influence fire growth and spread in the building. Direct evaluation by counting the pluses and minuses is thus an oversimplification. The + and – signs are not unambiguous without specifying the extent to which secondary consequences are considered and the time frame of the fire development considered. In the example presented in Table 16 a possible + is indicated by brackets since a quick alarm to the building's occupants and/or the fire and rescue service can lead to fire doors being shut and limitation of the spread of smoke and fire. At the same time, the risk of the fire spreading to adjoining buildings may increase if the structure collapses, which is indicated by (–).

6.5.2 Development of a generic and comprehensive procedure for verification

At present, verification resembles a patchwork of different operations, procedures and processes. We should therefore strive towards a more comprehensive and integrated process, which can also serve as a checklist. The development of a uniform or standardized design and/or verification method is one way of making it possible to control the safety in buildings with rules on this level of risk intervention, as rules can be issued that the method must be used. Such a demand means that the design procedures would be regulated more strictly than it is today, without placing demands on technical solutions. The potential for the development of such a standardized verification method were discussed in Section 5.5.3, but would also have impact on this level of risk control. This type of design method would provide a link between *safety output* and requirements placed on the risk analysis method used as a *safety procedure* in this section.

However, such a standardized method is not yet ready for implementation. Both the size of the trade-off that the suggested design constitutes compared with the fire protection system as a result of prescriptive design and the design of the building affect the need for verification. The extent of the analysis required for verification in order to determine how the total safety has been affected varies greatly, and must be decided in each case. An unnecessarily complicated analysis will be too demanding of both resources and money, while a minimal analysis may mean that it is not possible to estimate how the safety has been affected. Figure 61 illustrates how the various tools developed in this study can be connected in the process of analytic design to form a procedure for verification. The main purpose of this procedure is to ensure that key issues have been addressed in a transparent way, but it will not guarantee scientific or mathematical validity in itself.

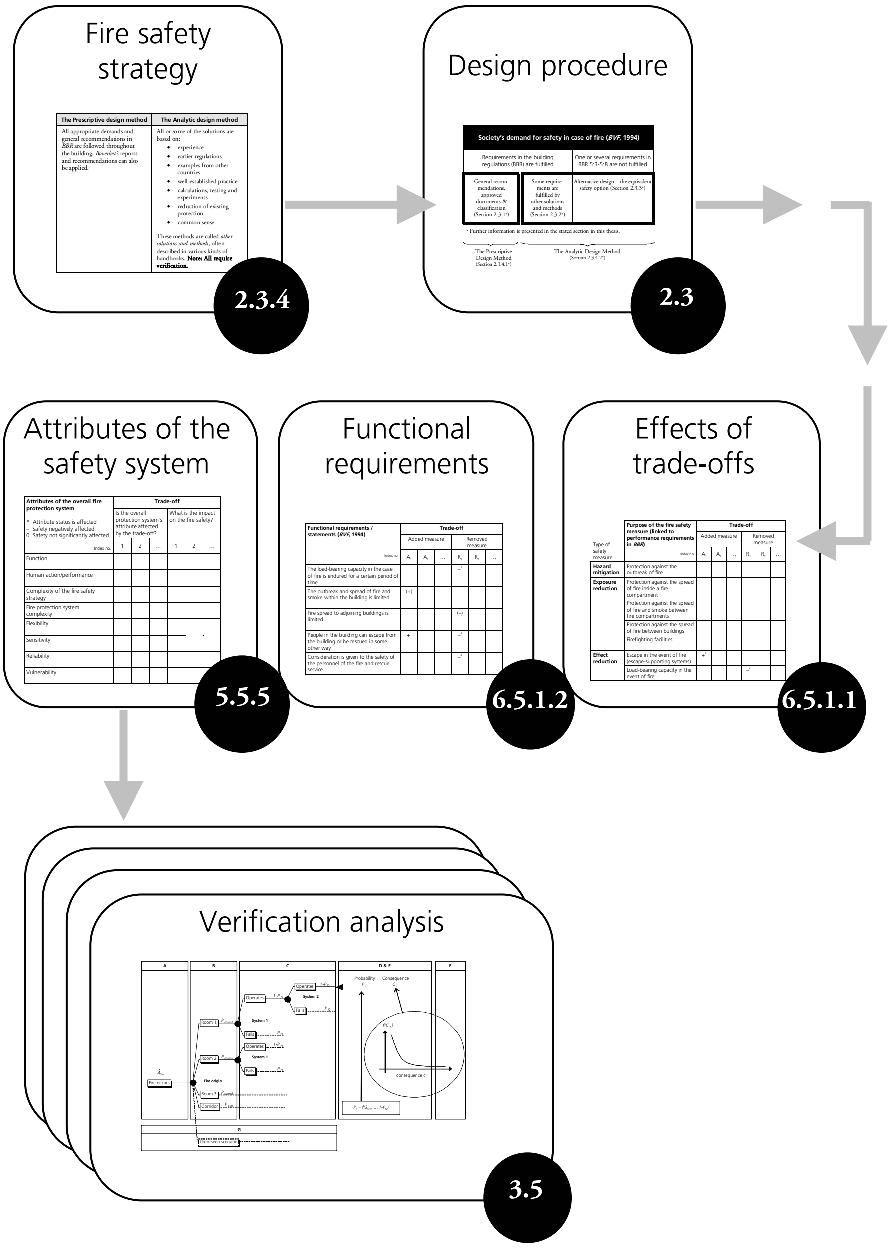


Figure 61. The process of analytic design as a generic procedure for verification.

A short description of the various parts is given in Sections 6.5.2.1 to 6.5.2.4, together with references to the sections in this thesis where they are described in more detail. These references can also be found in the black circles in Figure 61.

6.5.2.1 Deriving a fire safety strategy or fire protection solution

The suitability of a fire protection solution can be affected by many factors, and is often governed by the demands of the building owner and architect. In analytic design, there are essentially no restrictions on the method or approach used to derive the solution. However, verification must be performed, regardless of the method used to derive a fire protection system or a solution. The only exception is when prescriptive design is used (see Table 2 in Section 2.3.4).

6.5.2.2 Design procedures used to fulfil the regulations in BBR

At the design phase, the point of departure is often prescriptive design, but by using other solutions and methods to varying degrees parts of the fire protection system will be changed. Analytic design is regarded as changes in the fire protection system compared with the system that would have been designed using prescriptive design. An analysis of the parts of the prescriptive design that are not fulfilled is thus a natural step in reviewing the extent of the changes and their effects (see Section 2.3).

6.5.2.3 Analysis of the need for verification

Exactly *what* should be verified is affected by the extent of the changes in the fire protection system in an analytic design compared with prescriptive design, and the complexity of the building. The effects of changes in the fire protection system on fire safety must be identified through analysis in order to determine what must be studied in the verification process (see Sections 5.5.5 and 6.5.1). Note that different event tree analyses are likely be required, depending on the requirements on the verification analysis, e.g. the objectives of the performance requirements affected, the hazards necessary to study, the extent to which secondary consequences are considered, the time frame of the fire development, etc.

6.5.2.4 Verification analysis

The aim of verification is to demonstrate that the level of safety of the new solution is as good as, or better than, that which would have arisen from prescriptive design, or if all the relevant regulations in *BBR* had been fulfilled. The extent and method vary from one case to another, but is it suitable to use a general method of risk analysis, such as the event trees, to organize the analyses. In order to be able to make statements on the effects of safety, all the scenarios affected by the changes must be included (see Section 3.5). This analysis determines *how* the verification should be carried out. After this step handbooks and guidelines, e.g. SFPE Handbook (NFPA, 2002), BSI guidelines (2001) and International Fire Engineering Guidelines (IFEG, 2005), can be of great importance to model the consequences and probabilities in appropriate ways.

6.5.3 A simple tool to determine the need for design review

In despite of how sophisticated procedures that are suggested for verification external review will always be necessary, since the subjective judgement of the designer will still be a major source of uncertainty. The purpose of the tool presented in this section is to elucidate and help structure the design review problem, and also to offer a systematic approach to identifying the need for design review. The aim is to assist the designer and/or the building committee to determine the level of design review required to ensure high quality in analytic design based on fire safety engineering analysis.

In this section a matrix based on indicators is presented to assist the decision maker, see Table 17. The first step is to determine what type of design procedure has been used. There is no established relation between the verification requirements and the design procedure, i.e. the type of trade-off made, but when trade-offs are made according to the *alternative design* procedure the potential for flawed design is greater than when *other technical solutions and methods* are used (see Section 2.3). A number of indicators are used to identify the appropriate level of review. These indicators have been derived by studying the underlying problems causing the flaws in fire protection documentation investigated (c.f. Section 6.3.1). The different levels of design review are presented in Table 18.

In the matrix presented in Table 17 there is a column for each design procedure. When the appropriate column has been selected the list of indicators in the left column is evaluated. Each indicator is assigned a number representing the required level of review for the different design procedures. The decision maker then identifies which indicators apply to the design in question, examines them and then chooses the highest level of review given by these indicators. The matrix is followed by brief descriptions of the indicators.

Table 17. The level of design review depending on the design procedure and indicators.

	Design procedure		
Indicators	Prescriptive Design	Analytic design	
		Other technical solutions and methods	*Alternative design*
"Starting point"[I]	1	2	3*
Several and/or dependent safety measures are affected[II]	2	3*	3*
Complicated building with innovative solutions[III]	N.A.	3*	3
Uncomplicated building where traditional solutions are used[IV]	1	2	2
When a trade-off which affects multi-purpose requirements is made[V]	1	3*	3*
When design review is specifically required in the building regulations[VI]	N.A.	3*	3*
The maximum consequence is more severe after the trade-off[VII]	2	3*	3*
Common practice is used to verify the solution[VIII]	N.A.	3	3

N.A. Not applicable. The wrong design procedure has been chosen for the project in question.

* The level of review can be reduced by one step if the engineering company has a well-documented quality control system in use.

Description of the indicators presented in Table 17:

I. The starting point is the basic need for review for the different design procedures, based on the expected complexity and common knowledge of the solutions. For example, the requirements are higher for analytic design than for a prescriptive design. If an alternative design is used new design concepts are often introduced, which require careful investigation of how the total fire safety strategy is affected. Therefore, the basic level of review must be high, so that important aspects are not overlooked.

II. When several safety measures are affected by a trade-off the impact on the overall safety is considerable. There is a risk of hidden effects since the measures can have multiple purposes and fulfil multiple safety goals. It may be difficult for the designer to interpret how the protection system is affected by the trade-off and how this in turn affects the safety level. If several safety measures are replaced by a single one, the risk of common-cause failure is obvious.

III. Complicated buildings are defined as those buildings where there is a lack of tradition and experience. Prescriptive solutions can sometimes be questioned in these types of projects; often large buildings where the protection systems are integrated with other systems in the building. If new solutions are applied the degree of design complexity increases and with it the probability of error.

IV. If the requirements for evacuation safety are low and the building uncomplicated the design problem is normally well understood. Therefore, a lower level of review can be accepted.

V. If a safety measure has multiple purposes a higher level of review is necessary, by the same reasoning as in (I) above.

VI. If there is a specific requirement for design review in the building regulations the level of review should be high. It is important to check that the design review is carried out. Such a review consists of checking design assumptions, construction documents and calculations. It is not sufficient for the designer to refer to handbooks, codes of practice, tradition or former regulations.

VII. If a trade-off is made such that the consequences of system failure increase, there is reason to review the verification in detail. Risk aversion in Western society is high and the acceptance of serious accidents very low.

VIII. When common practice that is not well founded is used to verify a solution there is an obvious risk that the designer will use the same approach to verification and documentation as when prescriptive design is used. This often leads to inadequate verification, review and documentation.

Table 18. Different levels of review of the designer's verification.

Level of review	Description
1.	Self check – The designer is responsible for his or her own quality control.
2.	Internal review – Another designer with at least the same level of competence performs the quality control. This person may work for the same company as the original designer.
3.	Third-party review – The person performing the peer review should work for another company so as to be considered unbiased. This person should not have been previously involved in the design project.

A well-documented quality control system (referred to in key * in Table 17) is a quality assurance system that has been certified according to a quality standard, e.g. ISO 9001 (1998a), or a quality control system in a company that safeguards quality by:

- working actively with quality issues in the design process,
- having sufficient numbers of engineers employed so that the reviewing engineer does not take an active part in deriving the design solutions, and
- ensuring the competence level of the designer by certification and/or an appropriate university degree.

In addition to the complexity of the building and the design, and the formal quality control system of the company, the building committee must assess whether the design team has adequate competence, i.e. whether they have the appropriate knowledge of:

- the uncertainties involved,
- the regulatory system,
- the appropriate analysis tools in the specific situation, and
- how the conditions for the fire protection systems vary during the lifetime of the building.

Even if there may still be problems associated with subjectivity when applying the tool presented, one should not forget that the whole analytic design process is characterized by a high degree of subjective influence today. As long as we use risk assessment in the evaluation of trial designs for specific buildings, subjective judgment will be present (Lundin & Johansson, 2003; Johansson, 2003). It is important to remember that the building committee has the opportunity to perform spot checks on technical solutions when appropriate, but this is not their standard means of safeguarding quality. Situations can also occur when a spot check is appropriate, but the competence of the building committee for the specific project may be too low. In such a case the appropriate competence must be hired on behalf of the building committee.

This chapter have focused on the level of intervention in risk control denoted *safety procedures & safety case*. The following chapter (Chapter 7) deals with the third level of risk control, i.e. *direct risk control*.

7 Specifying rules for direct risk control

Direct risk control is the third level of risk control in the framework originally presented by Hopkins and Hale (2002), see Figure 62. On this level detailed rules for the execution of tasks are specified and freedom of decision at this level is thereby reduced. Regarding fire safety design, the regulations on this level of control consist of detailed demands for specific protection systems such as fire alarms, sprinklers or alternative escape routes, but may also involve architectural limitations on the building, e.g. the maximum walking distance to an exit.

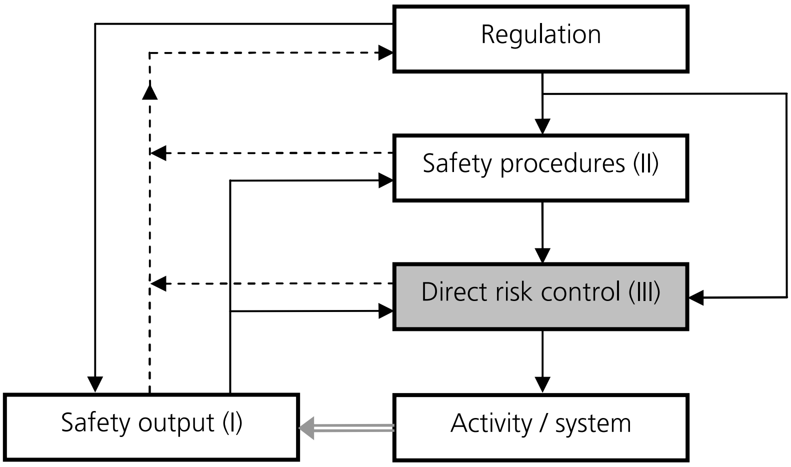


Figure 62. "Direct risk control" defines a level of risk intervention by which regulations can control safety in case of fire in construction works by placing demands on technical solutions.

This chapter is organized in the same way as Chapters 5 and 6 with the structure presented in Section 4.1. After a brief introduction, a short overview of the effects on rules for *direct risk control* of the fire protection of construction works due to changes in the building regulations are given (Section 7.1). A similar overview of how assessment of compliance with the regulations for *direct risk control* has been affected is presented in (Section 7.2).

Following this, problems and dilemmas identified at this level through the survey of fire protection documentation are discussed (Section 7.3). The effects of some of these problems on the ability of society to control fire safety in buildings are then addressed in Section 7.4.

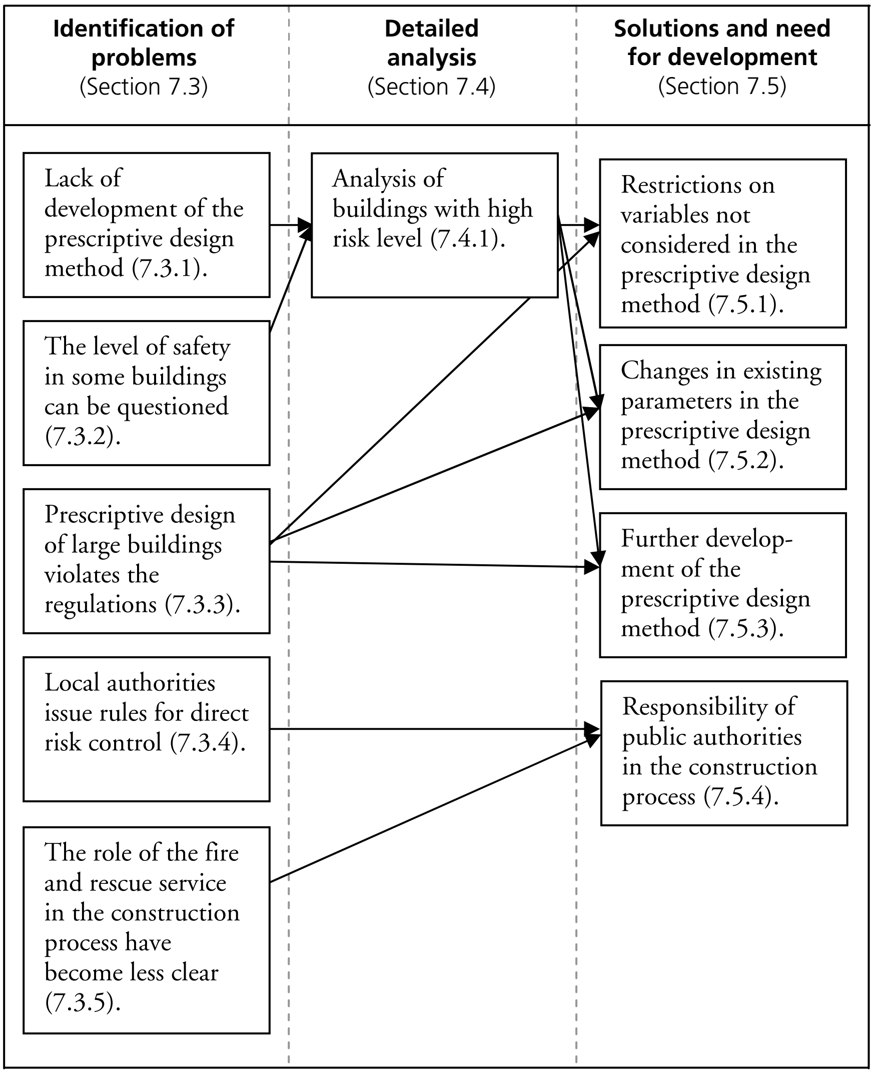


Figure 63. The structure of Sections 7.3 to 7.5 (see Section 4.1).

Finally, various strategies for dealing with some of these problems, together with specific suggestions for solutions, are given in Section 7.5. To clarify the structure of this chapter the links between the different sections are illustrated in Figure 63.

7.1 Changes in rules for direct risk control (see Table 4)

One of the major motives with introducing the performance-based building regulations *BBR* was to move away from detailed rules of *direct risk control* in the regulations. The former building regulations *NR* (1988) contained detailed *deemed-to-satisfy* requirements on technical fire protection systems and design restrictions on the building. Fire safety was thus controlled almost exclusively at this level of control. Changes in regulations actually began during the shift from *SBN* 80 (1980) to *NR* (1988), in that the number of detailed requirements was reduced and some demands were formulated as performance demands. The status of these remaining detailed requirements has changed significantly after the introduction of *BBR*, but they are still important in many ways from a design perspective. Instead of being stated as mandatory provisions in the regulations they are issued as general recommendations on how to fulfil the performance requirements in the code for most types of buildings, and constitute the prescriptive design method, i.e. one of two design methods that can be applied (see Section 2.3). The fire protection resulting from these recommendations is often used as a starting point in the design process even when analytic design is used. For uncomplicated buildings, such as dwellings and some types of industrial buildings, this may be the most effective form of design, taking the total cost of fire safety design and fire safety measures into account.

If detailed solutions not sanctioned by *Boverket* are used in design, verification according to analytic design must be carried out (see Table 2 in Section 2.3.4), since these solutions are not general recommendations. As a consequence it is difficult for organisations other than *Boverket* to issue general guidelines including detailed solutions. For such guidelines to be easy to use, i.e. the designer does not need to verify design solutions using calculations, the detailed solutions in the guidelines must already have been verified. General verification of technical solutions in different situations where the conditions are not known is difficult, if not impossible. The fact that there are shortcomings in the verifiability of performance demands creates further problems when trying to establish new solutions for *direct risk control.*

7.2 Changes in procedures for assessing compliance with the regulations (see Table 4)

The degree of checking compliance is of course low at this level in both *BBR* and *PBL,* since few demands are issued at this level, according to Section 7.1. Detailed control of the technical solutions should first and foremost be carried out within the framework of the developer's own verification, i.e. documented self-implemented control.

Before the changes in building legislation, the building committee checked compliance to current building regulations in detail. Designers turned to the local authorities (usually the fire and rescue service commissioned by the building committee) for review and approval before a building permit was issued and also to get their final approval to use the building granted. The question of responsibility was, however, unclear. Although the developer was responsible for the fire safety of the building, the impression was that the authorities had guaranteed the reliability of the solution. The quite extensive local adjustment of the fire safety protection was one of the reasons for changing the building regulations. In practice, there were a number of well-developed systems with local deviations from *NR* (1988), i.e. a number of accepted technical trade-offs, which were approved by the local fire and rescue services. A common measure employed to considerably reduce the need for fire protection was the installation of an automatic fire alarm connected to the fire and rescue service. It can, however, be questioned whether the protective effect of such a measure really compensates for the modifications made, e.g. longer escape routes, poor fire protection of ventilation systems and a lower class of compartmentation. One can even speculate whether the fire and rescue service had some degree of self-interest in approving such solutions as they benefited economically from them, due to the charges they made for having the alarm system connected to them, and for call-outs due to false alarms.

7.3 Identification of problems in the present situation – structure and discussion

The identification of problems at this level of risk control may appear surprising bearing in mind that the intention of changing the building regulations was to remove requirements at this level and introduce performance requirements at the safety output level (Chapter 5). However, during the survey of fire protection documentation it was found that the prescriptive design method still plays a considerable role in analytic design. The following points summarize the problems discussed in the coming sections:

- lack of development of the prescriptive design method (Section 7.3.1),
- the level of safety in some buildings can be questioned (Section 7.3.2),
- prescriptive design of large buildings violates the regulations (Section 7.3.3),
- local authorities issue rules for direct risk control (Section 7.3.4), and
- the role of the fire and rescue service in the construction process has become less clear (Section 7.3.5).

7.3.1 Lack of development of the prescriptive design method

It may be argued that the amount and degree of problems associated with the practical use of regulatory control at level I (*safety output*) and II (*safety procedures & safety case*) makes further development of level III (*direct risk control*) necessary. Despite the fact that the analytic design method has been considerably developed during recent years, a number of methodological problems have been recognized in Chapters 5 and 6, which limit the use of this new design method and lead to significant variation in quality. Therefore it is of importance to develop the prescriptive design method so that it can be applied to new kinds of buildings and to cases when existing buildings are renovated and put to different uses.

Some of the detailed solutions included in prescriptive design are in danger of becoming out-dated or obsolete. The conditions on which prescriptive designs are based may change. An example of this is in the care of the elderly, where nursing staff are sometimes organized in ”pools” that serve various functions, instead of being assigned to a specific department. The conditions for safe evacuation will be changed considerably as the number of staff available to help will be less (Frantzich, 1998). Another reason may be that new demands are being made on fire protection, or that flaws have been revealed in the design method, for example, the special needs for safe evacuation of disabled people are often not considered in the prescriptive design method. This seems contradicting to the performance demands in *BBR* 5:31 regarding satisfactory escape (see Section 6.3.2.3).

In other countries the prescriptive design method is being continuously developed and adapted (BSI, 2005) in parallel with the development of analytic design. Such a process is necessary in order to be able to use prescriptive design in new kinds of buildings and to be able to cope with changes in society that affect fire safety. The development of the prescriptive design method ceased in Sweden several years ago, which is unfortunate. Today, limited resources are devoted to this, and most of the resources available are used for harmonization of the existing classification system of prescriptive design with EU directives. There are, however, some exceptions. The technical report issued by *Boverket*, "Design for escape" has led to some updating of the prescriptive method (*Boverket*, 2004b).

Another reason why prescriptive design should be developed is that the performance demands in *BBR* are not formulated in such a way that they can be verified by calculations. Therefore, prescriptive design is needed in order to construct examples to which analytic design solutions can be compared, to verify that the solution is acceptable. Although it is hoped that it will be possible to develop a standardized analytical method of design with quantitative acceptance criteria, this lies far in the future, if it is even possible at all.

7.3.2 The level of safety in some buildings can be questioned

In Section 5.4.1 an analysis was presented in which the possible variation in risk level in a class of assembly halls was investigated. It was clear from the results that the variation can be considerable. Even if the average risk level in a class of buildings is acceptable, there is reason to question whether the risk level is acceptable in buildings with the highest risk, i.e. if the variation in risk is acceptable.

As the risk level resulting from prescriptive design is by definition acceptable according to *BBR* (for all buildings apart from those dealt with under *BBR* 5:13), it can be argued that a spread in risk within a certain class of buildings is acceptable. At the same time, one may question whether as large a variation as that found in Section 5.4.1 is desirable. If prescriptive design cannot be considered to lead to an acceptable level of safety in some buildings, then there is a need for review of, and changes to, the method. The mean risk for different buildings varied by a factor of 100 around the mean value for the whole class. If it is to be possible to define a risk level that can be applied as an acceptance criterion in analytic design then we must decide whether this variation is acceptable or not (see also Section 5.3.2).

Bearing in mind the fact that the activities taking place in this class of building are the same, the risk to which the occupants are exposed should be similar (i.e. the same order of magnitude). It does not seem reasonable that a person is exposed to different levels of risk depending on whether he or she is in a large building or a small one. However, other values must be considered such as cost-benefit-related principles, which could lead to a variation in safety level within a class of buildings. When such principles are included it is not the risk level that is the same, but the cost of each life saved. This principle of valuation has not yet been explicitly applied in design methods for fire protection of construction works, but has been used to a high degree in other areas, for example, traffic safety. When performance demands are analysed with the aim of making them measurable and analytically verifiable, the basis of valuation that is to apply in *BBR* should also be investigated and clarified.

7.3.3 Prescriptive design of large buildings violates the regulations

In Section 5.3.1 it was pointed out that, according to *BBR* 5:13, prescriptive design cannot be used for all kinds of buildings. Problems will arise as the majority of the performance demands in *BBR* are formulated such that a relative comparison with prescriptive design is the only way to verify that the demands are met using analytic design. Is it better to arbitrarily choose criteria for verification of the safety in this kind of building than to compare the solutions with prescriptive design? The question is whether there is also a need for prescriptive design in larger, but not necessarily more complex buildings. It is unfortunate that the building regulations prescribe which design method is to be used based on the type of building. The size and type of building do not necessarily correspond to the complexity of the building or the fire safety strategy required. It is true that it may be difficult to adapt prescriptive design to large buildings, but hardly impossible. Before *BBR* was revised in 1998 it was permitted to design fire safety in buildings higher than 16 stories using prescriptive design. No evidence has been found indicating that this method is inadequate, justifying its removal. A relevant question is whether we are better off using analytic design with no design criteria or agreed design procedure. High-rise and large buildings are common in many other countries, and are often designed with the prescriptive method. The re-introduction of prescriptive design for certain types of buildings should be considered, at least until suitable verification principles have been developed for analytic design. It should be possible to derive appropriate prescriptive solutions for these buildings by using standard layouts. If more sophisticated layouts are required, or if complex fire protection systems are to be used, then analytic design may be necessary. In such cases prescriptive solutions can be applied to large buildings with standard layouts, and it would then be possible to use these as reference buildings in analytic design to facilitate verification.

7.3.4 Local authorities issue rules for direct risk control

In its current form, building legislation can lead to dilemmas for local authorities whose responsibility it is to verify that fire safety regulations are followed. The current regulations allow great freedom on the part of the designer. At the same time, the performance demands are difficult to verify if the general recommendations are not applied. The authorities controlling fire safety during the design and/or the operational phase are thus faced with the question of what is acceptable and what is not according to *BBR* and *BVF* in detailed technical terms. The building committee must deal with this issue since it has the authority to carry out a detailed review during the design phase. The fire and rescue service can review the fire protection of the building as a part of the buildings total fire protection in the operational phase, and will hopefully avoid demanding a higher level of safety once a building is in service than that required of a new building. Some designer are likely to test the lower limit of fire safety, which will force the authorities to make a decision, despite the fact that they are not necessarily better qualified to determine what is acceptable and what is not than the designer. The result of this is that the local authorities will be forced to interpret *BBR*. Some local authorities have gone so far as to issue local detailed rules, which can be compared to the development of local prescriptive design regulations. This is naturally undesirable bearing in mind the ambition of *BBR*. Although it is against the rules to issue local regulations, it is not surprising that this happens. As long as consistent assessments and clear guidelines are not issued by *Boverket*, this will continue to happen.

7.3.5 The role of the fire and rescue service in the construction process has become less clear

Since the changes in building legislation, the role of the fire and rescue service has become less clear. In some municipalities the fire and rescue service is not involved in the construction process at all. In many municipalities they assist the building committee as experts during the construction process. In other municipalities the fire and rescue service acts as a consultant for the developer. In a few cases, they have both roles and act as experts for both the local authorities and the consultant. This can lead to a conflict of loyalties and jeopardize the ability of the fire and rescue service to represent the inhabitants of the municipality, but worst of all, create problems in carrying out objective inspection when the building is completed. Being involved in both the design and review process obviously leads to some problems and ought to be avoided.

7.4 Detailed quantitative analysis of a specific identified problem

It was found from the uncertainty analysis presented in Section 5.4.1 that the level of risk can vary considerably when using prescriptive design, even in a relatively limited class of buildings. It should be discussed whether this variation is acceptable or not. If the level of risk obtained through an acceptable prescriptive design cannot be used to define an acceptable risk level in analytic design, the building regulations will be inconsistent. In other words, the demand that must be met in order to achieve the same goals will depend on the design method used. Development of prescriptive design may be necessary in the future when the consequences of the choice of design method are analysed in detail. Even if the variation is acceptable, clarification of how to use this risk level and its variation when deriving an acceptance criterion is necessary in order to prevent an increase in risk level on a national level in buildings designed with analytic design (see Section 5.3.2).

7.4.1 Analysis of buildings with high risk level

The first step in the development of prescriptive design is to try to find a relation between buildings with high risk and certain variables or combinations of variables. The results of the uncertainty analysis (Section 5.4.1) can be used for this. A correlation analysis was performed for all types of uncertainties presented in Sections 5.4.1.4 to 5.4.1.7 to identify which variables have the greatest effect on the various risk measures. These results are presented in Appendix F. A separate correlation analysis was carried out for the cases where the risk measure is larger than zero in order to elucidate trends between certain variables and cases where the risk is high. There are no unambiguous criteria which determine whether the effect on the output due to the uncertainty in a input variable is to be regarded as important or not. In the analysis a correlation coefficient of 0.1 is chosen arbitrarily to exclude variables of less importance.

The variables that have the greatest effect on variation in the risk level are the same for fires of type 1 and type 2, namely ceiling height (*h*), area (*A*) and the number of people in the building (*N*). The importance of height and area was so high that a more detailed analysis was carried out as to how these are related to the risk measure ***individual risk*** (P_{ind}) and ***mean risk*** (R_{mean}). The results of this analysis are shown in Figures 64 to 67 for fire type 2 (i.e. the fire starts in an adjacent room). The parameter *P(R>0)* discussed in Section 5.4.1.3 can graphically be interpreted as the cases illustrated in these graphs in relation to the total number of cases simulated in the analysis (i.e. 10 000 iterations).

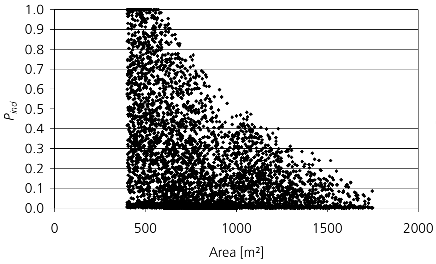


Figure 64. P_{ind} plotted against area for fire type 2.

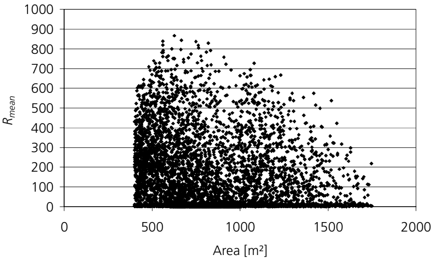


Figure 65. R_{mean} plotted against area for fire type 2.

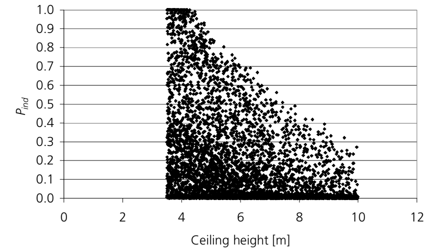


Figure 66. P_{ind} plotted against height for fire type 2.

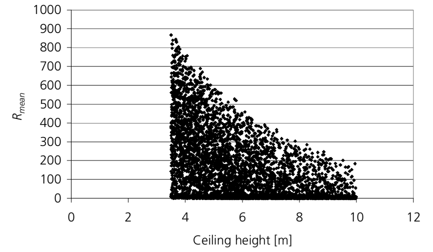


Figure 67. R_{mean} plotted against height for fire type 2.

The relation is very clear. Both the individual risk (P_{ind}) and the mean risk (R_{mean}) are high for assembly halls with small areas and low heights. The effect is so large that there is reason to study how these variables interact. This can be done by investigating if there is dependence between the risk measure and the volume of the building. It can be seen both from Figures 68 and 69 that there is a very strong relation between low volume and high risk level in the building. According to the analysis, the prescriptive design method leads to higher risk levels in buildings with a small volume than for the average building.

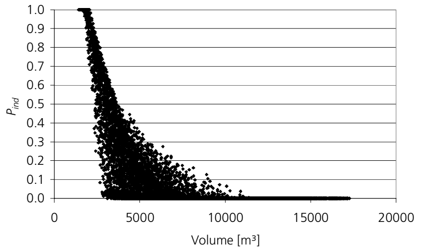


Figure 68. P_{ind} *plotted against volume for fire type 2.*

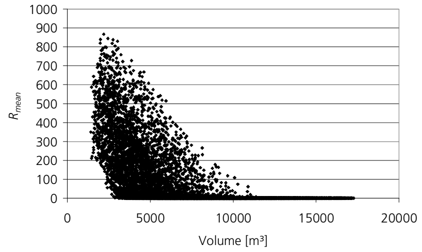


Figure 69. R_{mean} *plotted against volume for fire type 2.*

Each data point in Figures 68 and 69 represents the risk in a building of the same class as those studied in the uncertainty analysis. Therefore, no exceptional scenarios or outcomes are represented. The difference is so large that the method of prescriptive design should be reviewed, and better protection considered in buildings with the highest risk level. Figures corresponding to Figures 64 to 68 are shown in Appendix F for the all the uncertainty analysis which was presented in Section 5.4.1.

7.5 Solutions and need for development

If it is concluded that the variation in risk within a class of buildings is not acceptable it will be necessary to modify the prescriptive design method or its use. However, modifications must be made with caution. If the prescriptive design method is modified in order to improve fire safety in buildings with high risk levels (e.g. buildings with a low volume in Figures 68 and 69), this may lead to too high a level of fire protection in other buildings in the class that already have adequate protection (e.g. buildings with large volume in Figures 68 and 69). Therefore, the design method cannot be changed indiscriminately. The safety demands could also perhaps be reduced in buildings with a large volume. In such case it may be possible to reduce the variation in risk level without increasing the cost of buildings in this class as a whole.

The development of the prescriptive design method will require significant resources, and it may well be unrealistic for a small country like Sweden to be expected to make such investments. An alternative to national development is the adoption of international standards, such as those from the British Standards Institution (BSI), or the National Fire Protection Agency (NFPA) in the USA. Having said this, it is also important to consider the differences between countries which may lead to the same technical solutions resulting in different levels of safety (see Section 5.3.1.2). The Scandinavian countries previously worked together in the development of fire protection regulations through the Nordic Committee on Building Regulations (NKB). An advantage of such cooperation is that these countries have a similar attitude to fire safety and several of the conditions affecting the risk of fire, e.g. climate and culture, are also similar, thus allowing the same technical solutions to be employed. As detailed solutions from one country cannot simply be adopted by another, an investigation of how joint development should be carried out ought to be initiated. The section below provides a description of various methods that can be used not only in future development of the prescriptive design method, but also for use in reviewing the prescriptive method if the fire safety is regarded as being inadequate in some buildings.

As pointed out above, the fire safety in assembly halls is greatly affected by height and area, and the product of these two, volume. There is nothing to prevent a low building from being designed with prescriptive design method, and then changed according to *BBR* 5:11 so that the total width of the escape route is reduced, while the ceiling is raised. This may have considerable consequences on the design of the building, as well as a reduction in the average safety level of the class of building. The effects of this should be investigated and guidelines or demands developed, if for no other reason than to avoid an undesirable reduction in fire safety on a national level.

What can be done if the variation in risk due to the prescriptive method is not acceptable (see Figure 43 in Section 5.4.1.8)? Two possible strategies are suggested. One is to try to reduce the variation in risk by modifying the prescriptive design method for this class of buildings, and the second is to study specific cases where the level of risk is high, to establish whether measures can be taken to reduce the risk in these specific buildings. Both strategies involve changes in prescriptive design, which may be implemented in different ways, for example:

- restrictions on variables not considered in the prescriptive design method (Section 7.5.1),

- changes in existing parameters in the prescriptive design method (Section 7.5.2), and
- further development of the prescriptive design, i.e. introduction of new variables (Section 7.5.3).

By using the risk analysis method presented in Section 4.3 it is possible to model the effect of changes in prescriptive design, in order, for example, to evaluate how effective they are. It is also possible to study in greater detail which combinations of variables (i.e. buildings) lead to cases of high risk levels. The following sections describe the various ways of changing prescriptive design in order to influence the risk. Some examples of the effects of changing the design method are also given. A detailed description of the risk measures and histograms used to illustrate the results from the analysis can be found in Section 5.4.1.3. A fire in the room adjacent to the assembly hall is used for comparisons so that modification of the prescriptive method can be evaluated. The same approach can easily be used in other types of fires, e.g. a fire starting in the assembly hall, to see how the risk contribution from this fire is affected by changes in the prescriptive method.

7.5.1 Restrictions on variables not considered in the prescriptive design method

One way in which to influence safety is by governing or controlling certain variables that have large effects on the risk by imposing limits on them. Restricting variables by setting minimum or maximum values is possible but controversial and can be seen as a redefinition of the class of buildings. An example of this is defining a minimum ceiling height or area for an assembly hall when the current prescriptive method is used. Once the building is completed, it will be difficult to change these variables, and further control that the restrictions have been adhered to will not be necessary, unless the building is altered. Modifications of the prescriptive method can be made to suit buildings with low ceiling height or small floor areas thereby defining a new class of buildings: small assembly halls. Alternatively not allowing small assembly halls to be designed with the prescriptive method at all.

It is also possible to set limits on variables that are uncertain as a result of natural variation. For example, the number of people in the building can be limited. In order for such restrictions to increase the level of safety, which is the aim, it is important that there is a high probability that the limits will be respected. Restrictions are often meaningless if they are in conflict with the use for which the building is intended. It is therefore better to limit the number of people in the building through the number of seats than with a sign stating how many may be admitted.

Based on the sensitivity analysis both height and the number of occupants in a building have considerable effects on safety. In order to illustrate how the control of variables can affect safety, two examples will be given:

- limitation of the lowest ceiling height in the assembly hall (Section 7.5.1.1), and
- no uncertainty allowed in the number of people actually in the hall, i.e. the actual number of people in the hall is the same as that used in the design, $N = \rho_{design} \cdot A$ (Section 7.5.1.2).

The aim of these examples is to show that it is possible to analyse the effects of various proposed changes in prescriptive design, and not to illustrate the most suitable changes. The results are presented with the same risk measures and histograms previously described in Section 5.4.1. In the table showing the risk measures, a column has been added showing the decrease in the risk measures, compared with the case before the prescriptive method was modified presented in Section 5.4.1.5, see Eq. (25).

$$\Delta E(R) = \frac{E(R_P) - E(R)}{E(R_P)} \tag{25}$$

$\Delta E(R)$ = the relative change in a risk measure when the prescriptive design method is modified
R = the risk measure being analysed
R_P = the risk measure before modifications were made to the prescriptive method

7.5.1.1 Limitation of the minimum ceiling height in assembly halls

Height is one of the variables not considered in prescriptive design, but the risk will be affected by restricting the minimum ceiling height to 4.5 metres instead of 3.5 metres. The effects of this can be seen in Table 19 and Figures 70-72. The case studied was for fire starting in an adjacent room, in which variables from group 1 and 2 were varied, presented in Section 5.4.1.5.

Table 19. Parameter values from the uncertainty analysis for selected risk measures.

Risk measure (R)*	**E (R)**	**ΔE(R)**	**E (R) | $_{R>0}$**	**P(R>0)**
R_{mean}	51	36%	130	0.38
P_{ind}	0.069	37%	0.18	0.38
P_{worst}	0.27	21%	0.70	0.38

* The risk measures and parameters are described in Sections 5.4.1.1 and 5.4.1.3.

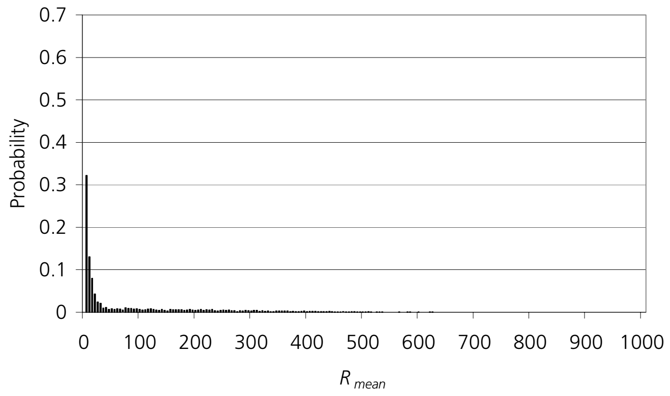


Figure 70. Histogram for $R_{mean} \mid_{R>0}$, minimum ceiling height 4.5 m.

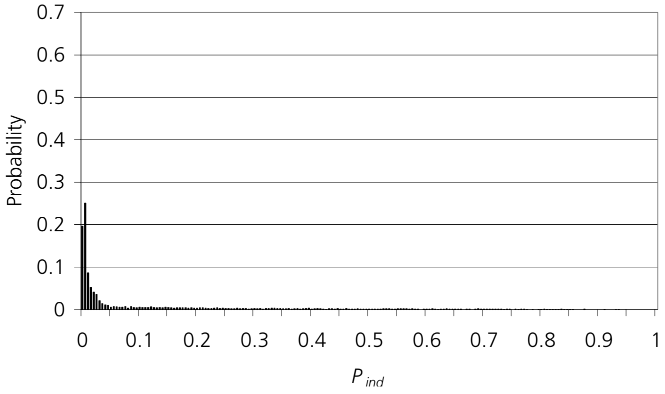


Figure 71. Histogram for $P_{ind}|_{R>0}$, *minimum ceiling height 4.5 m.*

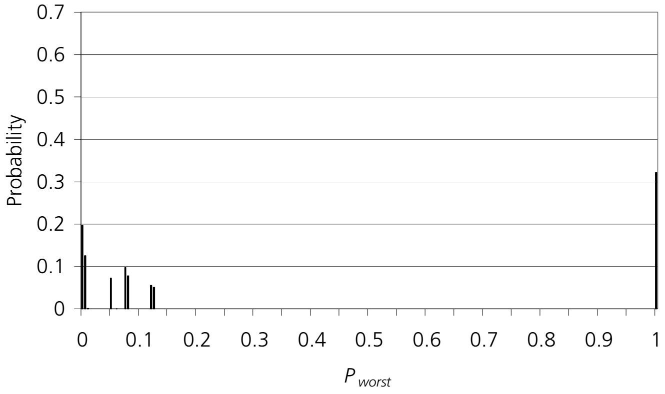


Figure 72. Histogram for $P_{worst}|_{R>0}$, *minimum ceiling height 4.5 m.*

In order to analyse the effect of height restriction, the results are compared with the uncertainty analysis of a fire in an adjacent room where the ceiling height is 3.5 m (see Section 5.4.1.5).

The mean risk is reduced by more than a third by increasing the ceiling height from 3.5 to 4.5 metres, while the variation in risk for the class of buildings is not significantly affected, regardless of the risk measure studied. Cases in which it is especially important to reduce the risk, i.e. scenarios with severe consequences, and where an individual is exposed to a high level of risk, are also reduced. The effect of the ceiling height on the total uncertainty decreases when the restriction is introduced, which indicates that the restriction has an effect. However, it is still the height together with the area and number of people that has the greatest effect on the variation in the level of risk according to the correlation analysis in Appendix F.

7.5.1.2 The number of occupants in the room corresponds to the design occupant density

If it is assumed that the actual number of people does not exceed the number for which the building was designed, then the risk will be affected. The results can be seen in Table 20 and Figures 73-75. The case studied was for fire starting in an adjacent room, in which variables from group 1 and 2 were varied (apart from *N*).

Table 20. Parameter values from the uncertainty analysis for selected risk measures.

Risk measure (R)*	**E (R)**	**ΔE(R)**	**E (R) | $_{R>0}$**	**P(R>0)**
R_{mean}	61	24%	110	0.54
P_{ind}	0.098	11%	0.18	0.54
P_{worst}	0.31	8.8%	0.57	0.54

* The risk measures and parameters are described in Sections 5.4.1.1 and 5.4.1.3.

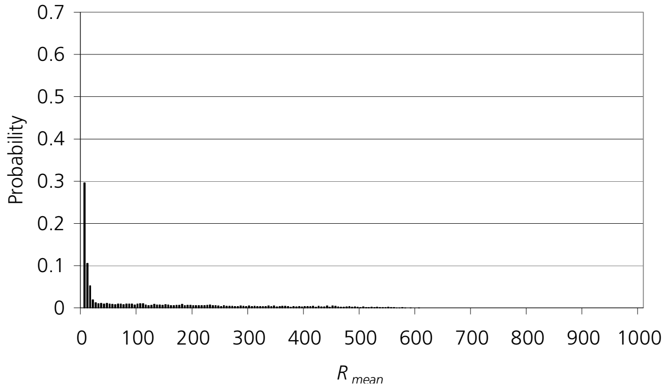


Figure 73. Histogram for $R_{mean} | _{R>0}$, when the number of occupants does not vary.

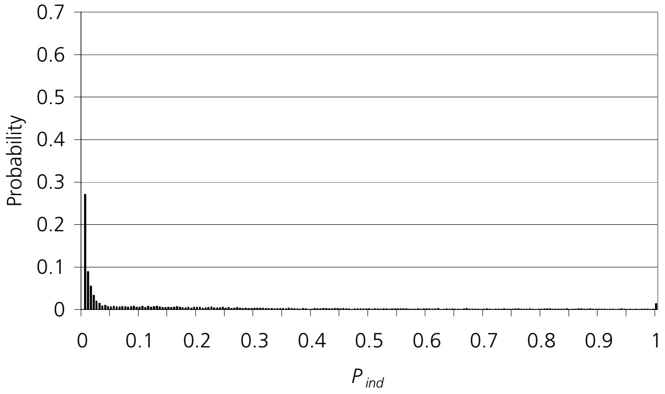


Figure 74. Histogram for $P_{ind} \mid_{R>0}$, when the number of occupants does not vary.

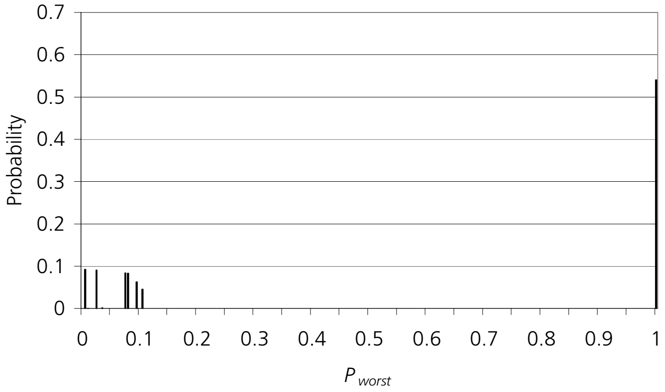


Figure 75. Histogram for $P_{worst} \mid_{R>0}$, when the number of occupants does not vary.

To analyse the effect of the restriction of the number of occupants a comparison can be made with the uncertainty analysis of a fire in an adjacent room when the number of occupants varies (Section 5.4.1.5). The R_{mean} is reduced by about 1/3 for the whole class of buildings. Cases in which it is especially important to reduce the risk, i.e. those with severe consequences, and where an individual is exposed to a high level of risk, are hardly affected by the restriction.

7.5.2 Changes in existing parameters in the prescriptive design method

Another way of influencing the risk is to modify the current design method. This can be done by changing certain parameters, e.g. the least number of escape routes or the minimum widths of escape routes. Identifying suitable modifications is an iterative process, in which the results of changes are evaluated using risk analysis, rather than trying to optimize the safety for a whole class of buildings. It is, however, unclear whether there is a simple way of modifying the current design method so that the variation is reduced.

Figure 76 shows how the individual risk varies with ceiling height for fires of type 2 when it is assumed that the number of people in the building is the number designed for. This number of occupants is determined by the area, and according to prescriptive design, the number of exits is dependent on the number of occupants.

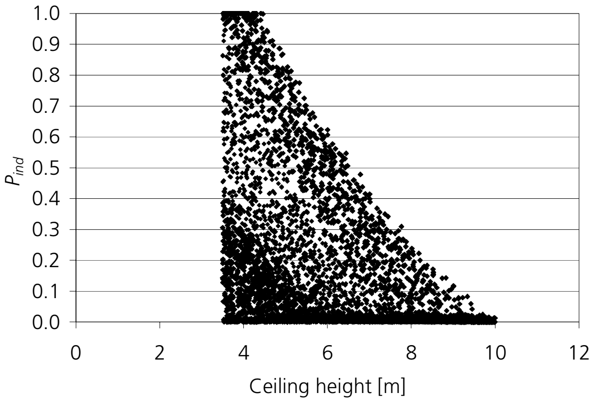


Figure 76. P_{ind} plotted against ceiling height when the number of occupants in the building corresponds to the design occupant density.

Figure 77 shows the same results with different symbols depending on how many exits there are. The level of risk is higher for all the cases where only two exits are available, i.e. an area less than 600 m^2. The results in Figure 77 say nothing about whether these buildings are over-represented among those with high risk because they only have two exits, or because they have a small area. However, it is interesting to study the impact on the risk resulting from the prescriptive design method by modifying parameters controlling the openings.

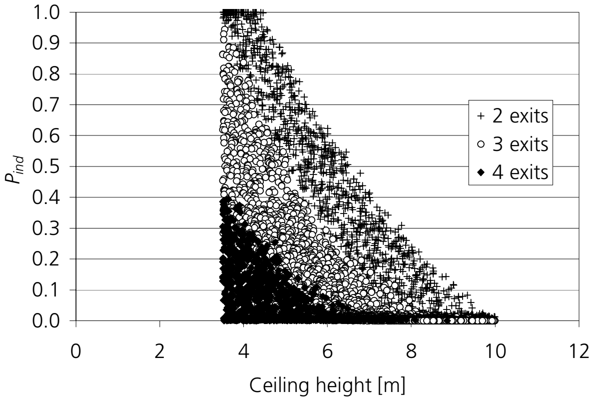


Figure 77. P_{ind} plotted against ceiling height when the number of occupants corresponds to the design occupant density, when the building has 2, 3 or 4 exits.

In this section two different types of changes to the prescriptive design method will be considered:

- demanding at least 3 exits from all assembly halls (Section 7.5.2.1), and
- changing the prescriptive method so that, for example, an exit width of 1 metre per 100 occupants is required instead of 1 metre per 150 occupants (Section 7.5.2.2).

As in Section 7.5.1 the aim of these examples is to show that it is possible to analyse the effects of various suggestions for changes in prescriptive design, not to illustrate the most suitable changes. A closer examination of the difference resulting from changing the prescriptive demands can be made by using Figures 68 and 69, which illustrate the risk level resulting from the prescriptive method before modifications were made. The results of the modification are presented using the same table of risk measures as in Section 7.5.1, and the risk measures P_{ind} and R_{mean} are plotted against the variable volume (V) to illustrate how the changes affect cases where the risk level was found to be high.

7.5.2.1 Demanding at least 3 exits from all assembly halls

The results for fire type 2 if a minimum number of 3 exits are required in the prescriptive design method are given in Table 21 and in Figures 78 and 79. Note that the total required exit width has not been changed, but that a minimum width of 1.2 m per exit is still used.

Table 21. Parameter values from the uncertainty analysis for selected risk measures.

Risk measure (R)*	**E (R)**	**ΔE(R)**	**E (R) $\|_{R>0}$**	**P(R>0)**
R_{mean}	77	3.4%	140	0.54
P_{ind}	0.10	9%	0.19	0.54
P_{worst}	0.33	2.9%	0.62	0.54

* The risk measures and parameters are described in Sections 5.4.1.1 and 5.4.1.3.

If a comparison with the prescriptive design method presented in Section 5.4.1.5 is made, a decrease in risk measures can be noted (see Δ$E(R)$ in Table 21), but there is still a significant number of cases with high risk for assembly halls with a small volume according to Figures 78 and 79.

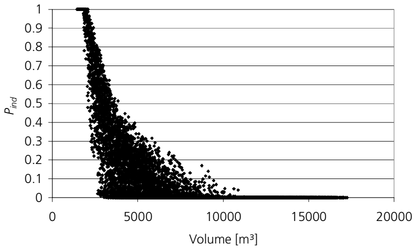


Figure 78. P_{ind} plotted against volume for fire type 2 with a minimum requirement of 3 exits.

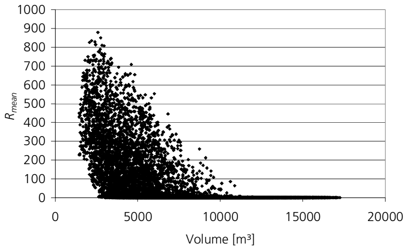


Figure 79. R_{mean} plotted against volume for fire type 2 with a minimum requirement of 3 exits.

7.5.2.2 Required exit width of 1 metre per 100 occupants instead of per 150 occupants

The results for fire type 2 if 1 metre exit width is required for 100 occupants instead of 150 are given in Table 22 and in Figures 80 and 81.

Table 22. Parameter values from the uncertainty analysis for selected risk measures.

Risk measure (R)*	**E (R)**	**ΔE(R)**	**E (R) |$_{R>0}$**	**P(R>0)**
R_{mean}	36	55%	120	0.31
P_{ind}	0.055	50%	0.18	0.31
P_{worst}	0.15	56%	0.48	0.31

* The risk measures and parameters are described in Sections 5.4.1.1 and 5.4.1.3.

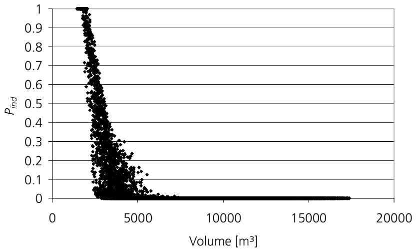


Figure 80. P_{ind} plotted against volume for fire type 2 with a total required exit width of 1 m for 100 occupants instead of 150.

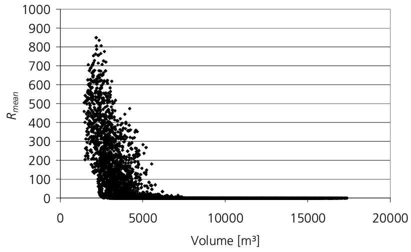


Figure 81. R_{mean} plotted against volume for fire type 2 with a total required exit width of 1 m for 100 occupants instead of 150.

It can be seen from the results that the changes to the prescriptive design method have effect. The average level of risk in the class of building is reduced according to all risk measures E(R). A comparison between Figures 68 and 80 shows that the number of cases with a small volume and high risk level ha been reduced.

7.5.3 Further development of the prescriptive method (introduction of new variables)

A more subtle way to modify prescriptive design is to study the factors that contribute to the spread in risk level, and those that cause the risk to be high. This can be done by including important variables in the design method, which have not been taken into account earlier. Various approaches are possible. Different design equations can be created for different sub-sets of the building class, regarding, for example, ceiling height. Another method is to include important variables in the actual design expressions. For example, the number of people per metre of exit width can be expressed as a function of the height or volume. If a greater number of people are allowed per metre of exit width in assembly halls with large volume than in smaller ones, the spread in safety will be reduced. These approaches are also iterative, i.e. a modification is proposed and the effect then evaluated. One advantage of introducing new variables to develop prescriptive design compared with previous suggestions is that there is a high probability of achieving the desired effect. A disadvantage is that the prescriptive design method will be more complicated.

7.5.3.1 Required exit width is expressed as a function of the volume of assembly halls

It can be clearly seen from Figure 68 and the correlation analysis presented in Appendix F that the volume has great potential in levelling out the variation in risk level if it is included in prescriptive design. As the relation between small volume and high risk is very clear, it would be appropriate to allow the total evacuation width to vary with volume. In order to investigate whether it is possible to reduce the risk in buildings with the highest risk level by introducing further variables into prescriptive design, analysis was carried out with an increased exit width of 100% in the smallest buildings in the class (2000 m^3). This increase was reduced linearly to 0% for buildings with a volume of 6000 m^3, see Eq. (26), but all other aspects are based on the uncertainty analysis of the fire in an adjacent room (fire type 2) where variables of both groups are varied, see Section 5.4.1.5.

$$w_{req} = \left\{ \begin{array}{rl} N \cdot \dfrac{2.5 - 2.5 \cdot 10^{-4} \cdot V}{150} & if \quad V \le 6000m^3 \\ N \cdot \dfrac{1}{150} & if \quad V > 6000m^3 \end{array} \right\} \qquad (26)$$

w_{req} = required total exit width [m]
V = volume of the assembly hall [m^3]
N = number of occupants in the assembly hall

The results are presented with the table of risk measures described in Section 5.4.1, and are shown in Table 23, together with Figures 82 and 83 illustrating the risk measures, individual risk and mean risk, in relation to the volume of the assembly hall.

Table 23. Parameter values from the uncertainty analysis for selected risk measures.

Risk measure (R)*	**E (R)**	**ΔE(R)**	**E (R) | $_{R>0}$**	**P(R>0)**
R_{mean}	49	39%	110	0.44
P_{ind}	0.068	38%	0.15	0.44
P_{worst}	0.22	35%	0.51	0.44

* The risk measures and parameters are described in Sections 5.4.1.1 and 5.4.1.3.

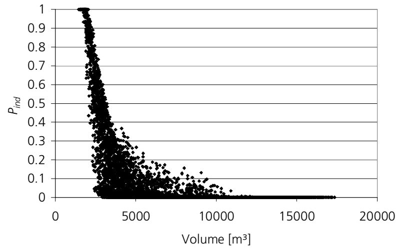


Figure 82. P_{ind} plotted against volume for fire type 2 when the required exit width is a function of the volume.

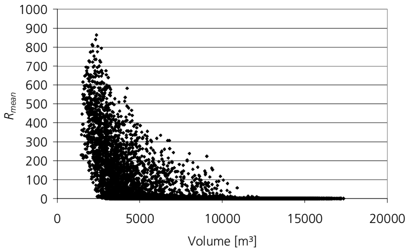


Figure 83. R_{mean} plotted against volume for fire type 2 when the required exit width is a function of the volume.

It is clear from the results that the risk level for the class of buildings is reduced by introducing the volume as a variable that affects the required exit width. A significant reduction of risk level for assembly halls with a small volume is noted.

The results of the uncertainty analysis warrant a more detailed analysis than was possible within the scope of this thesis. Several additional statistical central measures could be used for further studies, which could easily be derived for the distributions in Figures 64 to 83, for example the standard deviation of the risk for a class of buildings. In addition, the results presented can provide the basis for a risk-cost analysis of different modification strategies for the prescriptive design method. It can be concluded that a great deal of work remains to be done in this area and continued research efforts are necessary.

7.5.4 Responsibility of public authorities in the construction process

Performance based regulations were introduced with the explicit claim that engineers had the technical tools and professional independence to safeguard public safety (see Section 1.2). Some of the identified problems in Chapters 5-7 point in another direction. However, even if the responsibility that a proposed design is sufficiently safe is completely laid on the developer and designer this fact does not mean that the public authorities are supposed to act as bystanders in the construction process. If systematic flaws or shortcomings in this process are identified authorities have a public responsibility to act, both on a local and national level.

It appears that several of the identified problems associated with risk control are related to the organisation of the construction process. In order for societal risk control to function properly these issues must be addressed. The local authorities have an important role in exercising quality control over both the designers and their final solutions. However, this can not be achieved by pretending that the "old system" is still in place, i.e. when the building committee exercised control by interpreting the building regulations at the *direct risk control* level. Issuing local detailed mandatory rules is not the appropriate action either, since it undermines the risk governance system and lacks legal grounds.

The study of fire protection documentation indicates that the review process is not functioning properly. This problem must be addressed, not only so that flaws and mistakes by designers can be identified, but also to make designers conform to higher standards than today (see Section 6.3 for a list of shortcomings) in order to improve the quality of verification. Once again, even if the responsibility for a safe design is laid on the developer and designer, societal risk control can not rely completely on the designer assuming responsibility. From a societal perspective, it is not acceptable for a third person to be exposed to a high level of risk due to design errors. This may require the further development of tools and competence within building committees, and also calls for effective cooperation with other authorities within the municipality, e.g. the fire and rescue service. Such cooperation is in place in some Swedish cities, but not in others. It must be stressed that it is not suggested here that the responsibilities of the developer and designer should be changed, or that the building committee should once again assume responsibility on a project-specific level by approving the proposed designs.

If designers do not meet the requirements in the building regulations, appropriate measures have to be taken, otherwise the building regulations will be inadequate as means for society to exercise risk control. The demands set out by the building authorities are likely to make designers adapt, as they will be unwilling to risk delays in the design process. However, these demands must be relevant and compatible with the way in which the construction process is intended to work, and focus, for example, on how designers execute self-implemented control in practice. No detailed study of the organisation of the construction sector was made in this study, but it is believed to be of great importance regarding both societal risk control and solving some of the difficulties revealed.

8 Coordination between the design and the operational phases

Several problems were identified regarding the ability of society to control the risk of fire in construction works in the analysis presented in Chapters 5-7, which will be summarized in Chapter 9. Common to all these problems is that they arise in the design phase. Another kind of problem arises when the conditions for risk control are studied, based on the relation between the design phase and other phases in the life cycle of the building.

There are several reasons why the risk of fire in a building cannot be controlled by isolated activities in the design phase alone, but requires coordinations between different phases and actors. This chapter describes the connection and the need for coordination between the design phase and the phase in which the building is used, i.e. the *operational phase*, from three aspects:

- risks that cannot be dealt with by technical requirements on the construction work (Section 8.1),
- safety management systems in the operational phase (Section 8.2), and
- the need for coordination between the design and operational phases (Section 8.3).

8.1 Management of extreme events and gross errors

Some kinds of fire risks are difficult to prevent using fire protection related to technical requirements on construction works. The risks associated with extreme events and/or those caused by gross errors are examples of these, irrespective of the design method used. Both these kinds of risks can lead to large-scale accidents, or catastrophes (see Section 3.3.1). It is difficult to identify these risks with traditional risk analysis when using analytic design. When using prescriptive design, experience from previous events forms the basis of the design method, which means that the solutions are sometimes inadequate due to a lack of such events.

In Rasmussen's categorisation these risks belong to category 3 (see Figure 15 in Section 3.3.1), and arise due to uncertainties of types F and G (see Figure 17 in Section 3.5). As fire protection of construction works is limited in its ability to provide protection against these kinds of accidents, other kinds of fire protection measures, for example, organisational, are required as complement. This means that certain demands must be placed on the owner or operator, and these are not found in building legislation. However, such demands are made in the Civil Protection Act (2003) and the Work Environmental Act (1977). There is thus a need for coordination to ensure that fire protection covers the kinds of accidents considered here, and that it works in practice, since many important (and sometimes irreversible) decisions regarding the fire safety strategy are made in the design phase.

8.1.1 Extreme events

Extreme events affecting a building are often associated with *extremely high loads or stresses* on a system, e.g. very high winds, or a large mass of snow on a roof in a structural system, especially if these coincide. Extreme events are both severe and rare and are often associated with catastrophic consequences, but not necessarily so. For a further discussion on the definition of extreme events the reader is referred to Bier et al. (1999). Some of these events, with the potential of causing building disasters, can be predicted using extreme value theory, and both the cause and effect are known. Another kind of extreme events are those where the course of events is unexpected or unusual, leading to serious consequences. In the design of load-bearing structures these loads are called accidental loads (or effects) and are associated with events such as fire, explosions, aeroplane collisions, etc. In the context of fire safety design in buildings, examples of this type of event can be arson where fire is started simultaneously in several places or involving large amounts of inflammable liquids or sabotage of protection systems. This type of risk is caused by some independent hazard outside the control of the designer. In such cases, traditional extreme value theory is not adequate for designing protective measures, and safety measures other than protection related to construction works are necessary to ensure an adequate level of safety. The rescue service is an example of a resource that can be used in extreme events, and which has the potential to deal with several kinds of events. Training of personnel is another example. In the design of fire protection against extreme events, measures requiring preparedness for some kind of action, depending on the development of events, is often preferred.

8.1.2 Gross errors

It is seldom that serious accidents can be traced back to a series of random errors in the case of technical systems such as load-bearing systems (Albertsson et al., 1982), or in industries such as the chemical industry (Rasmusson, 1997). Other kinds of failure mechanisms usually lie behind such accidents. These are referred to as gross errors, and are characterized by the fact that they can cause unpredictable events and are not considered in fire safety design. These events cannot be predicted with statistical methods, as they are of a completely different nature. Such errors may take place during design, production or use of the building, and are usually associated with human error. Examples of the causes of gross errors are given below (Ellingwood, 1987):

- carelessness, nonchalance and negligence,
- insufficient knowledge,
- forgetfulness, mistakes and misunderstandings, or
- over-reliance on someone or something which means that the necessary controls are not performed.

Magnusson (1996) has elaborated on failure types relevant for the area of fire safety engineering which can lead to gross error. These are presented below:

- "Failures caused by present technology's inadequate understanding of the process, this is an epistemological problem (not knowing what you don't know).
- Failures occur because the designer fails to allow for some basic mode of behaviour well understood by existing technology. This is a problem of incomplete and/or improper scenario definition.
- Failures which occur through an error during construction and operation; these would be the result of poor control, poor inspection, poor procedures, poor management, poor communication leading to errors of judgement, the wrong people taking decisions without adequate consultation, etc.
- Failures that occur in a deteriorating climate surrounding the whole project; this climate is defined by a series of circumstances and pressures on the personnel involved; pressures may be of a

> financial, political or industrial nature and may lead directly to a shortage of time and money with the consequent increased likelihood of errors during both design and production processes."

No systematic compilation of gross errors encountered in the forty-six projects due to these kinds of events has been made here, but some examples of potential problems identified are discussed below.

- Gross errors that can occur during design include neglecting important fire scenarios in calculations, erroneous assumptions regarding the fire characteristics and the evacuation, computational errors, errors in technical drawings or fire protection documentation, and inadequate methodology in verification. Other examples are given by Lundin (2001).

- Gross errors during the production phase which may be due to: changes in the basic drawing data not being communicated to the fire safety engineer, changes in materials or components to something believed to be equivalent, but which has significantly poorer properties regarding fire safety, the building not being constructed according to the technical drawings due to decisions made at the building site, poor-quality installations, e.g. choosing emergency exit devices that are difficult to understand or operate, and neglecting sealing in fire compartment lead-throughs or poor installation of technical systems.

- During the operational phase, gross errors may be made by allowing activities for which the building was not designed, e.g. using classrooms for temporary sleeping accommodation or allowing dances in gymnasiums. Safety systems may also be out of order due to technical faults or having been disconnected for the sake of convenience, e.g. fire doors being propped open or fire exits being locked to prevent unauthorized access.

Gross errors may lead to serious consequences even if there is only a small fire. It is of the greatest importance to avoid a combination of an extreme event and a gross error which can lead to the type of event or causes not included in fire safety design. It is thus a serious mistake to completely ignore extreme events in analytic design (see Section 6.4.5) or to neglect the need for thorough design review when analytic design is used (see Section 6.3.4). If a designer consciously excludes an extreme event from the verification this event must be considered to be part of the acceptable risk. In prescriptive design some protection against extreme events is implicitly included and the risk for gross error is smaller compared to analytic design since the method is simple and the solutions are well known.

As mentioned before, some unpredictable events cannot be dealt with by employing technical fire protection measures. For example, making the evacuation routes wider is not an effective measure to counteract poorly founded assumptions or other mistakes in the verification. The potential for serious mistakes should instead be eliminated by effective review during design, production and operation (Albertsson et al., 1982). A number of different kinds of routines are employed in the construction process whose aim is to identify gross errors, and these form an important part of the quality assurance of the fire protection in a building.

The results of research show that third-party review is required to reveal gross errors (Ellingwood, 1987). This is because basic assumptions are questioned and strategies for solutions are thoroughly scrutinized and the original reasons for possible errors do not influence the reviewer's assessment.

Building committees have previously had a third-party control role in the construction process since they ensured that buildings were constructed according to plans by continuous review, control and final inspection. Today, safety review is mainly in the hands of the developer (see Sections 5.2, 6.2 and 7.2). If a building committee has special reasons, they may carry out an inspection or demand an inspection by an independent expert (third-party reviewer). However there are indications that the quality of the Swedish third-party review system in the construction process is insufficient (see Section 6.3.4). The building regulations also requires independent review when analytic design is used to design evacuation safety (*BBR* 5:14). Final inspection has been replaced by the issuing of a building certificate. No one from the building committee is required to visit the building site, and the certificate is merely acknowledgement that the developer and the building committee are in agreement that the building plans have been followed. The certificate provides no guarantee that the building or plant fulfils the legal requirements (*Boverket*, 1995).

During the analysis of fire safety documentation (see Section 4.2) and in discussions with designers and building officials, a number of factors were identified which make it more difficult to detect gross errors in the design phase.

- The documented self-implemented control may be inadequate in small consultancies as the number of employees is small, and it may be difficult to find an expert who is not involved in the current project. This could be one reason for the building committee to place higher demands on the level of control (see Section 6.5.3).

- Independent experts (third-party reviewers) are demanded too seldom by building committee and the building committee seldom carry out control themselves.

- The fire safety designer and the independent expert may become dependent upon each other if their roles are reversed in other projects. This may jeopardize the independence of the reviewer and can lead to the formation of cartels.

- Some building committees have not adapted to the new demands necessary in analytic design. Inspection is carried out in the same way as when prescriptive design was used, i.e. the administrator focuses on technical solutions instead of investigating the ability of the developer to fulfil his or her assignment in a systematic way.

- Local authorities do not always make use of the skills available due to internal problems associated with cooperation. This can result in the fire and rescue service not wanting to, or not being able to, participate in the construction process. Important information and experience from previous fires will then be lost.

- Personnel employed by the fire and rescue service sometimes act as fire safety planners, which means that they may not be completely objective if involved in fire safety inspections during the operational phase.

Considering that a number of cases of poor fire safety verification have been identified in this study, but not been captured by the review system in the construction process, and the above points, there is evidence of a clear threat to society's ability to ensure fire safety in buildings.

Poor quality in the construction process has also been noted in political circles, resulting in the Planning and Building Committee being commissioned by the government to perform a revision of parts of the building legislation and to propose changes to this legislation. At the time of writing

(July 2005), there are no final proposals, but several of the suggested changes discussed by the Planning and Building Committee, for example, the reintroduction of a site foreman and final inspection, may contribute to improving quality assurance in the design of safety in case of fire (Planning and Building Committee, 2004).

8.2 Safety management system in the operational phase

The importance of a well-functioning safety management system in the operational phase of a building to handle extreme events and gross errors must not be underestimated. Such a system may provide the conditions required for fire protection to work as intended, but may also contribute to new risks if it does not work properly. In the accident inquiries from a number of serious fires, inadequacies in safety management were deemed to be one of the main factors. Some examples of such cases are given below.

- *Fires in apartment buildings and hotels in Paris, France in 2005.* Four serious fires during a short period of time caused a large number of fatalities in Paris. Sixty-two people died and many more were injured in these fires. The investigations of the causes of the fires have not yet been completed, but there are several similarities, allowing them to be considered as a single case: the occupants were mainly poor immigrants, arson can not be ruled out, and the buildings were seriously run-down. In all the buildings it was obvious that the safety management system was inadequate (or non-existent). The building itself, its systems and the fire protection were below acceptable standards, i.e. maintenance had not been performed properly (International Herald Tribune, 2005a, 2005b, 2005c).

- *The fire at The Station Nightclub in Rhode Island, USA in 2003.* During a concert pyrotechnics were used which ignited polyurethane foam insulation lining materials on the walls and ceiling of the stage. The fire spread quickly along the ceiling area over the dance floor. One hundred people lost their lives (Grosshandler et al., 2005).

- *The fire at the regional psychiatric clinic in Växjö, Sweden in 2003.* Two people died in the fire, which occurred in a closed unit. Several remarkable faults were noted, which were directly linked to faults in the management system, e.g. poor planning of staff holidays, which meant that temporary staff with lack of knowledge of emergency routines were on duty, the evacuation plan was out of date, and routines and training were inadequate (Landstinget Kronoberg, 2003).

- *The fire at the Little Heaven café in Volendam, the Netherlands in 2001.*
  Thirteen people were killed and 250 people injured as fire swept through the café. The fire was probably caused by Christmas lights setting fire to ceiling decorations, and two out of three emergency exits were blocked (NBDC, 2005).

- *The dance hall fire at the Macedonian Society in Göteborg, Sweden in 1998.*
  The premises were used for a purpose for which they were not designed, regarding both the activity and the number of people on the premises. This, in combination with rapid and intense development of the fire, and the fact that the evacuation route was blocked, led to devastating consequences. Sixty-three young people lost their lives, and a large number were injured (SHK, 2001).

- *The fire at Kings Cross Station, London, UK in 1988.*
  A cigarette butt set fire to a wooden escalator and the progress of the fire was extremely rapid. In the inquiry into the accident, serious inadequacies in inspection and reporting routines were revealed. Similar ignition scenarios had been noted at other locations, but little notice was taken of the information and no changes in procedures were made (Reason, 1997).

One conclusion that can be drawn from these cases is that a safety management system that does not work as it should in the operational phase not only leads to the malfunction, or complete lack of function, of some safety systems, but also that new risks of fire can arise for which the total fire protection is not designed.

Many of the catastrophes exemplified above took place in buildings where large numbers of people are often gathered. One danger associated with analytic design is that the contribution to the total risk from such scenarios will be greater than when prescriptive design is used, due to differences in the way in which the fire safety measures are designed (see Section 6.4.5 for a more detailed discussion). When prescriptive design is employed there are demands on the distance to exits and there was previously also a demand on the area of fire compartments. When technical trade-offs are made and new solutions are introduced, a combination of faults can lead to much more serious scenarios than previously. The potential for catastrophe has been introduced, or increased, which places higher demands on the functioning of safety management systems as a complement to technical safety measures. It is hoped that such a system will lead to a low, constant probability of important systems malfunctioning, and that the building and its protection systems are properly maintained so that they work as intended, for example, not painting over sprinkler systems, not furnishing rooms so that exits are blocked, and not propping open fire doors. Similar strategies are used in so-called major hazard industries when the probability of potentially catastrophic accidents cannot be completely eliminated. With a well-functioning safety management system it is possible to create preparedness for unexpected situations which can considerably reduce the consequences of an accident. Good maintenance and control routines ensure that faulty systems are repaired and that the probability of serious accidents is kept low.

With the introduction of the Civil Protection Act (LSO, 2003) the responsibility of the owner or operator of the building for fire safety was made clearer, and demands made for *systematic fire protection management*, which is a kind of management system for fire protection. The management system should be adapted to each building/operation, and include a number of activities, e.g. continuous operation & maintenance of fire protection, regular checking of important fire protection systems such as sprinklers, and training. The owner or the user of the building must document the fire protection of the building and send a copy to the local fire and rescue service, which is responsible for ensuring compliance.

A safety management system that address fire risk during the use of the building can basically be arranged as general management systems with that consist of policy, procedures and instructions (see Section 3.1.1). For such a system to have any effect on a building or operation, assimilation to the conditions and regulations governing fire safety is necessary. Several specific concepts and products are available in the area of fire safety, see for example Hybring (2003), The Swedish Fire Protection Association (SFPA, 1995) and The Swedish Rescue Services Agency (SRSA, 2001), but there is no established comprehensive procedure. A general model of a fire safety management system has been presented by Santos-Reyes and Beard (2002).

The model consists of the following components:

- policy, procedures (routines) and instructions,
- planning and organisation,
- implementation and execution,
- measurements and evaluation, and
- review, revision and improvement.

By actively employing a fire safety management system, it should be possible to reveal shortcomings and errors in fire protection during the use of the building or operation of a plant, but this assumes that the fire safety systems were correctly designed from the beginning.

It has been found in other areas that for systematic safety management to work as intended, the employees must be motivated and committed to these issues. *Safety culture* is a generic term covering factors that characterize safety consciousness within a company or organisation, and is a very important component in general safety management. Culture related to safety is defined by Hale (2003) as:

"the set of attitudes, beliefs and perceptions shared by a natural group as defining norms and values, which determine how they act and react in relation to risk and risk control systems."

Examples of components affecting safety culture are (Hale, 2003; IAEA, 1991):

- organisational learning (e.g. reporting and documentation),
- management commitment and motivation to safety ,
- record keeping on accidents and accident investigation,
- attitudes and behaviour regarding safety,
- safety training,
- communication,
- safety rules and inspection,

- risk perception,
- working conditions,
- operation & maintenance procedures, and
- well-designed and functioning technical equipment.

It is thus considered necessary to approach these issues actively in order to create an effective systematic safety management system. A building owner or plant operator may have other areas of risk to consider than fire, e.g. the occupational health, effects on the external environment and other kinds of accidents. These are regulated in the same way as the risk of fire. However, it is often not possible an operator or owner to create a safety management system based on each set of regulations or risk. It is thus common to design an integrated safety management system covering all risks related to safety, health and the environment.

An alarming observation, according to a follow-up of the new requirements in the Swedish Civil Protection Act (LSO, 2003), is that only about 35% of the owners and users of buildings who are required to produce written documentation of the fire protection system of the building has done so (SRSA, 2005). After extensive media coverage of this issue the proportion increased to 55%. This is still a low number and is a clear indication that systematic fire protection has not been fully implemented. Several serious accidents have shown that a malfunctioning safety management system can contribute significantly to, or be the single dominating cause of, serious consequences. The small amount of documentation submitted is a clear indication that efforts have to be made to ensure that the requirements for fire safety are fulfilled.

In addition to serving as examples of poor safety management and contributing causes of major accidents, the cases presented at the beginning of Section 8.2 raise a number of social concerns linked to fire risk, for example, the recent fires in apartments and hotels in Paris. An increasing problem for many Western countries is that immigration is rising, economic inequality is widening and housing prices are continuing to rise. As a result, the amount of low-cost, run-down accommodation is likely to increase. It is not unreasonable to expect that there is a correlation between buildings with low fire protection standards and buildings for which documentation has not been submitted. If poor fire protection coincides with low building standards in general, an inadequate SMS and occupants with social problems, e.g. low income, drug abuse and foreign background, a new type of fire risk situation will appear. Even if the question of legal accountability is clear, i.e. the building owner is responsible, it is highly unlikely that this type of fire will be socially accepted. Since the fire and rescue services are supposed to base their supervision on fire safety documentation, and since many buildings where this new type of fire risk might occur are not even required to file documentation, e.g. apartment buildings, the current system will be inadequate in dealing with such a new threat. It is important to continue studying both the fact that SMSs are being produced and used, and also to monitor the development of other underlying causes of the accidents of the type that recently occurred in Paris.

8.3 Mutual dependence between the design and operational phases

In some kinds of industries, active safety management is natural during every phase of operation, e.g. the mining or oil industry. In such cases, all phases of the plant's life cycle can be included in a single safety management system, and one party can be responsible for all phases. In other industries, several parties or stakeholders may be involved in the different phases. When several actors are involved it is sometimes difficult to create a single safety management system as each of the actors has their own system. This leads to complicated safety management prerequisites, and places high demands on coordination between different actors and different phases. A good example of this situation is an airport, where there are many airlines operating, as well as organisations and authorities (Hale, 2001). The complexity of fire protection of construction works varies with the kind of activity. In public buildings and many kinds of assembly halls the users do not always play an active role in the design of fire protection or choice of fire safety systems during the design phase, consultants are hired instead. It is often not known who the lessee will be when the building is being planned. In such cases, separate safety management systems must be used for each phase. One system is employed to ensure the fire safety in the design stage, which evidently is focused on the design of the construction work and the work performed by the designer, and another system is used during the operational phase, i.e. that of the owner or operator (see Figure 84). Furthermore, a number of actors are involved in the operational phase and are affected by the design of the fire protection. Apart from the owner and the operator, the fire and rescue service has a need for information regarding both inspection of preventive measures and possible future fire fighting operations. *Boverket,* i.e. the regulator, is also an important actor as there is a need to verify that the regulations will work once they have been applied, and to investigate the need for revision and changes.

Regarding structural fire protection, it is important that both the design phase and the operational phase are monitored. From the point of view of the authorities, there is little need for control during the production phase; it is assumed that the owner can be relied upon to ensure that the developer has fulfilled his or her contractual obligations. The fire protection systems are determined in the design phase, while in the operational phase the safety management system is of the utmost importance for the total safety of the building and its occupants. A SMS may involve the coordination of several activities, e.g. training of personnel, fire drills and maintenance. Some of these activities are dependent on information from the design phase. There is no single piece of legislation that regulates the coordination of these activities, despite the fact that it is important in the control of safety, not least regarding gross errors and extreme events.

The introduction of analytic design may lead to an increased need for coordination, but knowledge and awareness of this are low. An attempt is made to survey the need for such coordination and exchange of information between these phases in order to control safety in Sections 8.3.1 to 8.3.14. Examples of important connections between the design phase and the operational phase are given, but further development of these is outside the scope of this thesis. The survey is by no means complete, but provides examples of the need for coordination between the design and operational phases. The examples are not arranged or ranked in any particular order.

The link between different phases, i.e. feedforward or feedback as illustrated in Figure 84, is given explicitly at the end of each section. This link is not necessarily restricted to one specific building project but should be seen in the perspective of the continuous learning processes of the different professionals involved in the process.

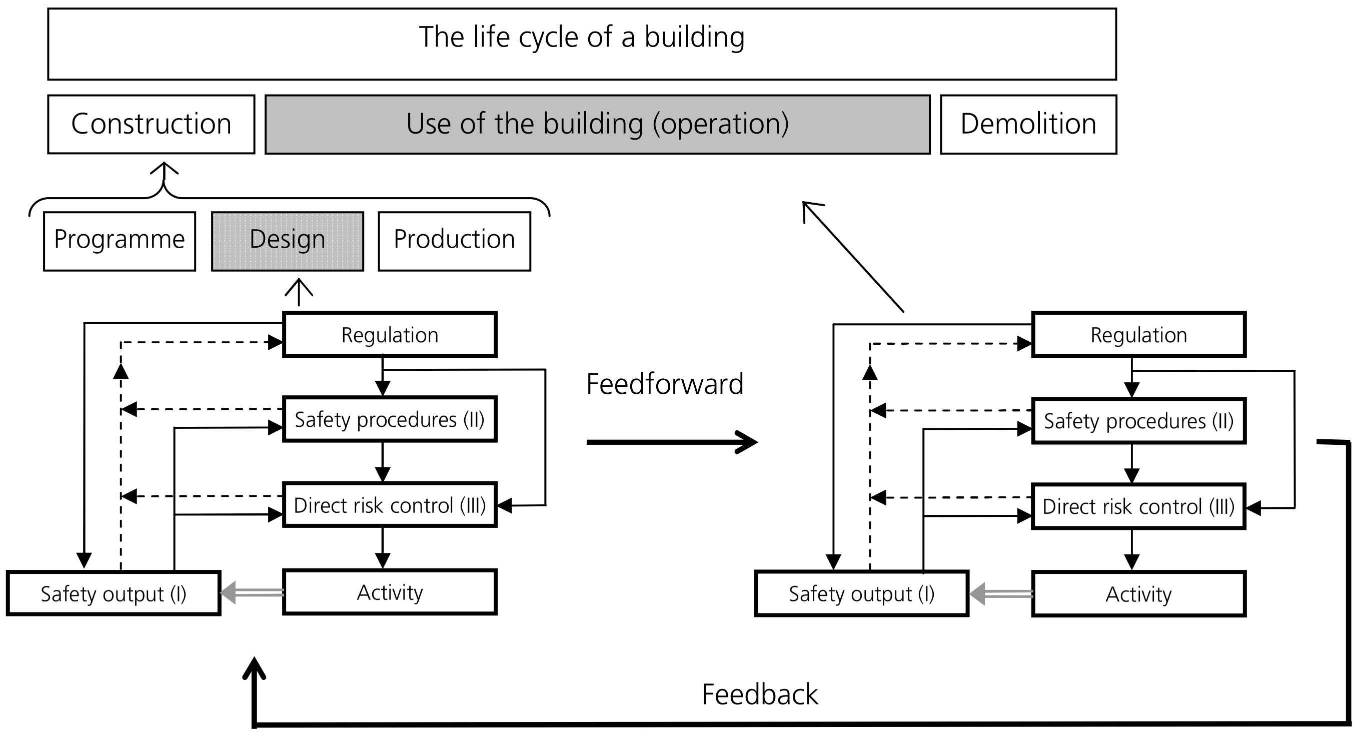


Figure 84. Where are the needs for coordination and exchange of information between the design and operational phases in order to control safety?

8.3.1 The level of fire protection related to the construction work in the operational phase

When inspecting the level of fire safety in the operational phase, the fire protection associated with the construction works should be assessed based on the level defined in the design phase. In the *BVL*, it is assumed that the functional requirements will be fulfilled during normal operation & maintenance, so a noticeable reduction in fire safety should not occur. On the other hand, supplementation may be necessary if the building is used for activities other than those assumed in the fire safety design, or if other conditions have changed, for example the capacity of the fire and rescue service, or the normal attendance time.

Link: Safety output in Design phase → Direct risk control in Operational phase.

8.3.2 Operation & maintenance plans should be drawn up during the design phase

BBR does not specify how the operation & maintenance of fire protection systems are to be undertaken during the operational phase. However, demands are placed on careful specification of how operation & maintenance are to be carried out in order to provide conditions such that the building's technical qualities will be maintained throughout the lifetime of the building. The choice of technical system during the design phase, e.g. sprinklers and fire alarms, affects the need for operation & maintenance in the operative phase. The fire safety designer who chooses the systems is in the best position to take in the whole situation and assess the need for operation & maintenance. This knowledge must be passed on so that it can be incorporated into the safety management system for the building in the operational phase. The designer must thus know how the system will work once the building has been commissioned, and he or she must be responsible for conveying the relevant information to the future owner or operator.

Link: Safety procedures in Design phase → Safety procedures in Operational phase.

8.3.3 Risk analysis as the basis for the SMS in the operational phase

If a risk analysis is carried out when analytic design is used, it will provide important information for the design of the SMS in the operational phase. This information will, however, require supplementation as the total fire protection in the building consists of other components than the technical fire protection of the building. Furthermore, more knowledge is available on (and it is easier to control), factors that affect the fire protection of the construction work once the building is in use.

Link: Safety procedures in Design phase → Safety procedures in operational phase.

8.3.4 Increased need for documentation of fire safety solutions

To allow inspection and control in the operational phase, it is important that fire safety solutions are well documented in the design phase. This normally takes the form of the fire protection documentation required by *BBR*. When verifying the fire safety in the operational phase it is important to ensure that the planned solution complies with the required level of safety, and to check that the actual fire protection in the building is that which was designed. Higher demands are thus placed on an understanding of the safety systems when inspecting and controlling fire safety in buildings designed using the analytic design method, compared with prescriptive design, as the solution will differ from traditional solutions. An inspector probably has less detailed knowledge of the solution when analytic design is used as it may be specific to that particular building. Good documentation is therefore of great importance in control and inspection.

Link: Safety procedures in Design phase → Direct risk control in Operational phase.

8.3.5 Integration between management systems for different kinds of fire protection

Fire protection of the construction work and other fire protection systems must be integrated. During the operational phase fire protection measures are usually integrated into one SMS, regardless of where the demands originated (i.e. in the systematic fire protection management). It may be necessary to bear this integration in mind in the design phase.

Link: Safety procedures in Design phase → Safety procedures in operational phase.

8.3.6 Difficulties in detecting errors in fire protection systems

Errors and inadequacies in fire protection systems are not detected in the same way as in other systems, e.g. heating or ventilation systems, as fire protection systems are not active in the normal part of the operation of a building. It may thus be necessary to have special alarms to bring attention to faults in such systems. For example, if a damper is not working correctly, it is important that the maintenance department be informed. Such alarm systems are best planned for in the design phase and are expensive to retrofit.

Link: Safety procedures in Design phase → Direct risk control in Operational phase.

8.3.7 Limited flexibility in the use of the building

When prescriptive design is used, it is relatively well-known how far the limits of the use of the building can be stretched before fire protection measures require supplementation. In the case of analytic design, the choice of protection system and the assumptions made can affect this flexibility. It is important that the limitations are communicated to the owner or operator of the building. The building may, for example, be designed for a certain number of people or a particular fire load. If these are changed the fire protection may be insufficient, although it would have been acceptable if prescriptive design had been used.

Link: Safety procedures in Design phase → Activity in Operational phase

8.3.8 Protection systems that require management in the operational phase

Some fire protection systems require that action is taken when a fire occurs in order to work. One example of this is the manual manoeuvring of fire ventilators. Documentation must thus be available to the owner for training of personnel. Other examples of this kind of protection system are alarms connected to a service centre so that the operator can check that the alarm is real before manually activating the evacuation alarm, or cases where the fire and rescue service is expected to deal with the evacuation of a building, for example using a public announcement system.

Link: Direct risk control in Design phase → Safety procedures in Operational phase.

8.3.9 Comprehensive picture in the formulation of regulations

Building regulations and legislation should be formulated based on the total investment made by society in fire protection in buildings. The resources available for preventive measures are distributed between different areas, i.e. not only fire protection of construction works, but also training and information, and the fire and rescue service in their preventive and fire-fighting capacity. It is therefore, not possible to apply prescriptive solutions from other countries uncritically, as resources may be distributed differently in different countries. Furthermore, the risks may differ between countries depending on the climate, demography and social structure.

Link: Regulation in Operational phase → Regulation in design phase.

8.3.10 Difficulties in modelling the effect of level on the management system

The level of operation & maintenance of systems in the operational phase affects the reliability of the protection system. It is important that reasonable assumptions are made on how the protection systems will work in the actual building, and that steps are taken in both the design phase and the operational phase to ensure that the system works properly. This means that assumptions must be made regarding how the safety procedure will work in the operational phase. There is currently only limited knowledge on how the extent and quality of safety management systems affect the fire protection in a building.

Link: Safety procedures in Operational phase → Safety procedures in Design phase.

8.3.11 Revision of the building regulations

It is important to revise the building regulations at regular intervals, especially as the concept of performance requirements is relatively new. Information must be gathered from both the design phase and the operational phase. Experience of how fire protection solutions work once the building is in use, and how they are affected by time provides important information which should be communicated to regulators.

Link: Direct risk control in Operational phase → Regulation in design phase.

8.3.12 Feedback

Feedback is important for several reasons if fire safety is to be controlled in a satisfactory way. The fire safety designer needs information on how the protection systems work in the operational phase, and what kind of operation & maintenance are required. In order to develop the design of fire protection of construction works in the long run, it is necessary for all the actors to assimilate feedback, so that the best systems can be used and inadequate solutions discarded.

Link: Direct risk control in Operational phase → Safety procedures in Design phase

8.3.13 Effect of age on the performance of a protection system

The performance of many protection systems deteriorates with age. It is therefore important that such systems be designed so that they fulfil the requirements not only when the building is new, but also after a certain degree of ageing and wear. The fire safety designer must therefore know how various systems are affected by aging in order to determine the requirements on operation & maintenance, and to be able to determine when the system must be replaced. If the protection system has a shorter lifetime than the building, as is the case for most fire alarm and sprinkler systems, the building must be designed in such a way that it is possible to replace these systems at a later time.

Link: Direct risk control in Operational phase → Safety procedures in Design phase.

8.3.14 Difficulty in controlling important factors not subject to regulation

Interior fittings, furnishings and decorations, and the kind of people using the building are factors that can greatly influence the risk in the operational phase, but these are not regulated by building regulations. A reasonable variation in the use of the building must be assumed in the design phase. It is unrealistic to assume that a public building will only be used by healthy, middle-aged people, not under the influence of alcohol. It is difficult to define the use of the building, but it should not be too narrow. The number of carers in a nursing home, for example, is crucial in the evacuation of the sick or elderly. Assumptions regarding these factors must be made using models of risk in the design stage, which undoubtedly introduces uncertainty into the estimate of the risk.

Link: Activity in Operational phase → Safety procedures in Design phase.

9 Discussion and future work

If we return to Becker's three basic conditions for incorporating new concepts into a professional field (Becker, 1999) (see Section 1.3), we can conclude that much work remains to be done before the introduction of performance-based building regulations can be regarded as successful. The results of introducing *BBR* will be discussed in Section 9.1 in the light of the safety-related consequences of the changes in building regulations. Suggestions for specific measures to assess the problems identified are summarized in Section 9.2, and the need for future research is presented in Section 9.3. Finally, the applicability and validity of the study are discussed in Section 9.4.

9.1 The consequences of changes in the building regulations

The introduction of *BBR* has led to changes in the tasks and responsibilities of the actors involved in the construction process. The way in which compliance with rules is assessed has also changed. A summary of the changes brought about is presented in Section 9.1.1 and in Section 9.1.2 examples are given of the results of the increased freedom of architects and fire safety engineers in the design of both buildings and fire protection.

Unfortunately, changes in the building regulations seem to have had a negative effect on the ability of society to control fire safety in buildings. In Chapters 5-8 a number of deficiencies were identified regarding the application of the regulations and the methods employed by many designers. The consequences of these shortcomings are discussed in Sections 9.1.3 to 9.1.7 from a general perspective, and extend, deepen and summarize the discussions in Chapters 5-8.

9.1.1 Distribution of tasks and responsibilities

In this section a brief summary of how tasks and responsibilities have changed at different levels of risk intervention will be presented. For a detailed presentation of the levels in Hale's framework, see Table 4 in Section 3.1.3.

- *Level I, box a: Establish goals for safety.* The level of requirements on fire protection of construction works is determined at the general level by a country's parliament and government through legislation. In Sweden, these are the *BVL* and the *BVF* (The Act and the Ordinance on Technical Requirements for Construction Works, etc.). These requirements are clarified by *Boverket* in the building regulations, *BBR*. The intention of introducing *BBR* was to formulate measurable performance demands so that the designer could show that the demands were fulfilled when analytic design was employed. When the prescriptive design method is used, it is assumed that the goals on this level are indirectly met, which was also the case when the earlier prescriptive regulations were in force (*NR*, 1988).

- *Level I, box b: Check that output goals are achieved.* In the prescriptive regulations there was no need for review at this level, but following the revision of legislation in connection with the introduction of *BBR*, it was decided that responsibility for review should be shared. The *PBL* (1995) states that: "control may be carried out through documented self-implemented control, independent experts, or, if justified by special reasons, the local building committee". In this case, control refers to the functional requirements in the *BVF*. The building committee decides who should carry out the control once the control plan has been established.

- *Level II, box c: Formulate rules for safety procedures & safety case and how they control risk.* At present many of the rules in the building regulations are aimed at this level of risk control. Demands are placed on documentation of the fire safety solutions, and the methods used to design fire safety are regulated. However, the designer is given great freedom in making many of the most important decisions, for example, the extent of the analysis, defining the performance requirement and the acceptance criteria. Level II, box c is therefore partly regulated by *Boverket*, and left partly to the designer to decide how the design is to be carried out. Under the previous regulations (*NR*, 1988) the designer was not required to make hardly any decisions at this level, as detailed requirements on technical solutions were prescribed. It was, however, possible to design fire protection of load-bearing structures with analytical methods.

- *Level II, box d: Check the structure and functioning of the safety management system.* The building committee decides who is to perform the control at this level, just as for level I, box a. As explicit performance demands are very vague and incomplete, control of the design will in effect mean control of the design procedures used, which should be described in the fire safety documentation. It is not made clear how the control is to be carried out. In the earlier regulations (*NR*, 1988) there was no need for control on this level.

- *Level III, box e: Formulate detailed rules for the execution level.* Depending on which design procedure the designer uses determines who will regulate this level (i.e. direct risk control level). If prescriptive design is used, the general guidelines in *BBR* must be followed, which means that *Boverket's* rules for designing technical fire safety protection are used. If analytic design is used, it is the designer who decides which rules to use for technical solutions, but he or she must verify that the solutions meet the demands at Level I, box a. In *NR* (1988) *Boverket* determined the rules at this level.

- *Level III, box f: Check that execution level rules are carried out.* Review and control at this level is affected by the formulation of the control plans. Here it is stated which controls are to be carried out, what kind of certification and other documents are to be presented to the building committee, and which notifications are to be made. The person responsible for quality matters ensures that the control plans are followed. Responsibility may be shared by various actors. Under the previous regulations the building committee carried out a detailed control, and they regularly sought the advice of the fire and rescue service in issues of fire safety. This option is still available if deemed necessary, but seem to be more and more sparsely executed.

One of the consequences of the changes in the building legislation is that the role of the fire and rescue service has become less clear. It is the task of the local authorities to ensure that planning and building act is followed. However, this responsibility is not regulated in detail at a local (municipal) level; the local authorities are expected to organize their own working procedures. It would be remarkable if the building committee or the equivalent authority did not require the expert knowledge of the fire and rescue service in some projects, while in another projects it was considered reasonable to rely on the self-implemented control by the developer. In some municipalities, the fire and rescue service has been engaged as an expert by different actors, for example, the builder or the owner, which may limit the ability of the building committee to make a suitable assessment of the need for control.

9.1.2 New buildings and new safety systems

The number of university-educated fire safety engineers in Sweden ten years after the introduction of *BBR* is approximately 450, and a large proportion of these are engaged in the construction process. The opportunity to design fire protection in a novel way has been exploited to a high degree. Examples of innovative solutions are blocks of apartments with a single evacuation route, high-rise buildings with double glass facades, public buildings with large open areas not equipped with sprinklers, and five-storey apartment buildings with wooden frameworks, to name just a few. New protection systems have also been introduced, including residential sprinklers and fire protection of ventilation systems with joint ducts.

The examples above indicate that several of the expectations associated with changes in the building regulations have been fulfilled (see Section 1.2), but there is a lack of a comprehensive systematic investigation. For example, no national investigations have been carried out into whether the total cost of construction has fallen, or whether the proportion of the total cost attributable to fire protection (including design) has been lowered. Unfortunately, it also appears that some expectations have not been fulfilled, e.g. those regarding safety. Deficiencies have been found in the application of the regulations (Section 9.1.3) and the engineering methods used in verification (Section 9.1.4). Furthermore, there is considerable need to revise the regulations in order to obtain better control of fire protection of construction works (Section 9.1.5).

9.1.3 Inadequate application of regulations in analytic design

Designers are eager to adopt the benefits of analytic design, but are sometimes reluctant to take on the extra work load and engineering responsibilities. The requirements concerning documentation, verification and review differ considerably depending on the design procedure chosen and the specific design project. Unfortunately, this difference is not always recognized by practitioners.

Serious shortcomings in quality have been identified in the study of projects where analytic design was used (see Section 6.3) to the extent that the aim of verification is not fulfilled. It is difficult to determine from the documentation whether a solution satisfies the demands laid down in the building regulations or not. This is due to both the content of the documentation and the method used in evaluating the safety. The result is inadequate control on the part of the designer, while self-implemented control and external review are, at the same time, problematic.

Considerable responsibility rests on the designer who often (consciously or subconsciously) finds him or herself in a moral dilemma. The designer is expected to ensure that the level of fire safety satisfies the demands of society, while, at the same time, designing the most cost-effective solution possible for the customer. It may thus be difficult to decide the scope of the analysis necessary in verification as high-quality verification is seldom required by the developer or customer. In most cases their concern in the fire protection is limited to the issue that the solution is acceptable to the authorities, and that it does not cause any delays in the construction process nor increase in project cost.

The designer thus risks finding him or herself in a situation where they feel pressured into reducing the scope of the analysis in order to be competitive or to ensure high returns for their own company. Extensive analysis may seem to represent an extra cost if there is not explicit demand that the solution would not be accepted otherwise. Such external demands are seldom made on verification. The potential conflicts between the designer's interests and those of society are obvious, but society still relies on the designer choosing a suitable degree of analysis in verification. The fact that the designer is expected to reject a solution found to be inadequate through verification, which was originally suggested by him or herself, leads to further conflicts of interest and indicates that the control system is perhaps far too trusting.

More of King Hammurabi's building code (see Section 1.1) would be desirable in order to solve this problem, instead of relying on the assumption that good verification means a competitive advantage which promotes quality. The market is becoming accustomed to a certain level of quality and cost for fire safety design, and many fire safety engineers have based their businesses on today's relatively good profit margins. It is therefore not realistic to expect this sector to make sweeping changes. The problem is of such gravity that the central authorities in question should act resolutely. At the local level, building committees could agree to be more stringent in their control in order to bring about changes in design practices. The danger is that they would be forced to place demands on a level of detail for which there is no expert knowledge available. Considerable national variation could also be expected and the construction process would then not proceed in the way intended.

9.1.4 Inadequate verification methodology

To achieve risk control in specific cases the effects on the *total* risk must be evaluated in verification, in order to determine whether a solution is adequate or not. All the scenarios contributing to the total risk whose contributions are affected by changes in fire protection must be included in the analysis. It should be a basic rule that scenarios that have the potential to affect the decision of whether a solution complies with the regulations or not should be considered. Identifying these scenarios is an important part of verification and a designer must be able to justify why a scenario has not been included in the analysis. The choice of measure of risk and method of analysis indirectly affects the extent of the analysis and the information on which the evaluation will be based. These choices are often rather arbitrary, which can lead to serious flaws in the assessment of safety; an inadequate solution may appear acceptable, and vice versa. Two kinds of scenarios often neglected are:

- those where technical systems fail, and
- those resulting from extreme events.

Both these kinds of events can lead to considerable contributions to the total risk. In cases of more extensive changes to fire protection it is probable that the contributions from these kinds of scenarios will be affected. A consequence-based risk measure can then give misleading information on which conclusions are based regarding the influence on the total risk (see Section 6.4.4). It is thus necessary to use a risk measure that is based on the contribution from all relevant scenarios, i.e. a mean risk, in order to ensure correct risk evaluation.

9.1.5 Need for development of performance-based regulations

One reason for the problems identified in application and methodology is believed to be that the prerequisites for the use of performance-based regulations, i.e. quantitative performance demands, have still not been developed. Resources must be invested in research in order to achieve this development. Gross (1996) presented three basic demands which must be met in order for performance-based regulations to work in practice.

1. *"User Requirement* is a qualitative statement giving the user need or expectation for the item being addressed. It is a subjective statement of what the product or assembly is intended to do.
2. *Performance Requirement* is a quantitative statement defining the level of performance required to meet the user needs or expectations for the item being addressed.
3. *Evaluation Methods* set forth the tests or other information upon which judgment of compliance with the performance requirement is based. It identifies the standards, inspection methods, engineering analysis, calculations, review procedures, historical documentation, test methods (be they laboratory or field, full-scale or less than full-scale, destructive or non-destructive) used in evaluating whether or not the performance requirement has been satisfied."

The study of the regulations carried out in this work revealed serious shortcomings regarding points 2 and 3 above. The ability of both designers and building officials to check fire safety in buildings is limited by the fact that several of the performance demands are ambiguous and have not been quantified, which leads to problems in verifying compliance with the regulations (see Section 5.3).

If the designer instead decides to follow the general guidelines in *BBR*, it is found that these are not sufficiently detailed or extensive for the design of fire safety in a building. A commonly employed method is to use so-called established common practice, which consists of a combination of previous building regulations, manuals, handbooks, guidelines and internal company reports in order to design acceptable solutions. Despite the fact that only the solutions given in the general recommendations of *BBR* and in *Boverket's* technical reports constitutes the prescriptive method (and thus fulfil the regulations without the need for verification with analytic methods) verification is seldom carried out when the above mentioned common practice is used.

Many of the solutions provided in earlier regulations probably fulfil the requirements of the current regulations, but they cannot simply be regarded as prescriptive solutions. There is no guarantee that previous regulations are adequate in all situations, and inadequate solutions have in fact been identified in earlier regulations. Another problem is that the definition of what constitutes common practice is unclear. As matters stand today, designers have taken it upon themselves to decide which manual, guidelines or report should be interpreted as common practice. As no demands are made on the quality of manuals, there is no guarantee that the solutions they provide really satisfy the demands in *BBR*. Many of these documents can probably serve as good examples, but if they are employed without verification, this implies that they are acceptable. It is obvious that the authors of manuals cannot verify detailed solutions for all possible cases in which they may be applied.

The demands made in *BBR* are not fulfilled by common practice in the way it is applied today. Does this necessarily mean that all the solutions developed from common practice are illegal? If the answer to this question is yes, that would mean enormous problems, and signify the failure of the control systems employed. If the answer is no, this means that society's control of fire safety is poor, as there are no demands on the quality of such manuals.

Shortcomings and difficulties in interpretation indicate a considerable need for the continued development of the performance-based demands in *BBR*, and a number of clarifications from the authorities. It is difficult for a single designer to find answers the following questions which are crucial for risk control:

- How far can the boundaries be stretched? In other words, to what degree can traditional fire protection be changed?
- Can trade-offs be made between different functional requirements?
- How extensive should the analysis be for a specific case?
- What is a suitable definition of risk?
- Which properties or attributes of a solution should be considered in verification?
- How should scenarios be chosen to ensure a sufficient basis for evaluation of the effects on the total safety in a relative comparison?
- How does one determine if a model adequately describes the case in question?
- How does one define an acceptable level of risk against which the solution can be verified?

- How should a reference building be defined if a relative comparison is used for risk evaluation?
- How can a basis for verification be obtained for the kinds of buildings in which prescriptive design is not applicable?

The building regulations must be interpreted, to a high degree, at the local level as decisions on what constitutes an acceptable solution have not been made at the national level, and guidance is therefore lacking. The uncertainties arising from the above questions mean that design is arbitrary, and factors other than those related purely to safety govern the verification. This may seem remarkable bearing in mind *Boverket's* agenda for development in this area, which was presented in 1997 (see Section 2.4). The idea was that designers should use their innovative capacity to design new buildings and new solutions for fire protection, not for the interpretation of the level of safety sought by society. The latter is to be determined by the regulating authority in question.

9.1.6 Controlling the safety in case of fire in buildings

The ability of society to control fire safety in buildings varies depending on which of the three levels of risk control that is used in regulations. If regulations consist of detailed rules on the layout of the building and specific fire protection measures (prescriptive demands), variation will arise as the demands must be formulated for a whole class of buildings in order to be practical in use. This variation in safety is unavoidable, and is the result of the method of design. If a particular design method causes a large variation in safety level for a particular class of buildings, then society has only limited control over the safety in a specific building. When a new building is designed, the level of risk may be anywhere in a broad interval, depending on its layout and design. Calibrating the design method so that it gives a *reasonable* level of safety involves a compromise between the cost of the fire protection for the buildings with the highest safety level in the class and the risks that the buildings with the lowest safety level are exposed to. In other words it means keeping costs down while maintaining an adequate level of safety. Such a compromise is difficult, but can be facilitated by a small variation in the risk level within the class of buildings. The extent of the variation can be affected, for example, by the degree of sub-division into building classes. The variation in risk due to the design method and/or technical solutions is acceptable. As *Boverket* has issued prescribed demands, society has good control over the safety of the class of buildings, and for single buildings there is control within the allowed variation for that class (assuming that the regulations are followed). The variation in risk for a class of buildings resulting from prescriptive demands was described in Section 5.4.1.

The potential for control will be quite different if performance-based demands are used to define the level of safety required. If one has complete knowledge of all the sources of uncertainty that affect the results of the calculation, and one assumed that suitable methods are used, adequate fire protection can be designed such that a given level of safety is achieved according to the performance demands. This is of course wishful thinking. Limitations on time, knowledge and the models necessary, mean that only a rough estimate of the safety can be made. The calculated level of risk and the actual level will therefore differ, and be associated with uncertainty. As these kinds of calculations are used to determine how much protection is necessary, there will be uncertainties in the correct amount of protection, and the actual safety in a class of buildings will vary, even when a specific level of safety is defined as desirable. Furthermore, if the level of desired safety is poorly specified, or not given at all, the uncertainty within a class of buildings will increase further, and the ability to check the safety will be reduced. Much evidence presented in this thesis suggests that it is currently not possible for society to control fire safety using only performance-based demands.

The third method of placing demands on safety involves regulating the approach, procedures and models used in fire safety design, and documented proof that the demands of building regulations have been met. This allows explicit demands to be placed on the treatment of uncertainties and stricter control to be exerted until the necessary knowledge and models are available. Some such demands are made in *BBR* today, but clarification and supplementation are needed for it to be possible to control the final result of design, i.e. the fire protection in a building. The conclusions drawn from the present work indicate that there is a considerable need to place clearer demands on fire safety design procedures using these kinds of regulations, partly because of the shortcomings identified in the methodology used, and partly the generally level of knowledge in the area. There should be a reasonable chance of developing suitably extensive regulations for the control of safety by society, while allowing the designer freedom to design technical solutions according to his or her abilities.

9.1.7 The consequences of the problems identified

Are the problems discussed above acute? According to fire statistics, Sweden is no worse than any other country (Wilmot, 2004), and no trends towards an increase in the number of fatalities due to fire since the introduction of *BBR* can be seen (SRSA, 2003a). There is thus no acute danger, but in the longer run, the consequences may be serious in several respects. Experience from other countries, e.g. Japan (Tanaka, 2004), show that it takes time before new design methods become widely established and used. It is thus probable that the use of analytic design will increase in Sweden, while a highly doubtful practice in the application of this method spreads throughout the country. The consequence will be that society will lose its ability to control fire safety in buildings. The present review system will not be able to handle the problems. Changes in traditional fire protection will continue, and the limits on the kinds of solutions that are accepted will be continuously tested. The problems identified in this work are not expected to decrease, but rather to increase.

One expected result of this is that the number of fires with serious consequences will increase in the longer perspective. As fire is a relatively rare phenomenon, it is reasonable to believe that it will take time for the erosion of fire protection quality to become clear. The political consequences of this, when such fire actually occurs, may well lead to the revision of legislation according to new directives. The opportunities for designers themselves to design suitable technical solutions will, with all probability, be limited. There is thus a risk that several of the solutions used today will not be accepted in the future, even if they provide sufficient safety. It is difficult to foresee the consequences of this for *Boverket*, but there is considerable risk that the public will lose confidence in building regulations, which may lead to serious repercussions for this authority.

9.2 Suggested measures to improve societal risk control

It is commendable that performance-based regulations give the designer the freedom to design technical solutions based on the specific needs in a building. However, it is not reasonable to give the designer complete freedom to make decisions regarding *what,* and *how* compliance with the regulations, should be verified, and how the regulations should be interpreted. The process of verification must be developed from being essentially an arbitrary consequence analysis, to being a reliable analysis of the risk if it is to fulfil its purpose. Both guidelines and to undertake corrective actions are necessary. Uncertainties in what constitutes a suitable or reasonable approach to verification, seen from the safety point of view, are so large that more stringent regulation of *safety procedures & safety case* is required than that in place today. If society is to be able to control fire safety in buildings it is absolutely necessary for *Boverket* to become more actively committed to the issue.

There will be no general, standardized method of calculation with which to guarantee a specific level of safety available for quite some time (if ever). On the other hand, some of the most serious deficiencies in quality identified here could be resolved with relatively small resources. The solution of other problems would, however, require long-term research. In Sections 9.2.1 to 9.2.5, proposals are given for specific measures, based on the results of this study. The need for further research is discussed in Section 9.3.

9.2.1 General demands on quality of verification

In order to specify the content and extent of verification in *BBR* more clearly, the current demands must be supplemented. In the short term, it may seem appropriate to refer to standards or manuals in the area, which would only require the minimum of effort. In the longer term, however, it would be better to formulate new demands, which are adapted to the conditions prevailing for verification, and to develop quantitative unambiguous performance-requirements.

The following points constitute the foundation of general demands that should be placed on verification. They are based on several standards and manuals on risk analysis (IEC, 1995; Morgan & Henrion, 1990; SRSA, 2003b), as well as the conclusions drawn from the extensive study of fire safety documentation. The list below is by no means complete, but ought to be a good starting point. For a more detailed description the reader is referred to the manuals cited above, and to Chapters 5, 6 and 7 of this thesis.

- *The relevance of risk analysis* – The aim of risk analysis in the verification must be made clear. Verification must be used as the basis for making decisions, and this must be stated in the goals and objectives of the analysis. The demands placed on the technical solutions must be made clear. The procedure used, according to *BBR*, must be described and the demands placed on the verification and review process.

- *Description of the building and systems* – A comprehensive description of the building and of the activities to be pursued therein is necessary. The proposed fire safety solution, or the technical trade-off, motivating the analysis must be presented.

- *Extent, limitations and demarcation of the analysis* – It is necessary to present the limitations and demarcation, as well as the extent of the analysis. It should be ensured that the scope is sufficient to satisfy the objectives of the analysis. A qualitative analysis of the effects on important safety-critical properties of the protection system and the functional requirements affected may be necessary to determine whether important issues fall outside the demarcation.

- *Assumptions and simplifications* – For the analysis to be transparent, it is important that the assumptions, simplifications and approximations made are clearly presented and justified, e.g. in system representation and model selection. Their effects on the final result must be studied in a sensitivity analysis before it is concluded that the assumptions and simplifications are adequate.

- *Definition of risk* – The qualitative and quantitative factors defining risk and safety must be defined. The methods used to measure probability and consequence should be described and used in a way consistent with these definitions.

- *Method of risk analysis* – The method of risk analysis employed and the approach used in verification should be specified and presented in a transparent way. The way in which the analysis method elucidates the actual change in risk in a relative comparison should be described.

- *Identification of scenarios* – The reasons for considering some scenarios but not others should be given. The extent to which possible accidents have been considered, and factors that contribute to them arising, should be described.

- *Calculation of the consequences* – The choice of model should be based on the specific needs in each case, not vice versa. The model must appropriately describe the case in question, and should not be used outside the area for which it has been validated. The model must be suitable for describing the expected physical course of events. The accuracy with which the consequences are modelled should be considered.

- *Calculation of the probability* – The available frequency and reliability data are often based on historical observation of other systems and have therefore limited relevance in the specific application. Uncertainty intervals for probabilities must therefore be used in combination with modelling of the specific system, e.g. fault tree modelling. Possible relations between the reliability of different systems must be considered. The effect of the uncertainty on the design decision should be studied in order to ascertain whether more information should be obtained to reduce the uncertainty.

- *The presentation of risk* – Care should be exercised in choosing the most suitable measure of risk to describe and evaluate the risk and that choice should be justified. Consideration must be taken as to how the risk is distributed throughout the building. It should be investigated whether the risk to individuals is greater in certain rooms or in the whole fire compartment. An average risk measure for a whole building is not sufficient. It should be shown that the results of the analysis do not depend on the way in which they are presented.

- *Evaluation of risk* – The way in which probability and consequence are combined to produce a measure of risk should be carefully considered. The risk attitude of the decision maker should be borne in mind as well as the preferences of other stakeholders, e.g. the people exposed to the risk. It must be determined whether inadequate measures can be differentiated from those that conform to the demands.

- *Acceptance criteria (decision criteria)* – The acceptance criterion must be clearly stated, bearing in mind the aim of the analysis, by specifying the attributes that define either the performance demand or level of safety to be fulfilled. If several attributes are used in making decisions, e.g. the number of people injured and the cost of damage, the rules governing the decision must be presented, e.g. if trade-offs between the attributes are allowed or not. If the consequences are measured in terms of several attributes, e.g. the number of injuries and fatalities, and these are considered together by the decision maker, the assigned weight to each attribute must be specified.

- *Results and conclusions* – The results and conclusions presented must be based on the actual analysis carried out. Verification provides the basis for decisions and must be unambiguous.

- *Uncertainties* – In order to be able to understand the results of a risk analysis, detailed knowledge of the uncertainties is necessary. The uncertainties in the various stages of the analysis must be presented, together with a description of how they have been treated and how they affect the conclusions. Systematic sensitivity and uncertainty analysis must be performed. The level of uncertainty analysis necessary depends on how conservative assumptions are made.

- *Review* – The verification must be reviewed by someone who has sufficient competence, and who is not working on, or is dependent on, the project. The most difficult task is not only understanding the report, but ascertaining whether something important is missing. (General checklists have been devised for this, e.g. SRSA, 2003b.)

- *References* – References must be given to models, assumptions, input data, etc. Expert judgement not based on a scientific foundation should be avoided.

- *Documentation* – The documentation should be formulated bearing in mind the fact that it must be possible for those not involved in the detailed design of the building to check and review the verification. The key words here are clarity and transparency. The reasons for all important decisions must be documented in order to be able to trace changes, which means that it is not acceptable to present a description of the final solution when the project is to be concluded.

- *Updating* – If conditions affecting the fire protection change, then the verification must be updated.

- *Safety management* – Verification is an important part of the process of ensuring that the completed building complies with the building regulations in the operational phase. A number of measures concerning information and coordination are necessary already in the design phase, e.g. connection to operation & maintenance routines, training plans, and the development of routines and instructions for the use of the building (both normal use and in emergencies).

The list of general demands must also be supplemented based on the needs of each specific project, bearing in mind the building, the fire protection systems chosen or the methods used for verification. A great deal of guidance can be found in the literature, e.g. quality demands for CFD calculations (Kumar & Cox, 2001) and fire safety engineering risk analyses (Hall, 1999), which can be useful in both the design and review process.

9.2.2 Proposed procedure for verification

How can a designer meet the quality demands stated in the previous section (Section 9.2.1)? Placing demands on verification is meaningless if guidelines and recommendations are not simultaneously developed showing how the demands can be satisfied in specific situations. There is a lack of such guidelines in the design of fire protection. Manuals and guidelines have been developed in many of the countries that first adopted performance-based building regulations. Examples are given below.

- International Fire Engineering Guidelines (IFEG, 2005).
- Fire Safety Engineering in Buildings (BSI, 2001).
- Fire Safety Engineering (ISO, 1998b).
- The SFPE Handbook (NFPA, 2002).
- SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design (NFPA, 2000b).

The problem is that almost all of these guidelines are directed towards the use of input data and models to analyse the course of a given fire in a well-defined scenario, where unambiguous quantitative acceptance criteria have been formulated. There are unfortunately no tools available to deal with most of the problems identified in the present work. One of the practical results of this work is a proposed procedure for verification using computational methods in connection with analytic design. The procedure consists of a number of important components, which are summarized in Section 6.5.2, and should be regarded as a tool or an aid for the designer in satisfying the demands on quality described in Section 9.2.1. This procedure is intended to act as a complement to the international manuals listed above, which have a slightly different focus. The procedure cannot, however, replace a proper understanding of the actual physics involved.

As it is impossible to avoid errors and inadequacies in verification, there is a great need for quality control in this process. The building committees play an important role in the construction process by providing a form of independent observation. National cooperation in the development of a method to ensure compliance with *BBR* would be desirable, although this is something that *Boverket* has avoided, and does not regard itself authorized to carry out (*Boverket*, 2004a). This thesis presents a proposal for a simple tool of this kind (Section 6.5.3) with the purpose of assisting building committees. The method is simple and straightforward, and is intended to support the decision maker who determines the appropriate level of review in order to identify potential errors made in verification. Such a decision can be aided by a simple analysis of certain indicators and the design procedure used to obtain an idea of the size of the trade-off made in an alternative solution compared with the prescriptive one. By developing a tool that is used independently of the designer's verification some of the concerns raised about the designer's subjectivity can be dealt with.

9.2.3 Future development of the prescriptive design method

A number of findings underline the importance of the continued development of prescriptive design. A short summary of the arguments presented in Section 7.3 is presented below.

- A simple method of design is required as an alternative to analytic design (even in the future).
- Prescriptive design must be revised when the conditions affecting the level of safety are changed.
- Further development is necessary to adapt the prescriptive method to new kinds of buildings and fire protection measures.
- The general recommendations in the building regulations cannot today be used to design a whole building. Earlier regulations and manuals must be used, but this may lead to unreasonably high demands on verification.
- Prescriptive design solution constitutes the best basis on which to decide what is, and what is not, an acceptable solution in analytic design.

- The safety level resulting from prescriptive design appears to be inadequate for some buildings. If the aim is to achieve a uniform level of risk in buildings of the same type, e.g. assembly halls, it is necessary to include variables such as height or volume in the design expressions.

In this thesis, various strategies for changing prescriptive design are given, and the risk analysis methods presented can be used to evaluate the effect of changes for a whole class of buildings (see Section 7.5). Variables and parameters of importance in especially vulnerable buildings can be identified. The prescriptive method can be modified and the safety-related consequences can be studied scientifically. As it is possible to study how technical trade-offs affect a whole class of building using this kind of analysis, it should be possible to design trade-offs that do not require verification in each case.

9.2.4 A national investigation committee

In Section 7.3 the increasing problem of lack of development of the prescriptive method was touched upon. One effect on the construction process is that designers and building committees may have conflicting opinions about how to interpret the demands in the building regulations. If it is not possible to arrive at a compromise it may be difficult to solve the conflict as there is no central organisation to which the parties can turn. *Boverket* is very frugal with its advice in such matters, and tries not to become involved in specific projects, as their advice will immediately be interpreted as an *acceptable solution* or common practice not requiring verification in the future.

The degree of detailed review that can be exerted by the authorities is directly dependent on the resources available. The public review system applied in Sweden is not especially demanding, while that in Japan, for example, is. In the latter country a national committee conducts investigations of large projects in which analytic design has been employed. This places high demands on resources, but means that there is a central body that decides what is acceptable and what is not. Bearing in mind the freedom allowed in the new building regulations, there may be reason to consider the establishment of a central body in Sweden that can be consulted when analytic design has been applied and it is unclear how the solution should be verified. Buildings designed according to *BBR* 5:13, which demands analytic design, are examples of buildings where this need may arise, especially considering the poor quality of some of the solutions identified in this study.

9.2.5 Other measures to improve the quality of analytic design

Most of the developmental work presented in this thesis has been devoted to the procedure for verification discussed in Section 9.2.2, but a number of other measures aimed at improving the quality and control of analytic design have been discussed in Chapters 5-7. These were not investigated in detail, but should be regarded as interesting additions to the verification procedure. Examples of such measures are:

- increased references in the regulations to standards and manuals,
- compulsory certification of designers,
- development of methods and guidelines for reviewers and inspectors,
- international collaboration, and
- increased research budgets for the development of the analytic design method.

9.3 Future research in fire safety engineering

Fire safety engineering is a young area of engineering. All areas of engineering are characterized by various stages of development where expert judgement and experience play an important role initially, but with time these must be re-evaluated and questioned in order for development to continue and make way for more scientific arguments. It is my hope that this thesis has contributed to this development by identifying problems associated with the analytic approach employed today, and proposing solutions. However, the need for continued research is considerable.

Following is a summary of some of the areas of research connected with analytic design, and a synthesis of the needs identified in this work. These needs have come to light at several international conferences, see for example SFPE (2000a) and UEF (2001), with the aim of systemizing the need for research in fire safety engineering. Four main areas of research are identified. The greatest emphasis is placed on the final area (Section 9.3.4), as it is closely associated with the study presented in this thesis.

9.3.1 The phenomena involved in fire

Understanding, quantifying and modelling the physical and chemical processes related to fire development and smoke spread in enclosures, i.e. fire initiation, fire growth and spread, and different stages of back draught, is essential for the validity of the verification. A number of issues should be addressed in order to develop design applications further.

- *The effect of ventilation conditions on the chemical and physical processes* – This has a significant effect on the production of soot and toxic gases, which must be considered when lethal or sub-lethal effects of fire and smoke are to be modelled.
- *The effect of different barriers and extinguishing systems on the spread of fire and smoke* – Interactions between different systems can present an additional challenge, e.g. the interaction between sprinklers and smoke ventilation and their effect on the spread of fire and smoke.
- *Development of modelling tools, e.g. CFD models, for both research and engineering applications* – There is a great need for tools to predict fire spread within an enclosure. An example of a phenomenon that is difficult to model is the effect of lining materials on the spread of smoke and time to reach untenable conditions.

9.3.2 Human behaviour

Escape is a crucial part of the fire safety strategy. Knowledge of human behaviour, performance and response is essential when modelling evacuation, yet our knowledge of how people react when fire occurs is limited. It is difficult to anticipate the response and behaviour of people who may be sleeping or have various degrees of disability. Another issue is that the effect of exposure varies considerably between different sub-populations. The design requirement can therefore vary considerably depending on whether a healthy person is used as the design occupant or a person from a vulnerable group, e.g. an asthmatic person, a child, an elderly person or a person with a disability. The amount of smoke and toxic gases causing incapacitation is one factor that differs substantially between these groups.

9.3.3 Input data

It is important to have relevant data to be able to predict the performance of fire safety systems and how building products, materials, equipment and furniture respond to fire. The behaviour of glazing is one example of a building component where more data are required. Another example is data on the correlation between variables and events, e.g. how the response time correlates with the size of a room, and if it is more likely that a second safety system will fail given that one system malfunctions. A third example is how the uncertainty in variables varies within a group of buildings. Is it reasonable to expect the same distribution of fires in a small shopping centre as in a large one? However, data collection and experiments are not the only activities required. Sharing information and learning how to use it in an appropriate way in design applications are equally important.

9.3.4 Risk management and design methodology

Advanced modelling tools alone will not be sufficient to identify the relevant aspects of fire risk when designing buildings. The performance-based building regulations have been introduced without the aid of a scientifically based design method which takes risk and uncertainty into account.

9.3.4.1 Risk evaluation

A method of risk evaluation for use during verification must be developed. A number of factors must be considered in such a method, for example:

- Society's and/or decision makers' attitudes to risk in the weighing of probabilities and consequences to give a suitable measure of risk (see Section 5.5.4), which may mean that small and serious consequences are given different weights.
- Attributes of fire protection other than the level of risk (see Section 5.5.5).
- The possibility to evaluate the consequences more subtly than just the number of people exposed to critical conditions. How can one choose between two solutions where one means that two people are exposed to critical conditions without being further injured, and one where one person is exposed to critical conditions and then dies?

9.3.4.2 A standardized risk-based verification procedure

The long-term work on the development of a general verification procedure in order to ensure that the required level of safety has been attained is based on being able to deal with the uncertainties for a group of buildings by connecting the method, input data and acceptance criterion. In order for such a method to provide practically useful results more knowledge must be gathered on uncertainties. Variables associated with uncertainties for specific buildings must be surveyed in each class of buildings. There is a need, for example, to know how variables that affect the risk vary in a specific building and in a class of buildings. Is this variation constant, or does it depend on area or height, for example? If it is possible to determine how the uncertainty varies for a class of buildings, it will be possible to determine design values and acceptance criteria which together ensure that a specified level of safety has been achieved.

One way to develop a standardized verification procedure is to create typical design scenarios that represent a group of scenarios. The total risk can be adequately represented by studying a sufficiently large number of typical scenarios. If the probability of these typical scenarios can be determined, it will be possible to analyse the level of risk in the case of fire by considering the various risk contributions.

9.3.4.3 Coordination and feedback between the design and operational phases

A new problem, previously given little attention, but which is highlighted in Chapter 8, is how coordination between the design phase and the operational phase should be approached when analytic design is employed. The conditions under which such coordination takes place are different using analytic design than when using prescriptive design, and this may have a significant effect on the fire safety.

9.3.4.4 Interaction with the fire and rescue service

The design of a building has a considerable effect on the ability of the fire and rescue service to extinguish a fire and on the safety of fire fighters. There is a lack of knowledge on the effects analytic design will have in such cases, but there are already indications that the fire and rescue service is of the opinion that changes in the building regulations have had a negative impact on their fire-fighting and rescue operations (SRSA, 2004b). One of the reasons for this is that even if the building satisfies the demands in *BBR*, rescue service personnel have less knowledge on how the fire protection in the building is designed. Previously, they knew which fire protection measures to expect, and how they should be dealt with, while today they can be faced with a completely new situation. This means that they must obtain information in new ways, and may even have to develop new methods of operation.

9.4 Applicability and validity of this study

In this section, the conditions, assumptions and simplifications affecting the reliability and validity of the study are discussed.

9.4.1 Choice of general analysis method – the framework for risk control

Löfstedt and Renn (2004) identified different ways of governing risk in society and categorized them into five different management styles (see Section 2.1.2). The main differences are related to the concepts of "selecting objectives, assessing and handling data and finding the most appropriate procedure for balancing pros and cons."

Two of these management styles are applicable in the area of fire safety design, i.e. *routine risk management* and *risk-based management*, and were used as a starting point when evaluating risk control. The similarities between these two styles are many, but the most important is that regulation is used in a similar way, i.e. as a tool for risk control where the safety objective is determined by society and not by the operator (or designer). The major differences are in the scope and complexity of the risk. When using the risk-based style, more sophisticated methods are necessary to collect, analyse and interpret data. Since it is not self-evident to which of these two styles fire risk in buildings belongs, no clear distinction between the two was considered necessary.

The other risk management approaches, not considered here, focus mainly on risks associated with a large degree of uncertainty, in particular ignorance, or ambiguity. For example, if there is a substantial lack of knowledge of the probability and/or consequences of a risk, traditional risk management approaches will be inadequate. Another example is when the risk leads to irreversible damage on a societal level (on an individual level all risks that cause fatalities can be seen as irreversible). Instead of struggling to find an appropriate level of risk, a more relevant question in such situations might be whether society should accept these kinds of risks even if they are controlled. However, these characteristics are quite different from those that apply to fire risks in buildings.

An extensive literature search was made to identify methods of comparing or analysing changes in regulations in general and safety legislation in particular. The only comprehensive systematic method found was the approach based on applying the framework for risk control originally suggested by Hale, which is well described by Hopkins and Hale (2002). This framework maps very nicely onto the use of regulation for risk control in the two risk management styles chosen as a starting point for analysing risk control. The framework has been applied to several types of major hazard industries and the transport sector when analysing how safety is controlled by regulations, and the effect of changing regulations, see for example Hale (2001). Kirwan et al. (2002) and van de Poel et al. (2002). However, in the area of fire safety engineering previous attempts to evaluate regulation have varied in their approach, and no underlying methodology has been presented.

In the method employing the framework, it is assumed that the system being analysed can be organized into three hierarchal levels, in a similar way to the commonly used organizational model presented in Section 3.1. The model has been found to work well, as building regulations are structured in this way. The framework describes the formal structure of the regulations well, and covers many aspects lacking in previous methods of comparing performance-based and prescriptive regulations. However, the suitability of using the framework for the design and review of safety management systems in organizations of other kinds than machine bureaucracy (see Section 3.1.1) has not been investigated.

Although the number of alternatives was limited, no direct disadvantages or shortcomings were identified in the general method used to achieve the goals of this work. On the contrary, the framework for risk control was found to be eminently suitable. The detailed study of the means and opportunities available for risk control seems to give a clear picture of the problem at hand; something which has not been done before. It should be noted that the model required detailed development on each of the levels as it has not previously been applied to this area.

One factor not taken into consideration by the analysis is the relation to the operational phase; only the general need for coordination has been studied. To gain a better understanding of the requirements for risk control throughout the whole life cycle of a building, the operational phase must also be included, and the learning processes involved, or which should be involved, should be studied in detail. This should not be regarded as a weakness of the method, but rather a limitation of this study.

9.4.2 Empirical material

Although the study of fire protection documentation presented in Section 4.2 is extensive, the number of projects is limited to forty-six cases, which means that the inventory of problems is far from complete. This affects both the reliability and the validity to some degree. Methods in fire safety engineering develop rapidly. This means that some of the problems identified in some documents may have decreased or disappeared, while others have arisen. If a larger number of documents had been scrutinized, this kind of problem would have been reduced, but not completely removed. The results are believed to be relevant, despite the fact that most of the documents were from the end of the 1990s and beginning of the new millennium. Continuous participation in review of design projects, observations at conferences and discussions with designers, inspectors and reviewers support this supposition. Making a complete survey of the problems associated with the building regulations is quite unrealistic, and not necessary to fulfil the objectives of this thesis. Even if only a few of the problems identified when designing buildings according to the new regulations could be studied in detail, this is sufficient to call into question the ability of the regulations to achieve risk control. Some relevant measures and necessary changes to *BBR* can therefore have been overlooked. This work will hopefully provide valuable input in the next revision of *BBR,* but should not be regarded as the only source of information.

Both the inductive study of fire protection documentation and the deductive study of the safety level in a class of buildings illuminate several weaknesses in the regulations. The implication is that we should question the ability of the current building regulations to achieve risk control. A compilation of the frequency of occurrence of each type of failure was therefore considered unnecessary, and there is no need to point out all the possible failures that could occur. The results of this study do not mean that every consultant is doing a bad job, but the study clearly shows that flaws occur in several cases. The mere fact that the identified problems exist ought to trigger action by both local and national authorities.

9.4.3 Choice of type of building

In the detailed analysis the type of building chosen was assembly halls. This decision was made as it is interesting from a design perspective, and also because the people exposed to risk are not able to influence the level of safety during the construction of the building (as in many types of buildings). Most of the problems identified are of a general nature, but the conclusions drawn regarding changes in prescriptive design are limited to the class of building studied here.

9.4.4 The validity of the results

It is difficult to assess the validity of the results quantitatively. Direct comparison of the output from the risk analysis with fire statistics is not possible as there is insufficient data on the barriers that failed. It is difficult to categorize damage or injuries as being the result of today's level of functional fire protection of construction works (i.e. buildings), malfunctioning fire protection, or the failure of other protection mechanisms in society. The class of buildings analysed is relatively small, and the data necessary for comparison in this class are limited. Furthermore, the calculated measures of risk are not normalized to the probability of fire, as there is a lack of quantitative data on this probability. However, the results of the study are supported by qualitative conclusions that can be drawn from accidents that have happened. For example, serious scenarios with many fatalities are likely to occur when fire starts in an unoccupied adjacent room, and one or more escape routes are inadequate, locked or blocked, either by contents in the building or by smoke early in the development of the fire. Another reason why a comparison with statistics from accident investigations may provide only a weak basis for the evaluation of validity is that the quantitative risk analysis was performed as deductive analysis. This means that uncertainty bounds for the input values in the analysis were chosen with the purpose of representing the range of buildings which can be designed according to the building regulations. The aim was to choose realistic values, which represent the range of input values that could be chosen by a designer, and which reflect the variation in the risk level given the constraints of *BBR*. The selection is based on good knowledge in the area, numerous observations, interviews, discussions with reference groups in research projects, etc. A detailed study of buildings that are actually being built, and weighting the distribution of input value against this information in an inductive way was not the purpose of the study. The results of the analysis reflect the possible variation in the risk in a group of buildings, not necessarily the exact variation in the risk in the present population of assembly halls.

9.4.5 Alternative risk analysis methods

Alternative methods of risk analysis were considered but rejected because of the need for flexibility in designing the analysis, and the ability to analyse the uncertainties was deemed not to be suitable using the commercial or research programs available, e.g. *SAPHIRE* (Charters et al., 2001), *CEASARE-RISK* (Beck, 1998) or *FiRECAM* (Yung et al., 2002). It seemed natural to base these studies on a quantitative analysis in order to study how the uncertainties affected the results in detail.

9.4.6 Organisational measures

One limitation of the risk analysis is that the effects of organisational measures and conditions, e.g. training, fire drills, etc. are difficult to model. These factors often have considerable effects on the variables in the risk analysis model. For example, the probability of someone extinguishing the fire manually will increase if the right equipment is available, if it is properly maintained, and people are trained in how to use it. The probability of fire occurring can also be affected by organisational factors. If there is some form of accident reporting system the potential to identify and prevent potential accidents is greater. Such measures are important and have considerable effects on the total risk. It is therefore important to understand the importance of risk analysis of complementary systems, and not purely that of fire protection of construction works in the design process. Otherwise there is a risk that important measures with highly protective potential will be ignored as they were not included in the calculations.

9.4.7 Assumptions and simplifications

It was necessary to make a number of assumptions and simplifications in order to create the risk analysis model and carry out the calculations. The modelling of fire scenarios has been carried out using a relatively simple model, the two-zone model, in rather large spaces. More precise results could have been obtained if a CFD model had been used. However, bearing in mind the large number of simulations required to study the course of a fire in a whole class of buildings, it was not possible to carry out such detailed calculations. This led to limitations in the accuracy for some buildings, but the accuracy was considered sufficiently good to identify trends in changes in the risk in a class of buildings (see Appendix B). The simulations were, however, not detailed enough to allow the results to be used for the design of a specific building without additional analysis. Examples of the assumptions and simplifications made are:

- The evacuation and fire modelling were greatly simplified.
- Underventilated fires were modelled with a two-zone model.

- The results depend on the building modelled. The aim was to choose a building of general character reflecting many kinds of building. This means that the results are less general, while some details have been ignored.

- The design of the building was chosen without competing interests, i.e. no architectural or functional demands were considered. Although a large number of combinations of variables were studied, these do not represent all possible designs in the class of building considered, although they constitute a large proportion. The results of the calculations therefore do not give a comprehensive picture of the variation in level of risk in a class of buildings, but provide a more extensive foundation for decisions than a study of a few cases.

- The sensitivity analysis of the variables that have the greatest effect was only carried out in the case of fire in an adjacent room, and it was assumed that the variables not included in the uncertainty analysis also have marginal effects on a fire in the assembly hall itself.

- Where knowledge and data were lacking, some variables and relations were based on estimates. It is believed that especially the area of the building has an effect on some of the other variables, e.g. reaction time and detection time, that could not be considered. The level of risk in small buildings may have been overestimated as the relation between these variables was not included in the modelling. Another relation that was not included is the effect of the probability of fire occurring as a function of area, for example.

- The information used as the basis for the assumptions regarding the probability of failure of the different technical systems was limited. In order to determine whether it was necessary to gather further information, an investigation was made to establish how sensitive the risk analysis results were when the probabilities were varied within quite wide intervals (see Section 6.4.4). For the case in question it was concluded that the uncertainty in these probabilities did not have a significant impact on the results or conclusions, as the differences between the scenarios when the technical systems operated and when they failed to operate, was limited. In the type of buildings considered, the delay in detection time if the automatic detec-

> tion system does not operate is marginal compared with other types of buildings (e.g. warehouses or hotels). Including the uncertainty in the probabilities of failure of the technical systems would lead to an even higher uncertainty in the risk level, and thus only strengthen the conclusions drawn from the analysis.

These assumptions and simplifications were subjectively made by the author, but a number of steps were taken to evaluate their effects on the results. Separate studies were carried out to illustrate the consequences (see Appendices A, C, E and G). Some of the consequences are presented in the appendices, while others are evident from the sensitivity analysis.

10 Conclusions

The effects of changing the building regulations on society's potential to control safety have been illustrated from different perspectives. In this chapter the major conclusions of this work are presented. The first section presents the major contributions, while the following sections give a more detailed presentation of the findings.

10.1 Major contributions of this study

- A systematic framework and evaluation tool have been adapted to the area of safety in case of fire in buildings. The framework has been applied to implement a systematic and thorough examination of the Swedish building regulations.

- The analysis of the present regulatory system has led to the identification of a number of shortcomings and ambiguities. These are, at least in some cases, of such a serious nature that it is recommended that the authorities responsible take action.

- Through an extensive risk analysis it has been shown that the risk level for a class of buildings designed with the prescriptive design method, which is an integrated part of the building regulations, can vary substantially. By using the risk analysis methodology the risk-reducing effects of potential modifications of the prescriptive method have been evaluated.

- Several problems associated with societal risk control have been identified by an extensive survey of fire protection documentation from forty-six projects, and by a quantitative risk analysis of a class of assembly halls. A detailed analysis of some of the specific problems shows that society's ability to control the fire risk in buildings is seriously threatened as a consequence of the way in which the new regulations are formulated and applied.

- A general procedure for safety verification, which consists of a compilation of tools, is suggested, together with general demands on quality of verification and a tool to determine the required level of design review, to address some of the problems identified.

10.2 The impact of regulatory changes on conditions for high quality design

The introduction of performance-based building regulations regarding safety in case of fire in *BBR,* in combination with revision of building legislation in Sweden, has led to a paradigmatic shift in fire safety design. This is evidenced by the following:

- Increased freedom for the architect and fire safety engineer in designing both buildings and fire protection systems.
- The availability of several design approaches and methods.
- The need for greater understanding of the building as a system in design.
- Changes in the tasks and responsibilities in the construction process of several actors in the building sector.
- Changes in demands on verification, review and documentation.
- An increased need for coordination between actors, both in the design and operational phases of buildings.

At the same time, there are several indications that society's ability to control fire risk in buildings has been impaired, and it was the main aim of this study to investigate this.

10.3 The impact of regulatory changes on the quality of verification

The quality of the verification of equivalent safety in fire safety engineering designs can be questioned, and many examples of potential flaws and shortcomings have been illustrated in the thesis. One example is that during verification, scenarios involving the failure of technical systems and those arising from serious events (e.g. fires starting in an adjacent room) are often ignored.

Designers exercise greater freedom than intended by the regulations having the possibility to subjectively and arbitrarily interpret both the methods used for verification and the level of performance requirements. This can result in solutions being accepted although they do not comply with the regulations. Such practice is a major threat to societal risk control, since the decision about what is an acceptable safety level is moved from the authorities to the designer, which was not the intention when introducing *BBR*.

The principles of design from other areas, e.g. load-bearing structures, cannot be simply transferred to the design of evacuation safety. A method of design suited to the specific application of fire safety engineering must be developed.

It is tempting to interpret these statements as signs of lowered quality levels in the verification process and increased limitation for effective societal control of safety in case of fire in buildings.

10.4 Shortcomings in the building regulations that needs to be addressed

Several of the important demands in *BBR* are neither unambiguous nor quantified, which leads to a number of difficulties in applying analytic design, for example in verification. *BBR* is even inconsistent on several issues, for example the basis for verification using the analytic design method, and is therefore difficult to apply properly to some buildings.

There is no limitation on how much traditional fire protection may be changed, while the tools available to show that new solutions satisfy the demands are sometimes poor and unreliable. The decision as to how safety and risk are defined, measured and evaluated is left completely to the designer and will become unnecessarily arbitrary.

Present guidance is inadequate regarding *what* should be verified in order to demonstrate equivalent safety for many practical design applications.

Stricter regulation of the verification procedure, in combination with the introduction of general quality demands, is necessary to ensure that the funding of the project is not the major external factor controlling the quality of the fire protection in the building.

10.5 Tools developed and presented in this thesis

A number of tools have been developed and presented in the thesis, aimed at helping to alleviate some of the problems identified. Some of these tools are combined into a qualitative procedure with the purpose of structuring the verification process, identifying the need for verification and to indicate the suitable scope for analysis. The tools have been developed for a specific type of building but are of general character.

The procedure also includes a risk analysis method which allows analysis of the level of risk for both a single building and a class of buildings. The effects of various kinds of uncertainties on the level of risk have been studied.

In order to identify any errors made in the verification process it is important to determine the appropriate level of review. Such a decision can be aided by a simple analysis of certain indicators and the design procedure used. By developing and presenting a tool that is used independently of the designer's verification some of the concerns raised about the designer's subjectivity have been dealt with. Independent review of proposed fire safety design solutions is important. Insight by authorities, such as the local building committee or rescue service, is deemed necessary.

10.6 Suggestions for development work of the prescriptive design method

It was shown that the level of risk resulting from prescriptive design can vary considerably in the type of buildings analysed in this study. In some buildings, the level of risk was deemed to be so high that it can be questioned whether it is acceptable. The individual risk is substantially higher in small buildings with low ceilings than in larger buildings, but it is unclear whether this variation is acceptable or not. Decisions regarding whether this risk level should be used, and how it should be used, as the basis for verification in analytic design, and whether it is necessary to modify prescriptive design or not, depend on this uncertainty being resolved.

In cases when the level of risk using prescriptive design cannot be used to define an acceptable risk with analytic design the building regulations will be inconsistent. In other situations the requirements for the same performance would differ depending on which design method was used.

In order to ensure a uniform level of safety in all buildings of the same class, or at least reduce the variation in risk, further development of the prescriptive design method is required.

The results of the following modifications have been analysed for the class of buildings considered here, i.e. assembly halls. These modifications are examples of how the design method can be altered in order to reduce the risk. No ranking or cost-benefit analyses are made of the proposals, which are presented below:

- limitation of the minimum ceiling height in assembly halls,
- restriction on the number of people in a building, or requirements to design for the maximum number of occupants of a building,
- demanding at least 3 exits from all assembly halls,
- 1 metre exit width is required per 100 people, instead of per 150 people, and
- required exit width is expressed as a function of the volume of assembly halls.

The continued development of prescriptive design is necessary, but this should not be pursued indiscriminately as it may lead to unnecessarily conservative protection in buildings that already have adequate fire protection. Several strategies for revision are presented in this thesis, as are methods for the scientifically based development of prescriptive design.

10.7 The analytic design method – shortcomings and recommended actions

In most building fires causing fatalities the number of victims is kept low. Occasionally, and with a low probability, a number of factors combine to create a multiple-fatality fire of disaster proportions. The contribution to the total risk of such fires cannot be neglected in the design of a building when analytic design is used, but at the same time it is difficult to say how large risk contribution from such scenarios is acceptable. The risk should, however, not be greater in analytic design than in prescriptive design. Neglecting such scenarios will in time lead to a reduction in catastrophic fire protection. Several approaches to address this issue have been discussed in the thesis.

In the field of fire safety, there are essentially no methods available for analysing and evaluating the basic properties of safety systems (e.g. defence in depth and catastrophic fire protection). In other areas, these methods are essential in making decisions on what is an acceptable solution and what is not. In connection with stricter regulation of the verification process, a method of evaluating the risk, taking these properties into consideration, should be included.

New kinds of gross errors can be introduced in analytic design, and fire protection solutions may be particularly sensitive to extreme events. Neither gross errors nor extreme events can be dealt with by technical fire protection measures in the construction works alone. Supplementary measures must be taken in the operational phase, for example, systematic fire protection management. There is a need for more extensive coordination between the design and the operational phase.

The needs of analysis in verification vary from one project to another, and it is therefore not meaningful to try to develop a general method of risk analysis that can be applied to all technical trade-offs regardless of the design and use of the building. One important task of the designer is thus to determine the need for risk analysis for each specific project. Competence, experience of analysis and sound knowledge on the methods available are required in order to determine the extent and complexity of the analysis required to gain a true picture of the risk. This knowledge cannot be replaced by a simple checklist.

To assess whether the level of safety obtained with analytic design is as good as or better than that obtained with prescriptive design, a relative analysis of the risk level of both solutions appears to be suitable. It is appropriate to use the number of people exposed to critical conditions to define the consequence instead of the number of fatalities, if the consequence is not treated as a multivariate variable where several degrees of injuries are studied. The choice of reference building is, however, critical to the outcome of such a comparison. A conservative choice is necessary so that the level of risk or the spread in the risk will not be higher than if prescriptive design had been used.

It is strongly suggested that *Boverket* develops guidelines for analytic design, or limits the scope for the introduction of new solutions, since the effects on safety cannot be adequately verified by designers and thereby threatens the societal control. Another suggestion is that *Boverket* requires, and assists, local building committees to check compliance when analytic design is applied, to force adaptation to higher standards in verification procedures. National coordination is necessary for efficient development of tools and to prevent differences between local authorities. By establishing a national committee to conduct investigations of large projects in which analytic design has been employed, national consensus and support for local building committees can be achieved.

10.8 The need for further research

A considerable need for continued research has been identified in order to overcome the problems, shortcomings and dilemmas revealed in this study. Research is also required to broaden the use of analytic design, for example, to design new protection systems in a cost-effective way, and to fill current gaps in our knowledge.

10.9 Final conclusions

The present situation is not the result of actions, or lack of actions, by a single actor in the construction process. It is the result of deregulation in a sector where insufficient resources have been invested in the risk governance system in order to safeguard public safety.

However, if no action is taken regarding the quality of verification, there is a risk that many of the advantages of performance-based regulations will be lost in future revisions of the building regulations. The current regulations allow the designer considerable freedom, which means that the philosophy of *managing risk* must be adopted rather than that of *proving safe* which is used when the designer aims at only meeting the minimum standards. The attitude of the designer cannot be controlled by regulations, but reflects the culture within the sector. *Boverket* should consider reducing the degree of freedom regarding the verification process, so that society has the ability to control fire safety. Guidelines for analytic design would also be appropriate, but lack of guidance is no excuse for making non-conservative assumptions (i.e. assumptions not on the safe side).

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Glossary of translated terms and list of abbreviations

In this section a short glossary of translated terms and list of abbreviations is presented containing Swedish translations of English key words, English explanations of the abbreviations used for building (i.e. construction) legislation and regulations, and English translations of names of Swedish authorities.

Translation of English terms and key words into Swedish

Amendment = tillägg
Analytic design = analytisk dimensionering
Building Committe (local authorities) = byggnadsnämnd
Building permit = bygglov
Common practice = praxis, vedertagna lösningar
Construction process = byggprocessen
Construction works = byggnadsverk
Design phase = projekteringsfasen
Developer = byggherre
Egress safety = utrymningssäkerhet
European Economic Area (EEA) agreement = EES-avtalet
Evacuation alarm = utrymningslarm
Evacuation safety = utrymningssäkerhet
Final inspection = slutbesiktning
Fire and rescue service = räddningstjänst
Fire protection documentation = brandskyddsdokumentation
Fire protection measure = brandskyddsåtgärd
Fire protection of construction works = byggnadstekniskt brandskydd
Fire protection system = brandskyddssystem
Fire safety design = brandskyddsprojektering, brandskyddslösning
Flashover = övertändning
Functional requirements = tekniska egenskapskrav
General recommendations = allmänna råd
Gross error = grovt fel
Mandatory provisions = föreskrifter
Person responsible for quality matters = kvalitetsansvarig
Prescriptive design = förenklad dimensionering
Performance requirement = funktionskrav
Operation & maintenance = drift och underhåll

Operational phase = brukarfasen
Ordinance = förordning
Performance-based = funktionsbaserad
Regulation = regel
Requirement = krav
Safety case = säkerhetsrapport (t.ex. brandskyddsdokumentation)
Safety in case of fire = brandsäkerhet
Self-implemented control = egenkontroll
Serious event = allvarlig händelse
Swedish national board of building, housing and planning = *Boverket*
Systematic fire protection management = systematiskt brandskyddsarbetet
Technical requirement = funktionskrav
Technical trade-off = tekniskt byte

Abbreviations of authorities, legislation and organisations

BBR =	Building Regulations (Boverkets byggregler)
BENEFEU =	Benefits of Fire Safety Engineering in the EU
BKR =	Design Regulations (Boverkets konstruktionsregler)
Boverket =	The Swedish National Board of Building, Housing and Planning.
BSI =	British Standards Institution
BVF =	The Ordinance 1994:1215 on Technical Requirements for Construction Works, etc. (Förordning 1994:1215 om tekniska egenskapskrav på byggnadsverk m.m.)
BVL =	The Act 1994:847 on Technical Requirements for Construction Works, etc. (Lag 1994:847 om tekniska egenskapskrav på byggnadsverk m.m.)
CCPS =	Center for Chemical Process Safety of the American Institute of Chemical Engineers
CIB =	International Council for Research and Innovation in Building and Construction
EAL =	European co-operation for Accreditation of Laboratories
EC =	Official Journal of the European Communities
EU =	European Union
FEMA =	Federal Emergency Management Agency
HSE =	Health and Safety Executive
IAEA =	International Atomic Energy Agency
IEC =	International Electrotechnical Commission
IFEG =	International Fire Engineering Guidelines

IMO = International Maritime Organization
ISO = International Organization for Standardization
LSO = Civil Protection Act 2003:778 (Lag om skydd mot olyckor 2003:778)
NBDC = National Fire Service Documentation Centre
NFPA = National Fire Protection Association
NKB = Nordic Committee on Building Regulations (Nordiska kommittén för byggbestämmelser)
NR = Regulations for New Construction (Nybyggnadsregler)
OECD = Organisation for Economic Co-operation and Development
PBF = Planning and Building Ordinance 1987:383 (Plan och byggförordning 1987:383)
PBL = Planning and Building Act 1987:10 (Plan och bygglag 1987:10)
SBN = Swedish building code (Svensk byggnorm)
SEC = U.S. Securities and Exchange Commission
SEPA = Swedish Environmental Protection Agency (Naturvårdsverket)
SFPA = Swedish Fire Protection Association (Svenska brandskyddsföreningen)
SFPE = Society of Fire Protection Engineers
SHK = Swedish Accident Investigation Board (Statens Haverikommission)
SRSA = Swedish Rescue Services Agency (Räddningsverket)
TNC = The Swedish Centre for Terminology (Tekniska nomenklaturcentralen)
UEF = United Engineering Foundation
VROM = Netherlands Ministry of Housing, Spatial Planning and the Environment

Nomenclature

α = rate of fire growth [kW/s²]

β = safety index

$\Delta E(R)$= the relative change in a risk measure when the prescriptive design method is modified

ΔH_c = heat of combustion [MJ/kg]

ΔH_{c_tot} = total heat of combustion (theoretical) [MJ/kg]

ΔH_{c_chem} = chemical heat of combustion [MJ/kg]

ΔH_{c_con} = the heat of combustion emitted as convection [MJ/kg]

ΔH_{c_rad} = the heat of combustion emitted as radiation [MJ/kg]

Δt = time margin [s]

Δt_{ME} = the time margin for people who escape via the entrance [s]

Δt_{OE} = the time margin for people who escape via the other exits [s]

ϕ = the equivalence ratio

$\phi_N()$= the normal distribution function

ρ_{design} = design occupant density [people/m²]

χ_c = combustion efficiency

χ_{rad} = radiative fraction of the rate of heat release

$\chi_{rad\ vc}$ = radiative fraction of the rate of heat release in a ventilation-controlled fire

A = the area of the premises [m²]

A_{fire} = the area of the combustible material [m²]

C = consequence

$C_{all\ work}$ = consequences in the scenario when all systems work

c_i = the consequences of scenario *i*

C_{max} = maximum consequence when an element of structure collapses

$C_{max\ ssf}$ = maximum consequence among the scenarios representing single source failures

c_{ME} = the consequences at the entrance for scenario *i*, i.e. the number of people exposed to critical conditions

c_{OE} = the consequences at the other exits for scenario *i*, i.e. the number of people exposed to critical conditions

$C_{worst\ case}$ = consequences of the worst-case scenario

F_{ME} = the fraction of people leaving through the main entrance

f_K = the flow of people through a known exit [p/(s · m)]

f_{UK} = the flow of people through an unknown exit [p/(s · m)]

h = the ceiling height of the room [m]

h_{crit} = the critical height of the combustion gas layer [m]
i = scenario index
j = event index
m = occupant index
$\dot{m}''$ = pyrolysis per unit area [kg/(s · m²)]
M = the number of events leading to scenario *i*
n = the number of scenarios
N = the actual number of occupants in the room
N_{dim} = number of occupants in a room used when designing the fire protection systems
N_{ME} = the number of people escaping through the entrance
N_{OE} = the number of people escaping through other exits
p_i = the probability of scenario *i*
P_{ind} = individual risk, the probability that an individual will be exposed to critical conditions should a fire break out
$P_{ind(i)}$ = the probability that an individual will be exposed to critical conditions in scenario *i*
p_j = probability of event *j*
p_{EB} = the probability that the entrance is blocked by the fire
p_f = the probability of failure for an element of construction
$p_{f\,max}$ = the maximum permissible probability of failure for an element of construction
p_{f_aut} = probability of failure of the automatic detection (smoke detectors)
p_{f_evac} = probability of failure of the evacuation alarm
p_{f_exit} = probability of an exit being blocked by furniture or being locked
p_{f_man} = probability of failure of manual activation of the alarm
$P_{m(i)}$ = the probability of occupant *m* of being exposed to critical conditions in scenario *i*
p_{OB} = the probability that some other exit than the entrance is blocked by the fire
p_{NB} = the probability that no exit is blocked by the fire
PS = polystyrene
P_{worst} = the risk to an individual located in the worst position in the case of fire
Q = rate of heat release [MW]
Q_{wv} = Rate of heat release, well-ventilated conditions [MW]
s_i = the sequence of events in scenario *i*
R = the risk measure being analysed
R_{mean} = the mean risk

R_p = the risk measure before modifications were made to the prescriptive method
R_s = load-bearing capacity (structural resistance)
R_{tot} = the total risk
S_s = loads on a structure (action effects)
t_{crit} = time to critical conditions [s]
t_d = detection time [s]
t_{d_aut} = detection time in the case of automatic detection (smoke detectors) [s]
t_{d_man} = detection time in the case of manual detection (pressing the button) [s]
t_{d_noal} = detection time when the alarm does not work (a person initiates evacuation) [s]
t_{esc} = escape time
t_{ME} = the travel time for the last person to leave through the main entrance [s]
t_{OE} = travel time for the last person to leave through any other exit [s]
t_{pre} = pre-movement time [s]
t_{trav} = travel time [s]
$T_{UL\ Room\ 1}$ = upper layer temperature in room 1 [°C]
U = the number of escape routes used excluding the entrance
V = volume of the assembly hall [m^3]
w = the width of an escape route (exit) [m]
w_{req} = required total exit width [m]
$y_{xx\ zz}$ = yield of substance xx, zz = ventilation conditions well-ventilated (wv) or ventilation controlled (vc)

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Appendices

Contents of the Appendices

Appendix A

Appendix A – Modelling of fires

Appendix A presents the modelling of well-ventilated and underventilated fires which are used in the simulation of the fire developments presented in Section 4.4.2.

A1 Well-ventilated fires

Fires starting in an assembly hall were modelled in a simplistic way. The growth was assumed to follow the well-known relation $\alpha \cdot t^2$ (see, for example, Drysdale, 1998), until a maximum value is reached, at which time growth abates and the rate of heat release remains constant. Since the assembly hall is large, there will be sufficient oxygen available for the fire to remain well ventilated during the period of interest. The theory of enclosure fire dynamics for these conditions is well described in numerous textbooks, e.g. Enclosure Fire Dynamics (Karlsson & Quintiere, 1999) and the SFPE Handbook (NFPA, 2002), and numerous models are available to model the fire development during the pre-flashover phase, e.g. CFAST (Jones et al., 2000). The modelling of fire type 1 will therefore not be described in any further detail in this thesis.

A fire starting in an adjacent room (fire type 2) was assumed to develop into a flashover fire. The rate of pyrolysis determines whether this type of fire remains ventilation controlled or becomes underventilated as only a limited amount of oxygen is available through the doorway. In order to make appropriate assumptions in fire modelling this must be analysed.

It is assumed that the fuel is a combination of wood and polystyrene, that the room is small compared with an assembly hall, and the fire load is high. An estimate of the rate of heat release is given below and is based on data from the SFPE Handbook (NFPA, 2002) and engineering judgement:

The area of the combustible material: $A_{fire} = 12\ \mathrm{m}^2$

Pyrolysis per unit area: $\dot{m}'' = 0.025\ \mathrm{g/(s \cdot m^2)}$

Pyrolysis in the room: $\dot{m} = A_{fire} \cdot \dot{m}'' = 0.3\ \mathrm{g/s}$

$$\Delta H_{c\_chem} = \Delta H_{c\_tot} \cdot \chi_c \qquad (A1)$$

ΔH_{c_tot} [MJ/kg] = total heat of combustion (theoretical)

ΔH_{c_chem} [MJ/kg] = chemical heat of combustion

χ_c = combustion efficiency

Polystyrene: $\Delta H_{c\_tot} = 40$ MJ/kg, $\Delta H_{c\_chem} = 27$ MJ/kg

Wood: $\Delta H_{c\_tot} = 20$ MJ/kg, $\Delta H_{c\_chem} = 12.4$ MJ/kg

Average value of wood and plastic: $\Delta H_{c\_tot} = 30$ MJ/kg, $\Delta H_{c\_chem} = 19.7$ MJ/kg

According to the specified data the rate of heat release in an adjacent room can be estimated to:

$$\dot{Q} = \dot{m} \cdot \Delta H_{c\_chem} = 0.3 \times 19.7 = 5.9\ MW \approx 6MW \qquad (A2)$$

According to Thomas' correlation (FEG, 2005) the rate of heat release leading to flashover in room 1 in the base case (see Section 4.4.1) equals 1.2 MW, which confirms that the assumed fire development in the adjacent room is consistent with a flashover fire. According to Drysdale (1998) ventilation-control arises at:

$$1.5 \cdot A_1 \cdot h_1^{0.5} = 1.5 \cdot 1.2 \cdot 2 \cdot 2^{0.5} = 5.1 \text{ MW} \qquad (A3)$$

where A_1 and h_1 are the area and height of the door opening. The conclusion is that even if the estimation of the area of the combustibles is crude and uncertain, the limit of ventilation control can be exceeded in the fire in an adjacent room, and modelling of such fires must be considered.

A2 Underventilated fires

An underventilated fire can result in rapid filling of the room with smoke, if combustion takes place outside the room of origin. The equivalence ratio is defined as the ratio between the fuel and air, divided by the stochiometric fuel-to-air ratio. An underventilated fire is characterized by $\phi > 1$. The equivalence ratio is one of the variables that affect combustion (i.e. the fire properties) and the generation of combustion products (i.e. the species yield). In CFAST v.5, it is possible to model this effect by specifying yield factors for different species (the relation between the masses of different combustion products), the heat of combustion, ΔH_c, and the proportion of heat emitted as radiation, χ_{rad}. All these are dependent on the ventilation conditions and the effects are described in the SFPE Handbook (Tewarson, 1995) and are necessary input data in order to model fire of type 2 in the class of buildings analysed in this thesis (see Section 4.4).

The following assumptions were made, apart from those described above, in modelling the fires:

- none of the windows in the room of origin breaks,
- the effect of ventilation is negligible if additional escape routes are used,
- leakages are modelled by a ventilation opening between the assembly hall and the outside which is 1 cm wide, and extends from the floor to the ceiling in room 2.

These assumptions were made for both well-ventilated and underventilated fires. The mass fraction of combustion products and the heat under well-ventilated conditions were taken from the SFPE Handbook, Table 3-4.11 (Tewarson, 1995). These values were then adjusted using relations that describe the change in the parameters as a function of the equivalence ratio (Tewarson, 1985). A detailed description of the input data required for CFAST v.5 can be found in the technical manual of Jones et al. (2000), but some clarifications are given in Eqs. (A4) and (A5). The adjusted values for the rate of heat release used in the sensitivity analysis are given in Tables A1 to A3.

$$\Delta H_{c\_chem} = \Delta H_{c\_con} + \Delta H_{c\_rad} \qquad (A4)$$

ΔH_{c_con} = the heat of combustion released as convection

ΔH_{c_rad} = the heat of combustion emitted as radiation

$$\chi_{rad\ vc\ \text{(input data for CFAST)}} = (\Delta H_{c\ chem\ vc} - \Delta H_{c\ con\ vc}) / \Delta H_{c\ chem\ vc} \qquad (A5)$$

$\chi_{rad\ vc}$ = the fraction of heat released by radiation in a ventilation-controlled (vc) fire.

$y_{xx\ zz}$ = yield of substance xx, zz = ventilation conditions well-ventilated (wv) or ventilation controlled (vc).

The species yield in CFAST is specified as S/CO2, H/C, HCl/f, HCN/f, CO/CO2 and O2/C, which represent mass fractions of different substances in the combustion products.

Table A1. *Input data for CFAST v.5 for different rates of heat release Q = 5 MW and Q = 10 MW.*

Q = 5 MW → $\phi = 1$

	y_{co2}	y_{co}	y_s	ΔH_{c_chem}	ΔH_{c_con}
Wood (red oak)	1.27	0.004	0.015	12.4	7.8
Polystyrene	2.33	0.06	0.164	27	11

	S/CO2	*H/C*	*HCl/f*	*HCN/f*	*CO/CO2*	*O2/C*	$\Delta H_{c\_chem\_vc}$	χ_{rad_vc}
Mixed	0.041	0.114	0	0	0.014	0	19.7	0.5
Wood	0.012	0.143	0	0	0.003	0	12.4	0.4
Polystyrene	0.070	0.084	0	0	0.026	0	27	0.6

Q = 10 MW → $\phi = 2$

	$y_{s\ vc}/y_{s\ wv}$	$y_{CO\ vc}/y_{CO\ wv}$	$y_{CO2\ vc}/y_{CO2\ wv}$	$\Delta H_{c\_chem\_vc}/\Delta H_{c\_chem\_wv}$	$\Delta H_{c\_con\_\ vc}/\Delta H_{c\_con\_\ wv}$	$\Delta H_{c\_chem\_vc}$	$\Delta H_{c\_con\_vc}$
Wood	1.8	50	0.66	0.67	0.3	8.31	2.34
Polystyrene	1.9	3	0.66	0.67	0.3	18.09	3.3

	S/CO2	*H/C*	*HCl/f*	*HCN/f*	*CO/CO2*	*O2/C*	$\Delta H_{c\_chem\_vc}$	χ_{rad_vc}
Mixed	0.117	0.114	0	0	0.178	0	13.2	0.77
Wood	0.032	0.143	0	0	0.239	0	8.31	0.72
Polystyrene	0.203	0.084	0	0	0.117	0	18.09	0.82

Table A2. *Input data for CFAST v.5 for different rates of heat release Q = 2.5 MW and Q = 7.5 MW.*

Q = 2.5 MW → $\phi = 0.5$

	$y_{s\ vc}/y_{s\ wv}$	$y_{CO\ vc}/y_{CO\ wv}$	$y_{CO2\ vc}/y_{CO2\ wv}$	$\Delta H_{c\_chem\_vc}/\Delta H_{c\_chem\_wv}$	$\Delta H_{c\_con\_ vc}/\Delta H_{c\_con\_ wv}$	$\Delta H_{c\_chem\_vc}$	$\Delta H_{c\_con\_vc}$
Wood	1	1	1	1	1	12.4	7.8
Polystyrene	1	1	1	1	1	27	11

	S/CO2	H/C	HCl/f	HCN/f	CO/CO2	O2/C	$\Delta H_{c\_chem\_vc}$	χ_{rad_vc}
Mixed	0.041	0.114	0	0	0.014	0	19.7	0.5
Wood	0.012	0.143	0	0	0.003	0	12.4	0.4
Polystyrene	0.070	0.084	0	0	0.026	0	27	0.6

Q = 7.5 MW → $\phi = 1.5$

	$y_{s\ vc}/y_{s\ wv}$	$y_{CO\ vc}/y_{CO\ wv}$	$y_{CO2\ vc}/y_{CO2\ wv}$	$\Delta H_{c\_chem\_vc}/\Delta H_{c\_chem\_wv}$	$\Delta H_{c\_con\_ vc}/\Delta H_{c\_con\_ wv}$	$\Delta H_{c\_chem\_vc}$	$\Delta H_{c\_con\_vc}$
Wood	1.7	26	0.8	0.8	0.6	9.92	4.68
Polystyrene	1.7	2.3	0.8	0.8	0.6	21.6	6.6

	S/CO2	*H/C*	*HCl/f*	*HCN/f*	*CO/CO2*	*O2/C*	$\Delta H_{c\_chem\_vc}$	χ_{rad_vc}
Mixed	0.087	0.114	0	0	0.088	0	15.8	0.61
Wood	0.025	0.143	0	0	0.102	0	9.92	0.53
Polystyrene	0.150	0.084	0	0	0.074	0	21.6	0.69

Table A3. *Input data for CFAST v.5 for different rates of heat release Q = 12.5 MW and Q = 17.5 MW.*

Q = 12.5 MW → $\phi = 2.5$

	$y_{s\ vc}/y_{s\ wv}$	$y_{CO\ vc}/y_{CO\ wv}$	$y_{CO2\ vc}/y_{CO2\ wv}$	$\Delta H_{c\_chem\_vc}/\Delta H_{c\_chem\_wv}$	$\Delta H_{c\_con\_\ vc}/\Delta H_{c\_con\_\ wv}$	$\Delta H_{c\_chem\_vc}$	$\Delta H_{c\_con\_vc}$
Wood	2.8	55	0.58	0.59	0.18	7.32	1.404
Polystyrene	2.8	3	0.58	0.59	0.18	15.9	1.98

	S/CO2	*H/C*	*HCl/f*	*HCN/f*	*CO/CO2*	*O2/C*	$\Delta H_{c\_chem\_vc}$	χ_{rad_vc}
Mixed	0.198	0.114	0	0	0.216	0	11.6	0.85
Wood	0.057	0.143	0	0	0.299	0	7.32	0.81
Polystyrene	0.340	0.084	0	0	0.133	0	15.9	0.88

Q = 17.5 MW → $\phi = 3.5$

	$y_{s\ vc}/y_{s\ wv}$	$y_{CO\ vc}/y_{CO\ wv}$	$y_{CO2\ vc}/y_{CO2\ wv}$	$\Delta H_{c\_chem\_vc}/\Delta H_{c\_chem\_wv}$	$\Delta H_{c\_con\_\ vc}/\Delta H_{c\_con\_\ wv}$	$\Delta H_{c\_chem\_vc}$	$\Delta H_{c\_con\_vc}$
Wood	2.8	60	0.43	0.45	0.08	5.58	0.624
Polystyrene	2.8	3.5	0.43	0.45	0.08	12.15	0.88

	S/CO2	*H/C*	*HCl/f*	*HCN/f*	*CO/CO2*	*O2/C*	$\Delta H_{c\_chem\_vc}$	χ_{rad_vc}
Mixed	0.268	0.114	0	0	0.325	0	8.86	0.91
Wood	0.077	0.143	0	0	0.439	0	5.58	0.89
Polystyrene	0.458	0.084	0	0	0.210	0	12.15	0.93

A3 Limitations of CFAST v.5

In the case of a flashover fire, additional factors than the equivalence ratio (ϕ) affect the combustion chemistry, e.g. the temperature. CFAST v.5 does not take this into account, which limits the possibility to predict the fire development and the temperature in the room of origin.

One difficulty associated with ventilation-controlled fires is that the fire properties can only be specified for one set of ventilation conditions. When the fire is underventilated combustion usually takes place both inside and outside the room of origin, where different ventilation conditions prevail. Tables A1 – A3 presents fire properties for different ventilation conditions (i.e. equivalent rations) in the room of origin. In CFAST v.5 there is only one variable for specifying the heat of combustion, and it is unclear whether this represents ΔH_{c_tot} or ΔH_{c_chem}.

If a fire grows into a ventilation-controlled fire, it is quite possible for pyrolysis to continue to increase due to radiation from the heated walls and ceilings in the room of origin, see e.g. Section 9.1 in Fire Dynamics (Drysdale, 1998). However, it is doubtful that combustion with flames occurs at ventilation factors of 3–4, according to Tewarson (1995). An increase in the equivalence ratio leads to less efficient combustion in the room of origin and greater combustion in the assembly hall. In cases of such high pyrolysis rates, the physical variables that govern the combustion and heat release rate will be greatly affected. This in turn will lead to a considerable reduction in the combustion efficiency which should influence the rate of pyrolysis so that it is reduced, the rate of heat release ceases to increase, and the equivalence ratio falls. As a consequence reduction in temperature should lead to an additional decrease in pyrolysis, thus decreasing the total rate of heat release.

This may mean that there is a rate of heat release or an interval of heat release rate during which the fire oscillates. It seems unreasonable that the rate of heat release should continue to increase uncontrollably with time. CFAST does not take into account that the ventilation conditions vary with time during the fire development and can be different at different places in the premises, but the sensitivity analysis shows that the intensity and rate of growth of the fire decrease significantly above 10 MW. A fire of 10 MW is very severe in a room of the size assumed for the adjacent room (see Section

4.4.2), and this is deemed the likely maximum heat release rate and a potential value for the fire to oscillate around.

The use of CFAST is based on that the conditions in the building are being similar to a two-zone model, and the simplified combustion model being regarded solely as a mass and energy pump. These assumptions are based on the ISO guidelines (1998b) and are verified in Appendix B.

Appendix B

Appendix B – Comparison between CFAST and FDS

It would take too long to perform all the smoke transport modelling required for the uncertainty analysis with a sophisticated model (CFD). Thus, a simpler model must be used, for example, a two-zone model. However, the quality of the results must not be such that incorrect conclusions can be drawn. Modelling a flashover underventilated fire with CFAST v.5 is a rather coarse approach, but Buchanan (1998) demonstrated good agreement for several cases, and some verification of this simplified combustion model has also been performed (Edstam & Söderström, 1998). These studies have shown that both the temperature and mass transport in adjacent rooms can be predicted reasonably well some distance away from the fire can be predicted with sufficient precision for the purpose of the present analysis.

B1 The combustion model

For fire type 2 some combustion takes place under underventilated conditions in the room of origin, while most of the combustion takes place outside the opening (i.e. in the assembly hall) under well ventilated conditions. In CFAST it is only possible to specify one set of fire parameters. It is thus difficult to know how to best represent the actual conditions, at the same time as it is difficult to obtain information on "real conditions" in such a serious fire. Experimental data are lacking and the results are significantly affected by changes in the equivalence ratio so an alternative validation method must be used. One possible approach is comparison with more sophisticated and detailed models (Lundin, 2005). A comparison with CFD models can hopefully provide information on the most suitable value of the equivalence ratio to specify the fire properties in CFAST. In order to verify that it is possible to estimate the temperature and smoke spread in the assembly room, a small number of simulations of a fire type 2 in the base case were performed with the well-documented CFD model, Fire Dynamic Simulator (FDS); see, for example, McGrattan et al. (2002) for a detailed description of the model.

B2 Definition of critical conditions

Different parameters can be used to define critical conditions when using a two-zone model. Examples are the temperature of the smoke layer, the temperature of the air, the smoke layer height and the visibility. The most suitable choice depends mainly on how the smoke spreads in the room/building, which in turn depends on the size of the fire and affects the suitability of the two-zone model to simulate the fire. By making comparisons with CFD simulations it may be possible to verify the suitability of the two-zone model, and even confirm the choice of variables with which to describe critical conditions. It is possible that the smoke cools far away from the fire and sink to the ground. If this happens, the two-zone model will not be a suitable representation of the conditions and the smoke layer height will not be suitable to define the critical conditions.

In a comparison between the two models, considerable differences were found in the results. The modelling of underventilated fires leading to flash over with the CFD model is new, and a great deal of verification remains to be done. The most important conclusion that can be drawn from a visual study of the CFD results is that a stable smoke layer is formed in the assembly hall, which does not sink the floor level at the main entrance, i.e. the exit furthest away from the room of origin. In a study of the conditions in the room of origin (Table B1), FDS and CFAST are compared for both well-ventilated (wv) and underventilated conditions (uv). Critical conditions in the FDS simulation can be calculated with an algorithm giving the height of the smoke layer (He et al., 1998) to facilitate the comparison, when the two-zone assumption is valid.

Based on the limited number of simulations studied, no conclusions could be drawn on whether the well-ventilated or underventilated fires modelled by CFAST best represented the real conditions. As the results were in quite good agreement in terms of describing the relevant variables of the fire development, $CFAST_{uv}$ was used to model the underventilated fire.

Table B1. Examples of comparisons between FDS and the two-zone model.

	$T_{UL\ Room\ 1*}$ [°C]		$T_{UL\ Room\ 2*}$ [°C]		t_{crit} [s]	$Q_{Room\ 1*}$ [MW]	$Q_{Room\ 2*}$ [MW]
	t= 200s	t= 600s	t= 200s	t= 600s			
FDS	940	1070	150	183	248	4	5
$CFAST_{wv}$	1000	1300	150	175	280	6	3.5
$CFAST_{uv}$	850	1100	160	175	320	5	4

* Room 1 = the room of fire origin (the adjacent room), Room 2 = the assembly hall.

Appendix C

Appendix C – Sensitivity and uncertainty analyses

As well as the actual risk analysis, comprehensive sensitivity analysis and a subsequent uncertainty analyses were conducted. Although the calculations were carried out in chronological order, the results are presented in reverse chronological order in Chapter 5-6 and in Appendices F-G in this thesis in order to coincide with the level framework for risk control (Hopkins & Hale, 2002) presented in Section 3.1.2.

Both the sensitivity and uncertainty analyses were performed using a deductive approach. The purpose was to analyse how the risk level varies for a class of buildings, according to the constraints set out by *BBR* (2002). Note that no specific analysis of a particular group of existing buildings was performed to determine how the risk level actually varies in the existing building population. The variation intervals and probability bounds were chosen so that they represent reasonable values, based on present knowledge and the current state of the art according to engineering guidelines and practice (e.g. BSI, 2001; Brandskyddslaget & LTH Brandteknik, 2002).

C1 Input data for the sensitivity analysis

The effect of varying the input data on the results given by the risk analysis model for fires of type 2 was studied in the sensitivity analysis. The output consists of measures of risk that can be used to express the level of risk to which people in the assembly hall are exposed. The conclusions drawn from the sensitivity analysis are used as the basis for the following uncertainty analysis.

Data from the building representing the base case (BC) were used as reference values, see Section 4.4.1. The reference value of a variable is denoted V_{BC} and the variable is varied in four steps, V1–V4, where $V1 = 25\% \cdot V_{BC}$, $V2 = 75\% \cdot V_{BC}$, $V3 = 125\% \cdot V_{BC}$ and $V4 = 175\% \cdot V_{BC}$. Values for the base case were obtained from All Saints' Church in Lund (Sweden), handbooks, or were estimated. In some cases, e.g. detection time and ceiling height, it was necessary to modify the interval of variation for practical reasons. For example, the time $t = 0$ defines the time at which smoke spreads into the assembly hall. If detection occurs before this point in time, e.g. if smoke detectors are installed in the adjacent room, this can be modelled by assigning a negative value to the detection time. This would mean that people begin evacuation before smoke spreads into the assembly hall.

Tables C1 and C2 give the variables and their reference values, the interval of variation and an index for each variable, together with a short description. The variables were changed one at a time, and the risk measures defining the output calculated for each change. In all, 25 variables were varied, which led to 125 calculations using the risk analysis model. The output of each simulation consisted of 6 risk measures. The graphical results in terms of diagrams showing the effect of varying each input variable for each risk measure are presented in Appendix G. A summary of the results is presented in Section 6.4.4. The conclusions drawn from the sensitivity analysis are presented in the following subsection.

Table C1. Variables included in the sensitivity analysis

Index	Description	Variable	V1	V2	V_{BC}	V3	V4	Comments
2_1	Rate of heat release (flash over)	Q [MW]	2.5	7.5	10	12.5	17.5	Fire properties adjusted according to ϕ.
2_2	Time to automatic detection	$t_{d\ aut}$ [s]	-30	-15	10	30	60	Smoke spread into the assembly hall at t =0.
2_3	Time until manual detection	$t_{d\ man}$ [s]	0	15	45	60	90	Does not affect $t_{d\ aut}$.
2_4	Pre-movement time	$t_{pre\ alarm}$ [s]	0	30	60	90	120	10 s delay if alarm fails.
2_5	Number of occupants (actual occupant load)	N [people]	250	750	1000	1250	1750	Occupant load varies, but no design effect.
2_6	The fraction of people choosing to leave through the main entrance	F_{ME}	0.18	0.53	0.7	0.88	1.0	
2_7	The flow of people through an unknown exit	f_{UK} [p/(s·m)]	0.2	0.6	0.8	1.0	1.5	
2_8	The flow of people through a known exit	f_K [p/(s·m)]	0.8	1.1	1.2	1.5	2.2	
2_9	Exit width, no design effect	w [m]	1.2	1.6	2.2	2.7	3.8	Affects the evacuation. No design effect.
2_10	The area in room 2, design effect according to prescriptive design	A [m^2] N [people] w [m] nbr. of exits	250 250 1.2 2	750 750 1.7 3	1000 1000 2.2 3	1250 1250 2.1 4	1750 1750 2.9 4	Constant occupant load (1 pers./m^2). Design effects according to the prescriptive method, i.e. N and w.
2_11	The ceiling height in room 2	h [m]	3	4	6	8	10	No effect on t_{det} or $t_{pre\ alarm}$.
2_12	The area in room 2, no design effect	A [m^2]	250	750	1000	1250	1750	Constant number of people and exit width. No design effect.
2_13	Exit width, design effect according to prescriptive design	w [m] N [people] Number of exits	1.2 360 2	1.65 742 3	2.2 1000 3	2.75 1650 4	3.85 2310 4	Affects the evacuation and N. 3 exits are assumed with minimum width of 1.2 m / exit.
2_14	Door width for room 1	w_{1a} [m]	0.75	0.9	1.2	2.0	2.4	No effect on the equivalence ratio or the evacuation.

Table C2. *Variables included in the sensitivity analysis*

Index	Description	Variable	V1	V2	V_{BC}	V3	V4	Comments
2_15	Probability of failure (p_f) of the evacuation alarm	p_{f_evac}	1	3	5	10	15	
2_16	p_f of the automatic detection system	p_{f_aut}	1	5	3	10	15	
2_17	p_f of manual activation of the evacuation alarm	p_{f_man}	12.5	37.5	50	62.5	87.5	
2_18	p_f of a single exit	p_{f_exit}	2	10	5	15	20	
2_19	Rate of heat release, well-ventilated conditions	Q_{wv} [MW]	2.5	7.5	10	12.5	17.5	No account taken to ϕ
2_20	Fuel typ		-	wood	Mix	PS	-	
2_21	Definition of critical conditions		$OD2_{UL}$	$OD2_{tot}$	Layer 2	$OD3_{UL}$	$OD3_{tot}$	See key *
2_22	Definition of critical conditions, well-ventilated*		$OD2_{UL}$	$OD2_{tot}$	Layer_2	$OD3_{UL}$	$OD3_{tot}$	See key *
2_23	Heat of combustion	ΔH_c [MW/kg]	10	15	13	20	30	
2_24	Proportion of Q emitted as radiation	χ_{rad}	0.25	0.5	0.77	0.85	0.95	
2_25	Design occupant load	ρ_{design} [people/m^2]	0.8	0.9	1.0	1.1	1.2	

* OD = optical density, 2 = room 2, 3 = room 3, UL = upper layer (smoke), tot = the whole room, layer = the smoke layer

C2 Conclusions drawn from the sensitivity analysis

The information obtained from the sensitivity analysis was used to decide which variables to include and study in the uncertainty analysis. The results of the sensitivity analysis are presented in Section 6.4.4 and Appendix G. The variables having little effect on the risk measures were found to be the following.

- Q (2_1)
- p_{f_evac} (2_15)
- p_{f_aut} (2_16)
- p_{f_man} (2_17)
- p_{f_exit} (2_18)
- w_{1a} (2_14)

These variables were therefore not included in the uncertainty analysis. Two additional variables studied in the sensitivity analysis were not included in the uncertainty analysis, despite the fact that they had considerable effects on the safety.

- w (2_9)
- ρ_{design} (2_25)

The reason for not including w was that the width of the exits corresponds to the width required by the number of people allowed in the building, according to prescriptive design. Including this variable in the sensitivity analysis was considered justified in order to obtain an estimate of its importance regarding safety, but it is not relevant when investigating the level of risk associated with prescriptive design.

The design value of the occupant load, ρ_{design}, was not included in the uncertainty analysis as it is considered to be a constant design variable for the class of buildings considered here. However, in a more detailed analysis, where the activity pursued in the building is varied, this variable should be included. Although the design value of the density of people may be constant, the actual number of people in a building may vary (the variable N). The analysis clearly shows that the risk increases when the number of people in a building exceeds the design value. Overly crowded pubs and discotheques are unfortunately quite common and a number of tragic fires have occurred in such premises, e.g. the dance hall fire in Göteborg (SHK, 2001) and the fire in a café in Volendam (NBDC, 2005). The accident investigations following these fires concluded that local authorities did not always take any action when regulations were not adhered to, for example, when the permitted occupant load specified in the operating licenses or permits was exceeded. After serious accidents the inspection frequency is often somewhat increased, but is seldom maintained at a high level. It was concluded after studying the actual and design occupant load in the sensitivity analysis that it is important that a building be designed for the purpose to which it is subsequently put. However, to make risk modelling realistic, the actual number of occupants (N) will not be assumed to be the number used for design $(A \cdot \rho_{design})$, but will be treated as an uncertain variable (see Section C3.1).

The effects of certain assumptions were also studied in the sensitivity analysis, for example, the definition of critical conditions. The way in which critical conditions are defined has a considerable effect on the results of risk analysis calculations. The limits for visibility and the smoke layer height are not reached at the same time, which means that different numbers of people will be affected by critical conditions depending on which limit is chosen.

Defining critical conditions in terms of visibility in the smoke layer in the case of two-zone formation is not a suitable alternative, as the visibility quickly becomes critical in the upper layer if the smoke is not diluted. Such a definition would lead to critical conditions being reached long before the smoke layer posed a threat to people evacuating the building, and would not give a true picture of the effects on the occupants. If, however, the smoke is mixed with air, for example, due to turbulence, then the visibility provides a good measure of critical conditions when determining the consequences. The sensitivity analysis showed that it is important to use critical conditions that reflect the conditions in the building. This choice may have a considerable effect on the estimation of the risk. In the further analysis of the building representing the base case, only the height of the smoke layer was used as an indication of critical conditions. This is based on an analysis of smoke spread in a building using the Fire Dynamic Simulator (FDS) model (McGrattan et al., 2002), see Appendix B.

C3 Input data for the uncertainty analysis

If a class of buildings is studied instead of one specific building, the fire protection will be affected by changes in the building layout. If variables like area were allowed to vary independently of the number and with of the exits, this would not give the correct picture of the actual variation in the risk level. It is thus necessary to consider the relation between variables resulting from prescriptive design. For example, the number of exits and the total evacuation width depend on the number of people in the building. There must be more exits, or exits of great width, in a building designed for a large number of people, than one designed for a smaller number. The relations between variables according to the prescriptive design method, e.g. number of people and total evacuation width, were included in the uncertainty analysis in such a way that the variation in risk level corresponded to that achieved with prescriptive design. The variables included in the uncertainty analysis and the intervals used to represent the uncertainty are given below.

C3.1 Group 1 (natural variation and uncertainty in knowledge)

γ (uniform 0.5–1.5)	*Number of occupants.* It is a fact that the number of people in public premises varies, although the interval is not known. In some kinds of public premises, e.g. shops, accurate data can be obtained, while in other kinds of buildings rough estimates must be used. In the present study it was assumed that the number of occupants varied by ±50% of the design value, i.e. $N = A \cdot \gamma \cdot \rho_{design}$.
t_{d_aut} (triang 0;0;20) [s]	*Detection time.* When the automatic fire alarm works, it is assumed that it activates as soon as smoke spread into the assembly hall. The fire will be fully developed and the smoke production large. When the fire starts in the assembly hall it is assumed that it is detected immediately.
t_{d_man} (triang 30;30;60) [s]	*Detection time.* Even if the automatic alarm does not work, people will quickly become aware of the fire. There will be only a marginal delay due to someone having to activate the manual alarm.
t_{d_noal} (triang 30;60;90) [s]	*Detection time.* If the alarm does not sound, people in the room will quickly

	become aware of the fire. When smoke spread into the room, the fire will be fully developed and the smell, sight and sound of the fire are expected to be important. There will be a slight delay compared with detection due to the sounding of an alarm. Greater variation can also be expected as everyone will not become aware of the fire simultaneously.
t_{pre_alarm} (uniform 50–70) [s]	*Pre-movement time.* The pre-movement time is also expected to be short if the people in the building are assumed to be alert and sober, and their attention is directed in the same direction (Frantzich, 2001). This reaction time will therefore not be representative for dance halls and bars.
t_{pre_noal} (uniform 50–90) [s]	*Pre-movement time.* If the alarm does not work, the person towards whom attention is directed, e.g. an artist, may give the pertinent information. If this does not happen, the threat will become so obvious that people can be expected to act on their own (Frantzich, 2001).
F_{ME} (triang 0.60;0.70;0.80)	*Exit choice.* It is assumed that a fraction corresponding to 70% of the occupants choose to leave through the same exit they entered by, in this case the main entrance, based on a study of warehouses by Frantzich (2001). A study on the evacuation of a department store gave similar results (Sandberg, 1997). This kind of behaviour can be expected even in buildings of other types.
α (triang 0.001;0.01;0.1) [kW/s^2]	*Fire growth rate.* The rate of growth of the heat release depends on a number of parameters, and can vary considerably in most kinds of buildings. The amount,

type and configuration of combustible material are examples, as are where the fire starts, and if extinguishing systems are available in the vicinity. The uncertainty in this variable is described as large or very large. Previous studies have shown that this variable also has a considerable effect on the result (see, e.g. Angerd, 1999). In order for the interval of variation to cover a broad spectrum of cases, while not being unnecessarily conservative, Angerd's study from 1999 was used to determine a reasonable interval. The rate of growth of heat release was included as it has such a large effect on the results, although it was not studied in the sensitivity analysis as it does not vary in fires of type 2.

C3.2 Group 2 (variation with respect to design decisions)

h (uniform 3.5–10) [m]	*Ceiling height.* The height of room 2 was varied in an interval that is common in the kind of buildings studied, i.e. assembly halls.
A (uniform 400–1750) [m^2]	*Area.* The area of room 2 was varied from a small to medium-sized assembly hall. It is necessary to restrict the variation to the size of buildings considered so that the variation is not too great. This interval, together with the height, defines the size of hall for which the results are valid. The area of room 1 was not varied.

There is a lack of knowledge on how the uncertainty in a variable changes within the class of buildings, i.e. as a function of A and h. For example, is the reaction time the same in large and small assembly halls? This lack of knowledge and information means that it is difficult to determine the interval describing the uncertainty with high accuracy. In these cases, uniform distributions are often used, which means that all the values a variable may take in an interval have the same probability. There are variables for which only a small amount of research would give better information. By studying the actual buildings, using the real estate register or similar information, it should be possible to determine the distribution of A and h with higher precision, and perhaps even identify a correlation between them. Even if it were possible to determine the distribution of some variables more accurately, in order to reduce the uncertainty in these variables, it is not obvious that this is better. As these variables are generally used in the design of new buildings, it is not certain whether today's distribution necessarily reflects the future variation. Bearing in mind the purpose of uncertainty analysis, the "potential variation" is thus more appropriate. The intervals used in some cases are rough estimates, but it is important to choose an interval that credibly describes the possible values that a variable may take. In this work, these intervals were estimated based on a combination of expert judgement of the available data and a number of assumptions. The results of the uncertainty analysis are presented in Section 5.4 and Appendix F.

Appendix D

Appendix D – CFAST input data file for the base case

```
VERSN  3 BaseCase
#VERSN 3 BaseCase - fire in an adjacent room
TIMES   1000      0      5     20      0
DUMPR BASECASE.HIS
ADUMP BASECASE.XLS NS
TAMB       293.150    101300.    0.000000
EAMB       293.150    101300.    0.000000
HI/F       0.000000   0.000000   0.000000
WIDTH      3.00000    25.0000    6.00000
DEPTH      2.00000    40.0000    3.00000
HEIGH      2.40000    6.00000    2.40000
CEILI      CONCRETE   CONCRETE   CONCRETE
WALLS      CONCRETE   CONCRETE   CONCRETE
FLOOR      CONCRETE   CONCRETE   CONCRETE
#CEILI     CONCRETE   CONCRETE   CONCRETE
#WALLS     CONCRETE   CONCRETE   CONCRETE
#FLOOR     CONCRETE   CONCRETE   CONCRETE
HVENT  1  2  1  1.20  2.00 0.00 0.00 0.00 0.00
CVENT  1  2  1  1.00  1.00 1.00
HVENT  2  3  1  2.20  2.00 0.00 0.00 0.00 0.00
CVENT  2  3  1  1.00  1.00 1.00000
HVENT  2  4  1  0.10  6.00 0.00 0.00 0.00 0.00
CVENT  2  4  1  1.00  1.00 1.00
HVENT  2  4  2  1.20  2.00 0.00 0.00 0.00 0.00
CVENT  2  4  2  1.00  1.00 1.00
HVENT  3  4  1  2.20  2.00 0.00 0.00 0.00 0.00
CVENT  3  4  1  1.00  1.00 1.00
CFCON  1  4 outside 2
CFCON  4  2 outside 1
CFCON  2  4 outside 2
CFCON  3  4 outside 2
CHEMI  16.0000  50.0000  10.0000 1.32000E+007
293.150  493.150 0.770000
LFBO 1
LFBT 2
CJET ALL
FPOS -1.00000 -1.00000 0.000000
FTIME       1.00000       1000.00
FAREA       6.00000       6.00000       6.00000
FMASS      0.000000      0.757576      0.757576
```

```
FQDOT       0.000000  1.00000E+007  1.00000E+007
HCR         0.114000      0.114000      0.114000
O2      1.00000E-004  1.00000E-004  1.00000E-004
OD          0.117000      0.117000      0.117000
CO          0.178000      0.178000      0.178000
SELECT 1 2 3
#GRAPHICS ON
DEVICE 1
WINDOW    0.    0. -100. 1280. 1024. 1100.
LABEL  1  970.  960.    0. 1231. 1005.   10. 15
00:00:00 0.00  0.00
GRAPH  1  100.   50.    0.  600.  475.   10. 3 TIME
HEIGHT
GRAPH  2  100.  550.    0.  600.  940.   10. 3 TIME
CELSIUS
GRAPH  3  720.   50.    0. 1250.  475.   10. 3 TIME
FIRE_SIZE(kW)
GRAPH  4  720.  550.    0. 1250.  940.   10. 3 TIME
O|D2|O()
HEAT   0 0 0 0 3   1 U
HEAT   0 0 0 0 3   2 U
HEAT   0 0 0 0 3   3 U
TEMPE  0 0 0 0 2   1 U
TEMPE  0 0 0 0 2   2 U
TEMPE  0 0 0 0 2   3 U
INTER  0 0 0 0 1   1 U
INTER  0 0 0 0 1   2 U
INTER  0 0 0 0 1   3 U
O2     0 0 0 0 4   1 U
O2     0 0 0 0 4   2 U
O2     0 0 0 0 4   3 U
```

Appendix E

Appendix E – Response surface replacement of CFAST

When performing sensitivity analysis or uncertainty analysis it is necessary to study the model output for a large number (several thousands) of input parameter combinations (see Section 3.4.4). To generate the input data files and execute the smoke transport model manually is unreasonable due to the time required. In this study the uncertainty analysis is performed with the software @Risk (Palisade, 1996).

E1 Estimating an analytical model

In order to be able to carry out an uncertainty analysis with @Risk, it is necessary to express the model studied in the form of equations, i.e. analytical expressions. As the consequences obtained from the risk analysis were partly calculated with the model CFAST v.5, such equations can be derived by using response surface replacement (other approaches are available, see for example Notarianni, 2000). The response surface replacement is a method of approximating output data using a regression model (Iman & Helton, 1988). It has previously been applied on output data from CFAST with good results (Frantizch, 1998; *Boverket*, 1997). An analytical expression is created which approximates the output data from a simulation model for a limited interval of input data. The response surface is then only valid for that interval.

Different kinds of regression analysis can be used to create regression models for other variables. The most simple is linear regression, see Eq. (E1), where the aim of regression analysis is to determine the parameters *c* and *m*.

$$y = m \cdot x + c \qquad \text{(E1)}$$

y = output data, observation
x = given value, independent variable
c = constant
m = slope of the line

Regression analysis can also be carried out using exponentials or higher-order polynomials, e.g. see (Magnusson et al. 1995). The choice of regression model is a compromise between complexity and the accuracy of the results. When using regression analysis it is possible to calculate parameters that describe how well the results reproduce the original data. An example is the coefficient of determination, R^2.

In the uncertainty analysis of the risk calculations, two analytical expressions are required: one that approximates the time when critical conditions are reached in the assembly hall when the fire starts in the assembly hall, and one that approximates the time when critical conditions are reached in the assembly hall when the fire starts in an adjacent room. After studying the results of the sensitivity analysis, the dependent variables are chosen. In the case of fire starting in the assembly hall, area, height and rate of fire growth (α) were chosen, and for the fire starting in the adjacent room, area and height.

To form a basis for the regression analysis a large number of simulations were performed. The input data were varied systematically in the interval chosen for the sensitivity analysis, using the values below:

A = 250, 750, 1000, 1250 and 1750 m^2

h = 3, 4, 6, 8 and 10 m^2

α = 0.001, 0.005, 0.012, 0.05 and 0.1 kW/s^2

For the fire starting in the assembly hall 125 simulations were performed with CFAST, and for the fire in the adjacent room 25 simulations with the same model. In each simulation, the time required to reach critical conditions was derived by analyzing the smoke layer height as a function of time. The results are analysed using different regression models, and the one that best reproduces the results, i.e. has the maximum value of R^2, is chosen. R^2 can have values from 0 to 1, the higher the value, the better the model.

E2 Fire starting in the assembly hall (fire type 1)

The results obtained from regression analysis for the fire starting in the assembly hall are presented below. The multi-variable regression analysis with the maximum value of R^2 is presented in Eq. (E2).

$$t_{crit} = m_1 \cdot \ln(h) + m_2 \cdot A + m_3 \cdot \ln(\alpha) + c \qquad \text{(E2)}$$

where: c = -488, m_1 = 116, m_2 = 0.34 and m_3 = -123

$R^2 = 0.95$

The analytical expression used to estimate the time to critical conditions when the fire starts in the assembly hall is expressed in Eq. (E3).

$$t_{crit} = 116 \cdot \ln(h) + 0.34 \cdot A - 123 \cdot \ln(\alpha) - 488 \qquad (E3)$$

E3 Fire starting in the adjacent room (fire type 2)

The results obtained from regression analysis for the fire starting in an adjacent room are presented below. The multi-variable regression analysis with the maximum value of R^2 is presented in Eq. (E4).

$$t_{crit} = m_1 \cdot \ln(h) + m_2 \cdot A + c \qquad (E4)$$

where: c = -359, m_1 = 197 and m_2 = 0.31

$R^2 = 0.93$

The analytical expression used to estimate the time to critical conditions in the assembly hall when the fire starts in an adjacent room is expressed in Eq. (E5).

$$t_{crit} = 197 \cdot \ln(h) + 0.31 \cdot A - 359 \qquad (E5)$$

Appendix F

Appendix F – Results of the uncertainty analysis

The variables regarded as having the greatest effect on the uncertainty in the measure of risk and included in the tables have a correlation coefficient greater than 0.1.

R_{mean} = the mean risk (the expected number of people exposed to critical conditions).

P_{ind} = the individual risk (the probability of a randomly chosen person being exposed to critical conditions).

P_{worst} = the probability of being exposed to critical conditions for the most vulnerable individual.

A complete list of definitions of the variables can be found in Appendix C.

F1 Fires of type 1 in assembly halls as a class of buildings

Table F1. Correlation analysis of the total number of cases simulated.

	R_{mean}[1]	P_{ind}[1]	P_{worst}[1]
R_{mean}	1.00		
P_{ind}	0.91	1.00	
P_{worst}	0.79	0.77	1.00
α	0.37	0.36	0.39
N	0.36	0.29	0.38
Volume $(h \cdot A)$	-0.28	-0.34	-0.33
A	-0.24	-0.33	-0.31
h	-0.21	-0.21	-0.19
F_{ME}	0.10	0.08	0.08

Table F2. Correlation analysis of the cases where R >0.

	R_{mean}[1]	P_{ind}[1]	P_{worst}[1]
R_{mean}	1.00		
P_{ind}	0.90	1.00	
P_{worst}	0.76	0.73	1.00
α	0.44	0.43	0.46
N	0.40	0.29	0.40
h	-0.27	-0.28	-0.24
Volume $(h \cdot A)$	-0.15	-0.30	-0.12
F_{ME}	0.14	0.11	0.10
A	0.03	-0.18	0.04

[1] The risk measures are presented in the beginning of Appendix F.

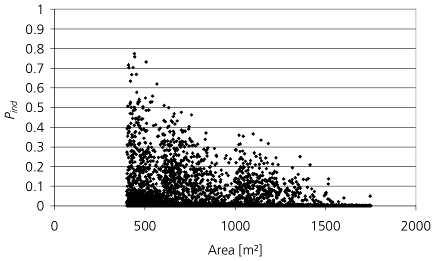


Figure F1. P_{ind} plotted against area.

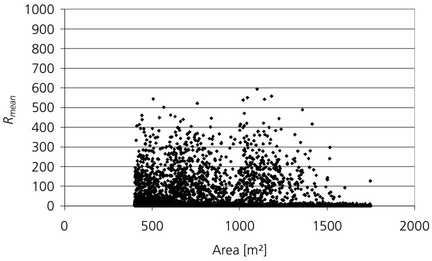


Figure F2. R_{mean} plotted against area.

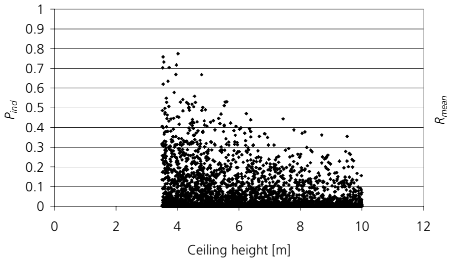


Figure F3. P_{ind} plotted against height.

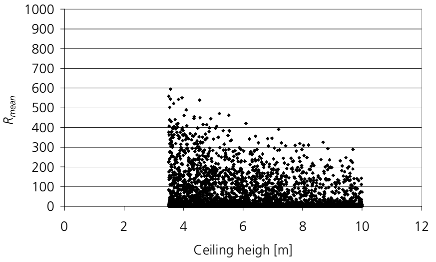


Figure F4. R_{mean} plotted against height.

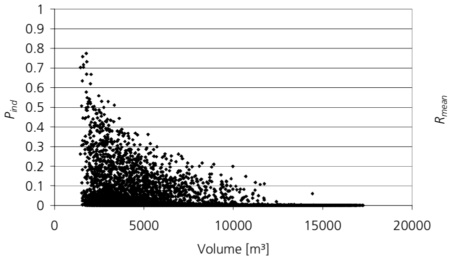


Figure F5. P_{ind} plotted against volume.

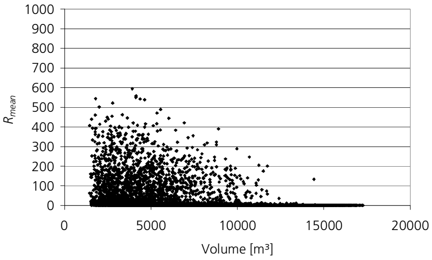


Figure F6. R_{mean} plotted against volume.

F2 Fires of type 2 in assembly halls as a class of buildings

Table F3. Correlation analysis of the total number of cases simulated.

	R_{mean}[1]	P_{ind}[1]	P_{worst}[1]
R_{mean}	1.00		
P_{ind}	0.89	1.00	
P_{worst}	0.75	0.70	1.00
Volume $(h \cdot A)$	-0.55	-0.58	-0.63
h	-0.49	-0.45	-0.45
A	-0.41	-0.52	-0.50
N	0.39	0.22	0.39

Table F4. Correlation analysis of the cases where R >0.

	R_{mean}[1]	P_{ind}[1]	P_{worst}[1]
R_{mean}	1.00		
P_{ind}	0.85	1.00	
P_{worst}	0.64	0.59	1.00
Volume $(h \cdot A)$	-0.55	-0.70	-0.49
h	-0.53	-0.46	-0.41
N	0.35	0.07	0.27
A	-0.21	-0.47	-0.19

[1] The risk measures are presented in the beginning of Appendix F.

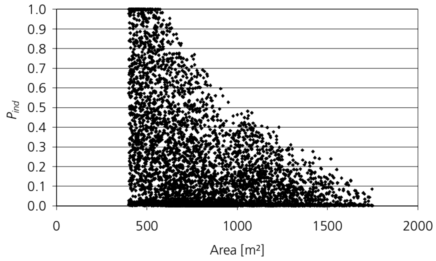


Figure F7. P_{ind} plotted against area.

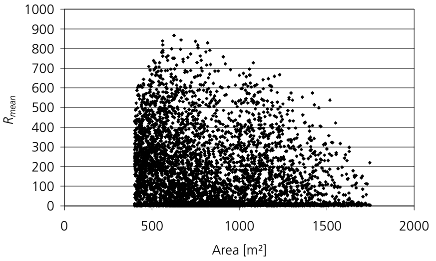


Figure F8. R_{mean} plotted against area.

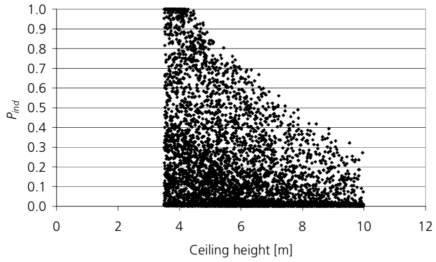


Figure F9. P_{ind} plotted against height.

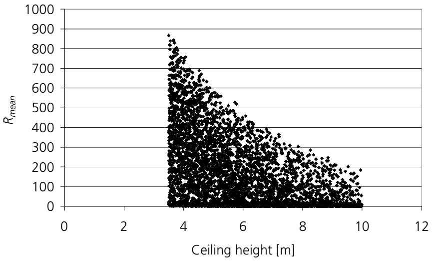


Figure F10. R_{mean} plotted against height.

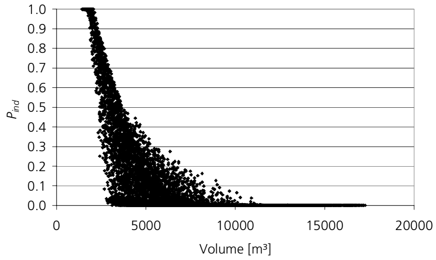


Figure F11. P_{ind} plotted against volume.

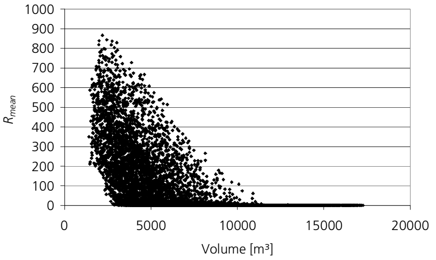


Figure F12. R_{mean} plotted against volume.

F3 Fires of type 2 in a specific building (the base case)

Table F5. Correlation analysis of the total number of cases simulated.

	R_{mean}[1]	P_{ind}[1]	P_{worst}[1]
R_{mean}	1.00		
P_{ind}	1.00	1.00	
P_{worst}	0.81	0.83	1.00
N	0.73	0.74	0.81
F_{ME}	0.24	0.26	0.14

Table F6. Correlation analysis of the cases where R >0.

	R_{mean}[1]	P_{ind}[1]	P_{worst}[1]
R_{mean}	1.00		
P_{ind}	1.00	1.00	
P_{worst}	0.70	0.72	1.00
N	0.81	0.81	0.76
F_{ME}	0.32	0.34	0.13

[1] The risk measures are presented in the beginning of Appendix F.

Area and height are not varied since these variables belong to variables of group 2, and therefore no diagrams are available.

F4 Fires of type 2 in assembly halls as a class of buildings with respect to design decisions

Table F7. Correlation analysis of the total number of cases simulated.

	R_{mean}[1]	P_{ind}[1]	P_{worst}[1]
R_{mean}	1.00		
P_{ind}	0.96	1.00	
P_{worst}	0.76	0.70	1.00
Volume ($h \cdot A$)	-0.64	-0.62	-0.73
h	-0.59	-0.51	-0.59
A	-0.49	-0.54	-0.55

Table F8. Correlation analysis of the cases where R >0.

	R_{mean}[1]	P_{ind}[1]	P_{worst}[1]
R_{mean}	1.00		
P_{ind}	0.95	1.00	
P_{worst}	0.69	0.62	1.00
Volume ($h \cdot A$)	-0.82	-0.83	-0.78
h	-0.62	-0.51	-0.59
A	-0.33	-0.46	-0.25

[1] The risk measures are presented in the beginning of Appendix F.

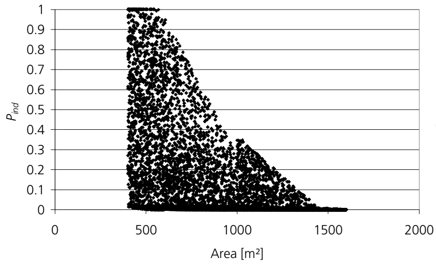


Figure F13. P_{ind} plotted against area.

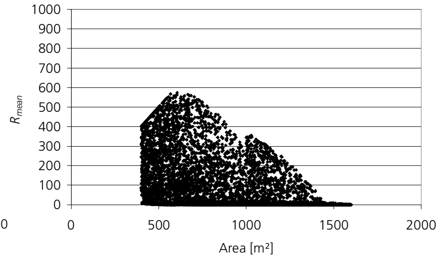


Figure F14. R_{mean} plotted against area.

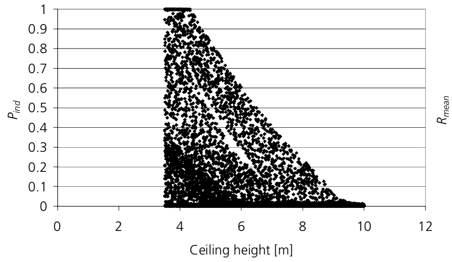


Figure F15. P_{ind} plotted against height.

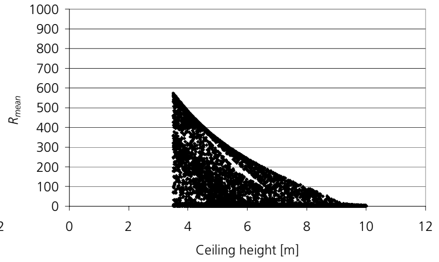


Figure F16. R_{mean} plotted against height.

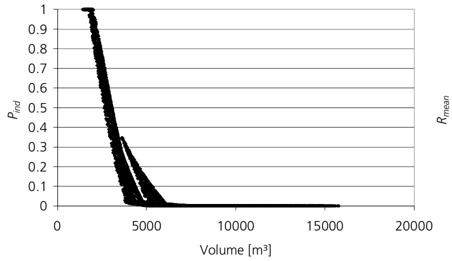


Figure F17. P_{ind} plotted against volume.

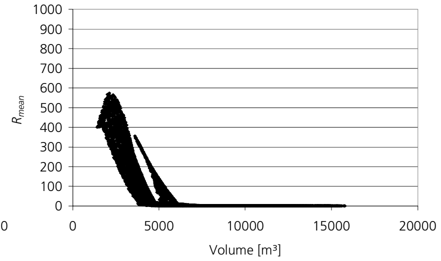


Figure F18. R_{mean} plotted against volume.

F5 Limitation of the minimum ceiling height in assembly halls

Table F9. Correlation analysis of the total number of cases simulated.

	R_{mean}[1]	P_{ind}[1]	P_{worst}[1]
R_{mean}	1.00		
P_{ind}	0.92	1.00	
P_{worst}	0.80	0.74	1.00
Volume ($h \cdot A$)	-0.42	-0.44	-0.49
h	-0.40	-0.37	-0.44
A	-0.34	-0.39	-0.38
N	0.33	0.22	0.36

Table F10. Correlation analysis of the cases where R >0.

	R_{mean}[1]	P_{ind}[1]	P_{worst}[1]
R_{mean}	1.00		
P_{ind}	0.91	1.00	
P_{worst}	0.76	0.69	1.00
h	-0.46	-0.41	-0.49
Volume ($h \cdot A$)	-0.44	-0.49	-0.48
N	0.33	0.17	0.34
A	-0.30	-0.41	-0.30

[1] The risk measures are presented in the beginning of Appendix F.

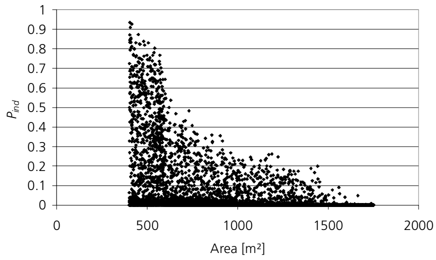


Figure F19. P_{ind} plotted against area.

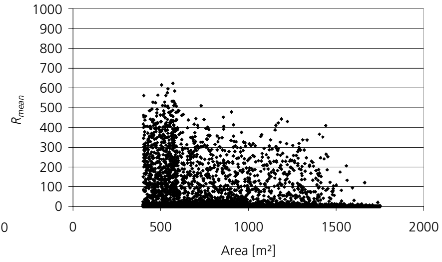


Figure F20. R_{mean} plotted against area.

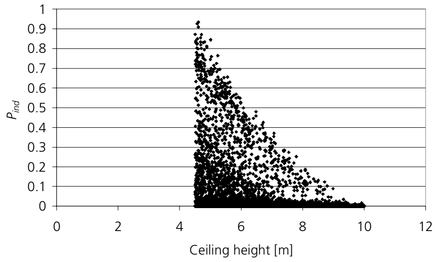


Figure F21. P_{ind} plotted against height.

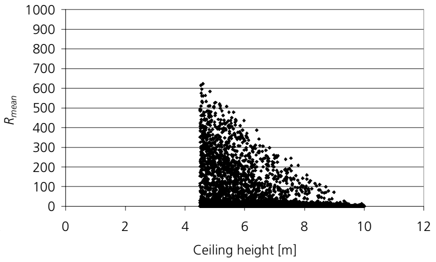


Figure F22. R_{mean} plotted against height.

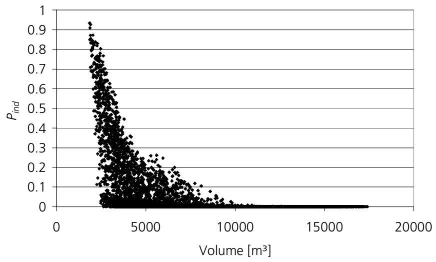


Figure F23. P_{ind} plotted against volume.

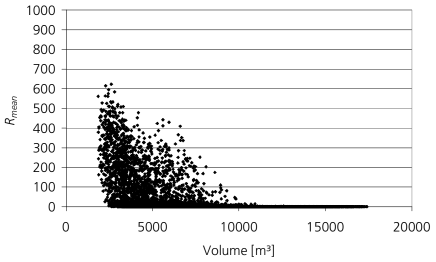


Figure F24. R_{mean} plotted against volume.

F6 The number of occupants in the room corresponds to the design occupant density

Table F11. Correlation analysis of the total number of cases simulated.

	R_{mean} [1]	P_{ind} [1]	P_{worst} [1]
R_{mean}	1.00		
P_{ind}	0.96	1.00	
P_{worst}	0.76	0.70	1.00
Volume $(h \cdot A)$	-0.61	-0.59	-0.70
h	-0.55	-0.47	-0.53
A	-0.49	-0.53	-0.57

Table F12. Correlation analysis of the cases where R >0.

	R_{mean} [1]	P_{ind} [1]	P_{worst} [1]
R_{mean}	1.00		
P_{ind}	0.95	1.00	
P_{worst}	0.68	0.62	1.00
Volume $(h \cdot A)$	-0.80	-0.81	-0.76
h	-0.63	-0.52	-0.59
A	-0.32	-0.46	-0.24

[1] The risk measures are presented in the beginning of Appendix F.

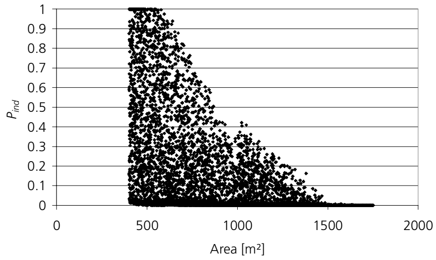


Figure F25. P_{ind} plotted against area.

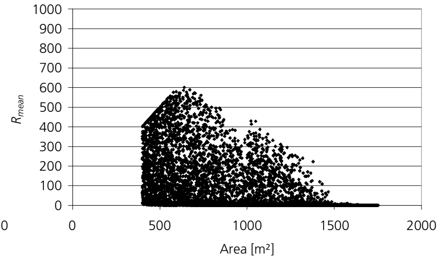


Figure F26. R_{mean} plotted against area.

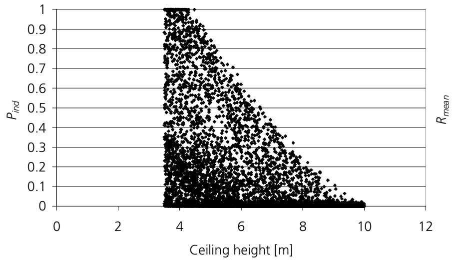


Figure F27. P_{ind} plotted against height.

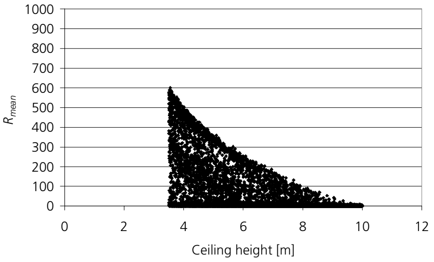


Figure F28. R_{mean} plotted against height.

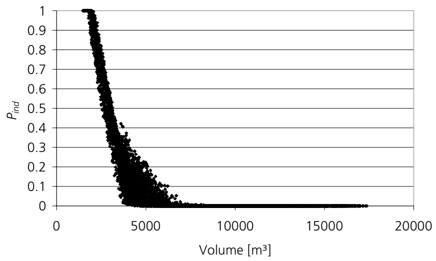


Figure F29. P_{ind} plotted against volume.

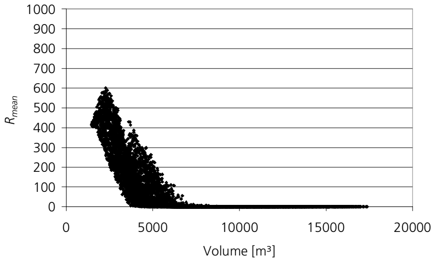


Figure F30. R_{mean} plotted against volume.

F7 Demanding at least 3 exits from all assembly halls

Table F13. Correlation analysis of the total number of cases simulated.

	R_{mean}[1]	P_{ind}[1]	P_{worst}[1]
R_{mean}	1.00		
P_{ind}	0.88	1.00	
P_{worst}	0.75	0.69	1.00
Volume $(h \cdot A)$	-0.53	-0.57	-0.62
h	-0.51	-0.48	-0.46
A	-0.38	-0.50	-0.50
N	0.38	0.20	0.39

Table F14. Correlation analysis of the cases where R >0.

	R_{mean}[1]	P_{ind}[1]	P_{worst}[1]
R_{mean}	1.00		
P_{ind}	0.85	1.00	
P_{worst}	0.65	0.59	1.00
h	-0.56	-0.52	-0.46
Volume $(h \cdot A)$	-0.52	-0.68	-0.47
N	0.35	0.07	0.29
A	-0.14	-0.40	-0.14

[1] The risk measures are presented in the beginning of Appendix F.

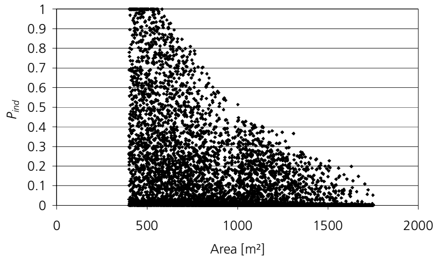


Figure F31. P_{ind} plotted against area.

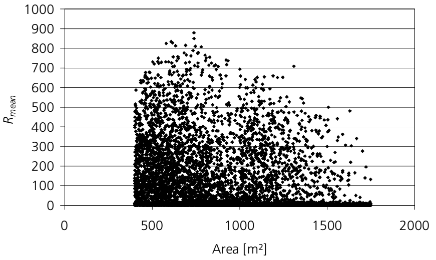


Figure F32. R_{mean} plotted against area.

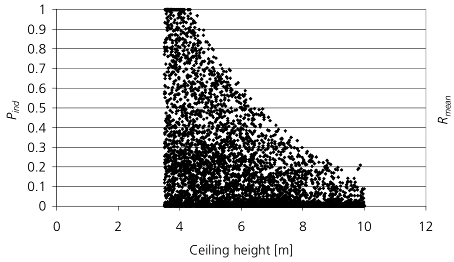


Figure F33. P_{ind} plotted against height.

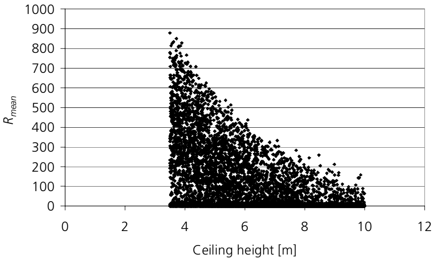


Figure F34. R_{mean} plotted against height.

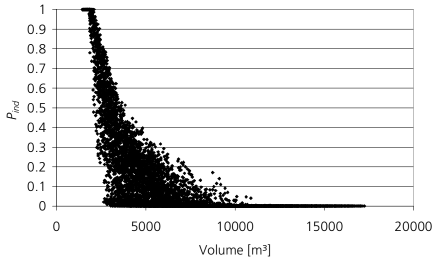


Figure F35. P_{ind} plotted against volume.

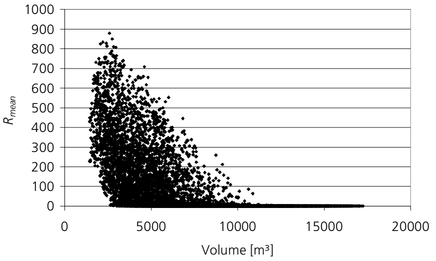


Figure F36. R_{mean} plotted against volume.

F8 Required exit width of 1 meter per 100 occupants

Table F15. Correlation analysis of the total number of cases simulated.

	R_{mean} [1]	P_{ind} [1]	P_{worst} [1]
R_{mean}	1.00		
P_{ind}	0.93	1.00	
P_{worst}	0.79	0.77	1.00
Volume $(h \cdot A)$	-0.43	-0.44	-0.52
h	-0.40	-0.38	-0.43
A	-0.37	-0.41	-0.46
N	0.24	0.14	0.22

Table F16. Correlation analysis of the cases where R >0.

	R_{mean} [1]	P_{ind} [1]	P_{worst} [1]
R_{mean}	1.00		
P_{ind}	0.91	1.00	
P_{worst}	0.71	0.68	1.00
Volume $(h \cdot A)$	-0.63	-0.71	-0.66
h	-0.48	-0.45	-0.46
A	-0.30	-0.44	-0.31
N	0.23	0.02	0.11

[1] The risk measures are presented in the beginning of Appendix F.

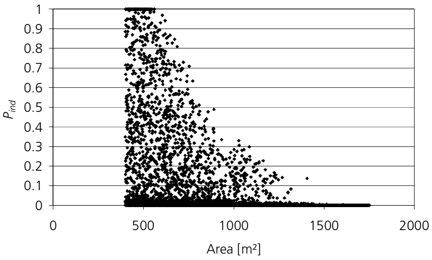


Figure F37. P_{ind} plotted against area.

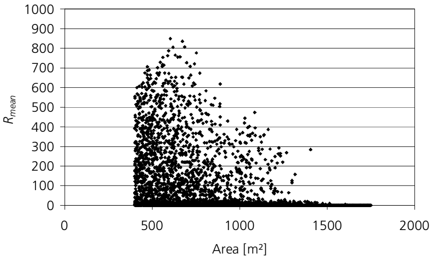


Figure F38. R_{mean} plotted against area.

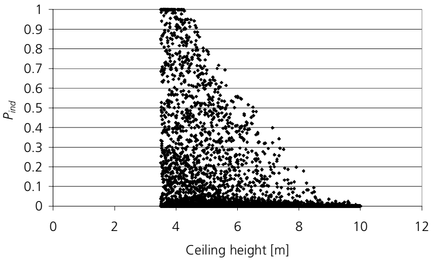


Figure F39. P_{ind} plotted against height.

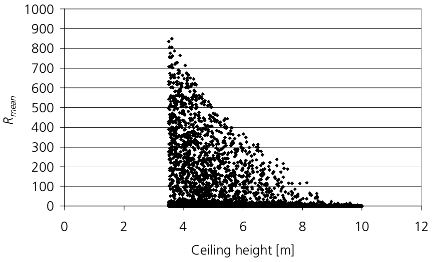


Figure F40. R_{mean} plotted against height.

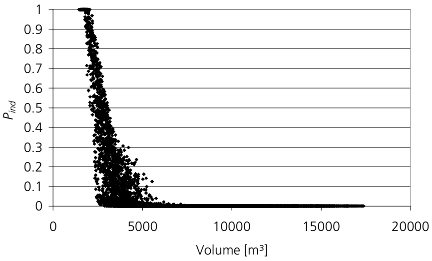


Figure F41. P_{ind} plotted against volume.

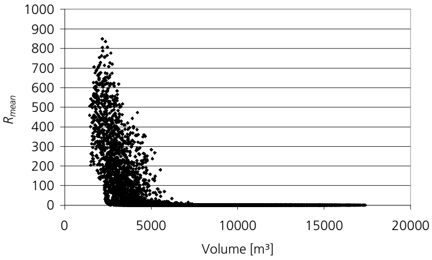


Figure F42. R_{mean} plotted against volume.

F9 Required exit width as a function of the volume of assembly halls

Table F17. Correlation analysis of the total number of cases simulated.

	R_{mean}[1]	P_{ind}[1]	P_{worst}[1]
R_{mean}	1.00		
P_{ind}	0.92	1.00	
P_{worst}	0.76	0.70	1.00
Volume $(h \cdot A)$	-0.48	-0.48	-0.54
h	-0.44	-0.41	-0.45
A	-0.39	-0.44	-0.44
N	0.31	0.17	0.36

Table F18. Correlation analysis of the cases where R >0.

	R_{mean}[1]	P_{ind}[1]	P_{worst}[1]
R_{mean}	1.00		
P_{ind}	0.90	1.00	
P_{worst}	0.69	0.62	1.00
Volume $(h \cdot A)$	-0.55	-0.62	-0.49
h	-0.52	-0.48	-0.49
A	-0.29	-0.45	-0.21
N	0.20	-0.03	0.18

[1] The risk measures are presented in the beginning of Appendix F.

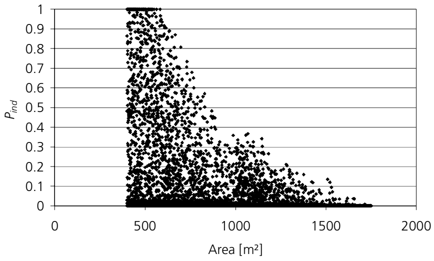


Figure F43. P_{ind} plotted against area.

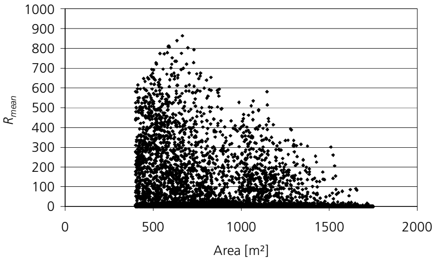


Figure F44. R_{mean} plotted against area.

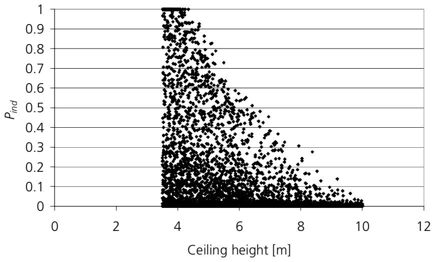


Figure F45. P_{ind} plotted against height.

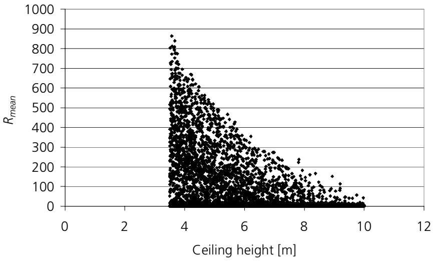


Figure F46. R_{mean} plotted against height.

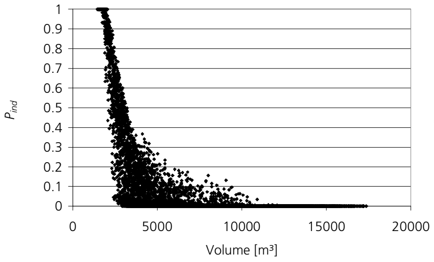


Figure F47. P_{ind} plotted against volume.

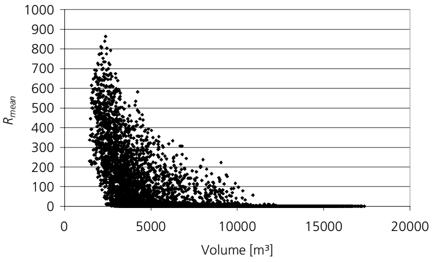


Figure F48. R_{mean} plotted against volume.

Appendix G

Appendix G – Results of the sensitivity analysis

A complete list of definitions of the variables can be found in Appendix C.

Variable: *Q* (2_1)

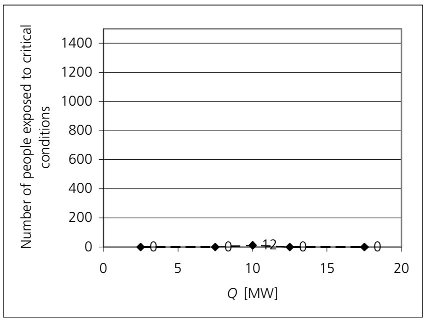


Figure G1. The consequence when all system work, $C_{all\ work}$.

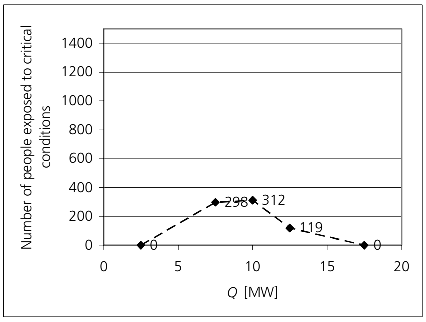


Figure G2. The maximum consequence of a single source failure, $C_{max\ ssf}$.

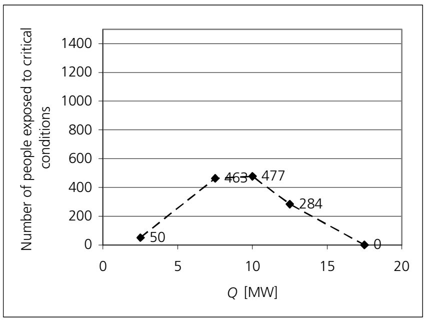


Figure G3. The consequence of the worst case scenario, $C_{worst\ case}$.

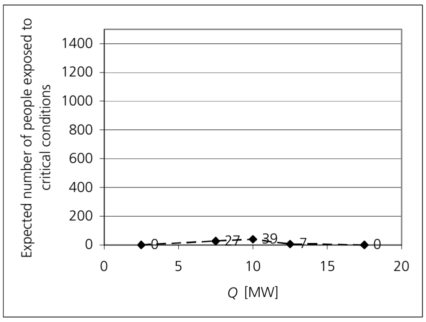


Figure G4. The mean risk, R_{mean}.

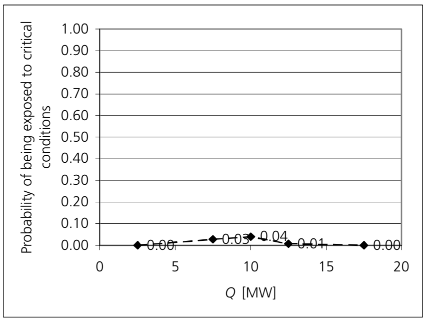


Figure G5. The individual risk, P_{ind}.

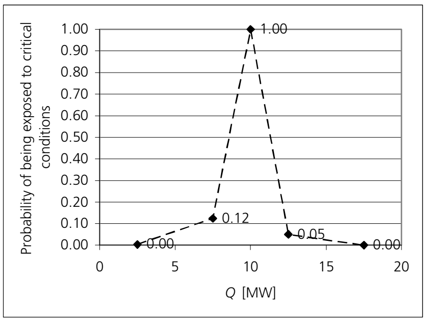


Figure G6. The individual risk to the most exposed person in the building, P_{worst}.

Variable: t_{d_aut} (2_2)

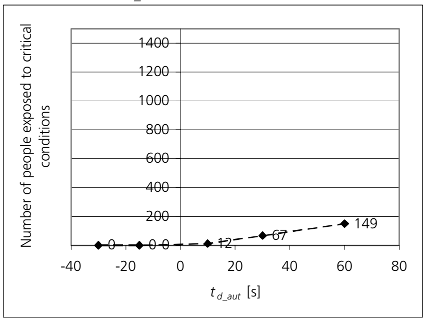


Figure G7. The consequence when all system work, $C_{all\ work}$.

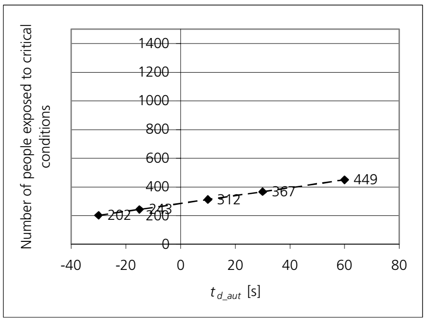


Figure G8. The maximum consequence of a single source failure, $C_{max\ ssf}$.

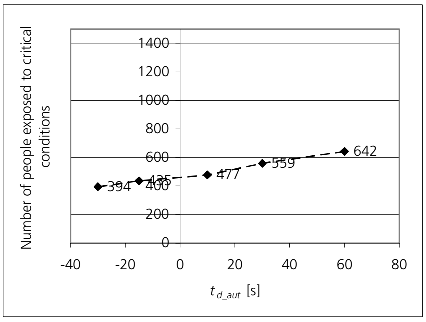


Figure G9. The consequence of the worst case scenario, $C_{worst\ case}$.

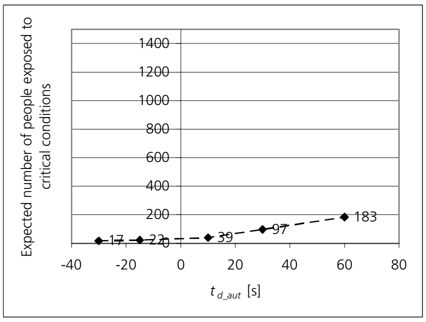


Figure G10. The mean risk, R_{mean}.

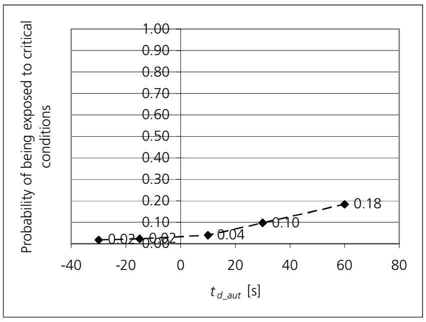


Figure G11. The individual risk, P_{ind}.

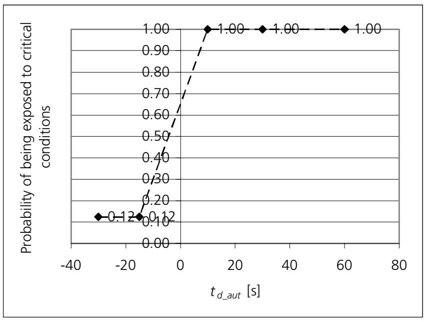
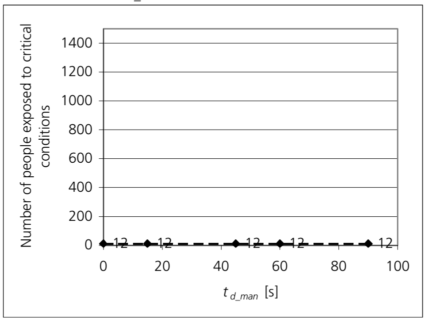


Figure G12. The individual risk to the most exposed person in the building, P_{worst}.

Variable: t_{d_man} (2_3)



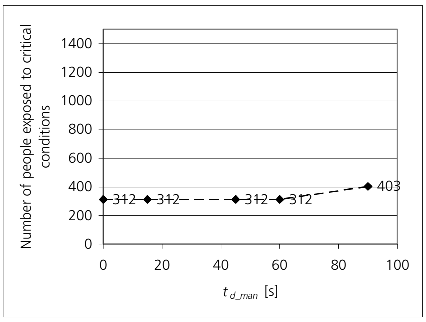
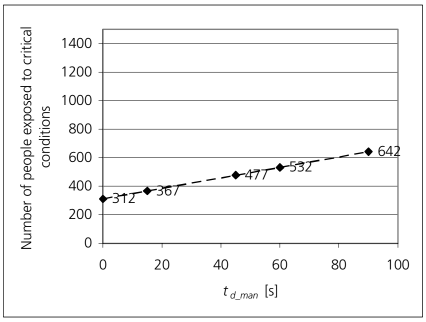


Figure G13. The consequence when all system work, $C_{all\ work}$.

Figure G14. The maximum consequence of a single source failure, $C_{max\ ssf}$.



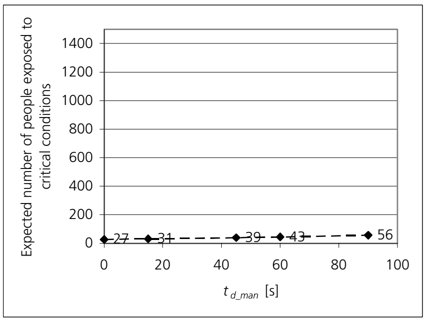
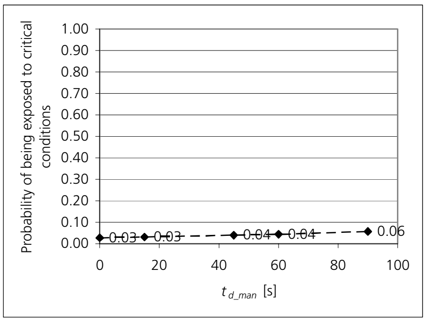


Figure G15. The consequence of the worst case scenario, $C_{worst\ case}$.

Figure G16. The mean risk, R_{mean}.



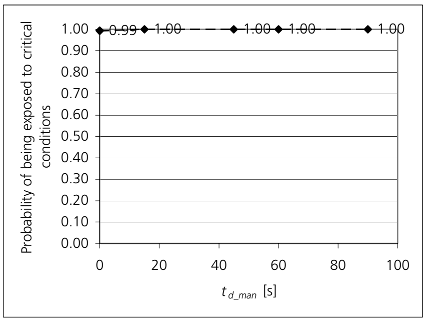


Figure G17. The individual risk, P_{ind}.

Figure G18. The individual risk to the most exposed person in the building, P_{worst}.

Variable: t_{pre_alarm} (2_4)

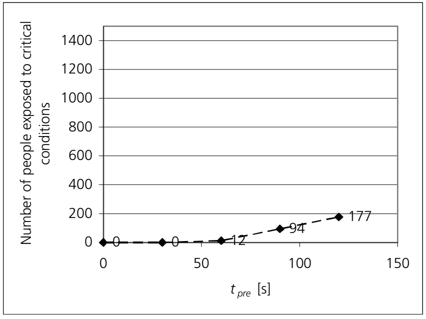


Figure G19. The consequence when all system work, $C_{all\ work}$.

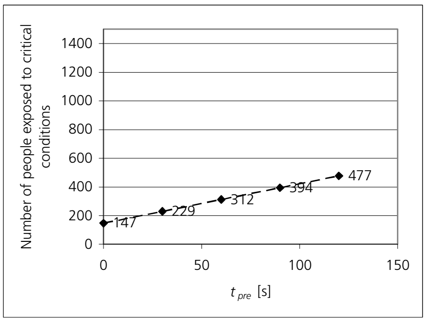


Figure G20. The maximum consequence of a single source failure, $C_{max\ ssf}$.

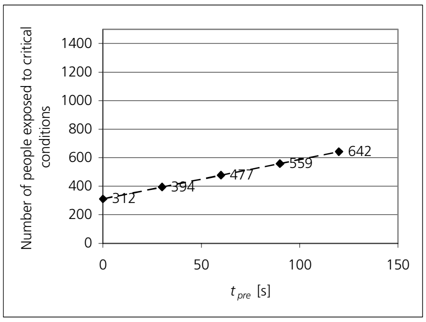


Figure G21. The consequence of the worst case scenario, $C_{worst\ case}$.

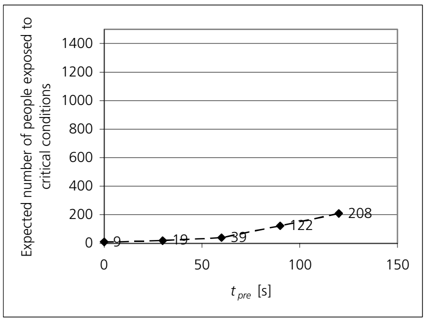


Figure G22. The mean risk, R_{mean}.

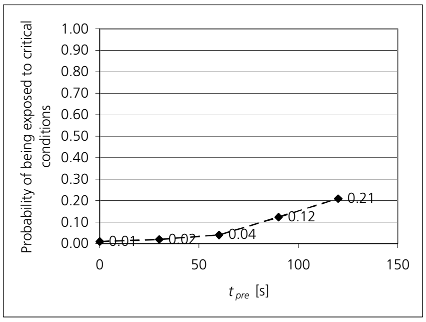


Figure G23. The individual risk, P_{ind}.

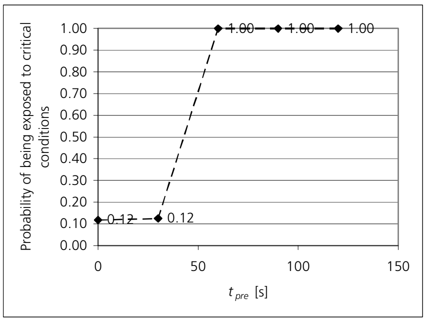


Figure G24. The individual risk to the most exposed person in the building, P_{worst}.

Variable: *N* (2_5)

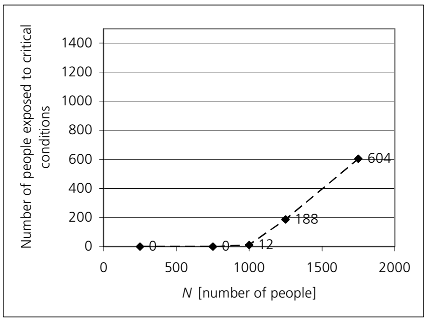


Figure G25. The consequence when all system work, $C_{all\ work}$.

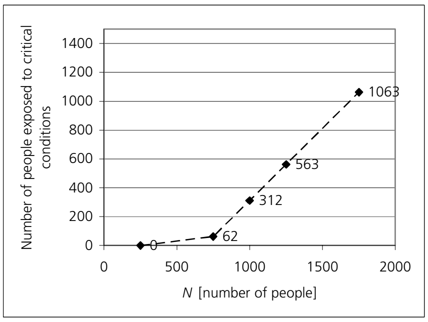


Figure G26. The maximum consequence of a single source failure, $C_{max\ ssf}$.

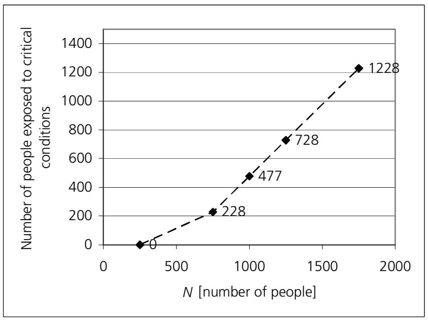


Figure G27. The consequence of the $_{worst}$-case scenario, $C_{worst\ case}$.

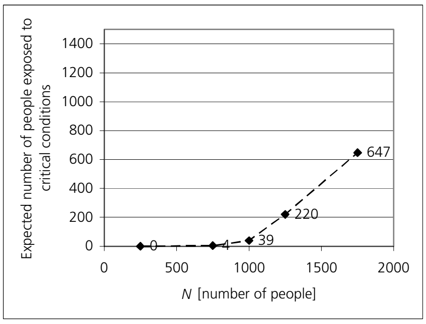


Figure G28. The mean risk, R_{mean}.

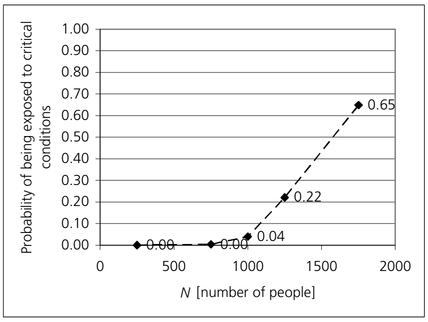


Figure G29. The individual risk, P_{ind}.

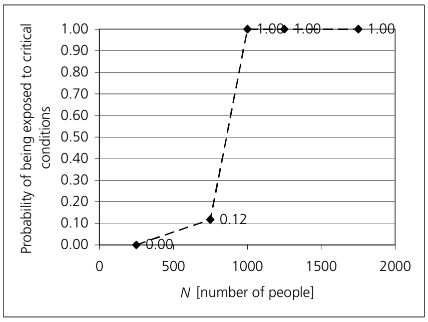


Figure G30. The individual risk to the most exposed person in the building, P_{worst}.

Variable: F_{ME} (2_6)

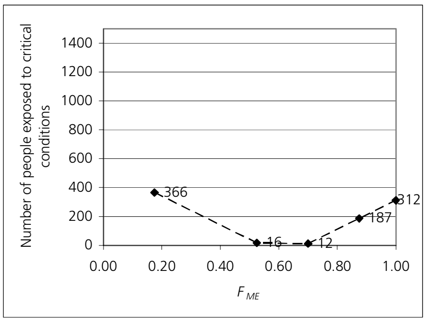


Figure G31. The consequence when all system work, $C_{all\ work}$.

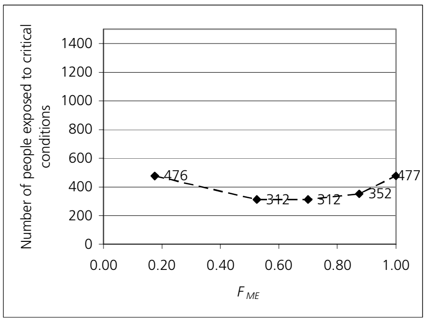


Figure G32. The maximum consequence of a single source failure, $C_{max\ ssf}$.

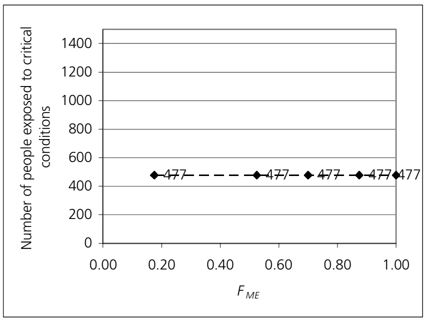


Figure G33. The consequence of the worst case scenario, $C_{worst\ case}$.

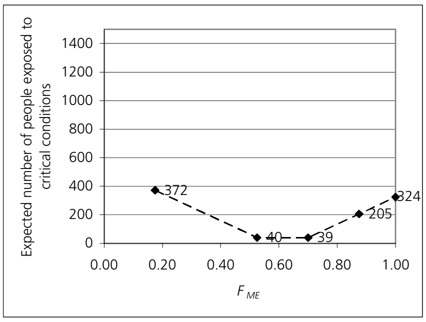


Figure G34. The mean risk, R_{mean}.

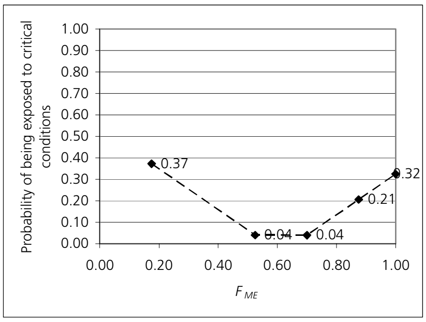


Figure G35. The individual risk, P_{ind}.

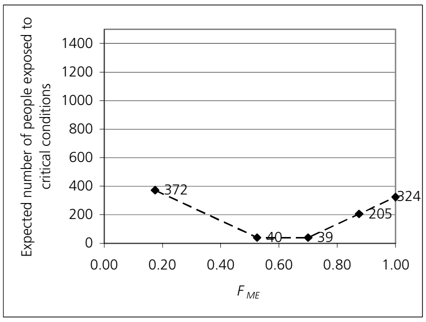


Figure G36. The individual risk to the most exposed person in the building, P_{worst}.

Variable: f_{UK} (2_7)

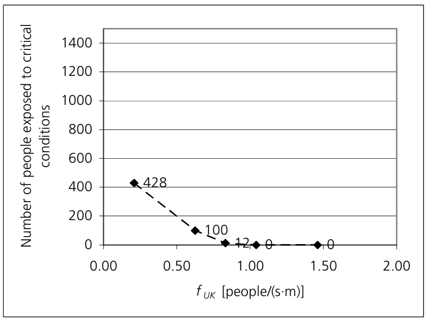


Figure G37. The consequence when all system work, $C_{all\ work}$.

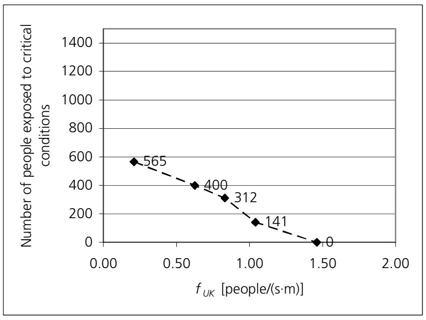


Figure G38. The maximum consequence of a single source failure, $C_{max\ ssf}$.

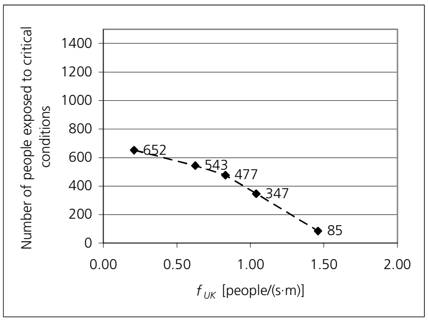


Figure G39. The consequence of the worst case scenario, $C_{worst\ case}$.

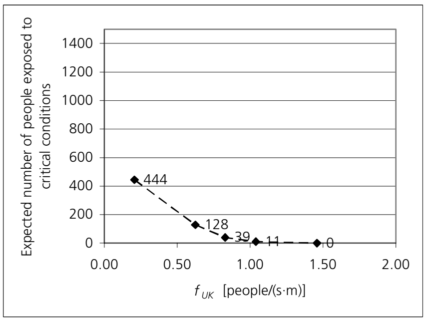


Figure G40. The mean risk, R_{mean}.

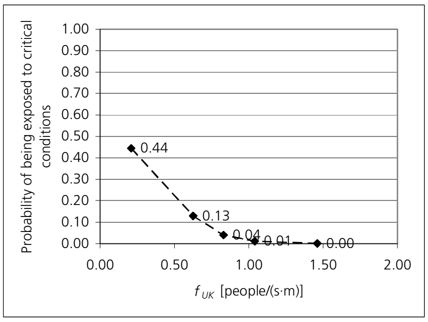


Figure G41. The individual risk, P_{ind}.

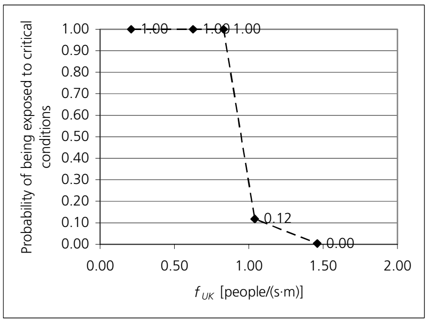


Figure G42. The individual risk to the most exposed person in the building, P_{worst}.

Variable: f_K (2_8)

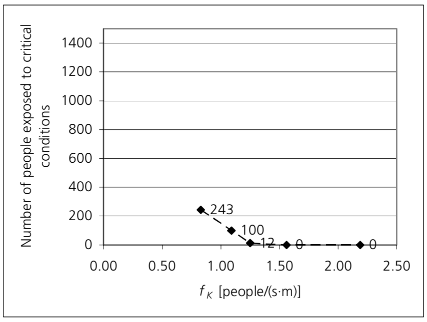


Figure G43. The consequence when all system work, $C_{all\ work}$.

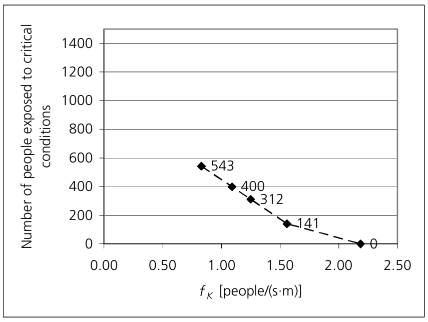


Figure G44. The maximum consequence of a single source failure, $C_{max\ ssf}$.

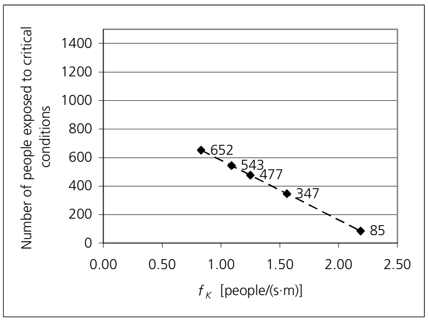


Figure G45. The consequence of the worst case scenario, $C_{worst\ case}$.

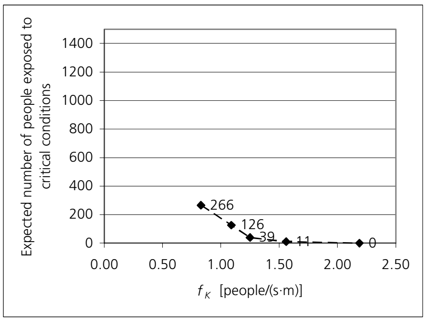


Figure G46. The mean risk, R_{mean}.

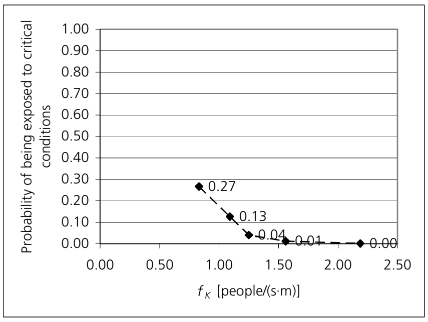


Figure G47. The individual risk, P_{ind}.

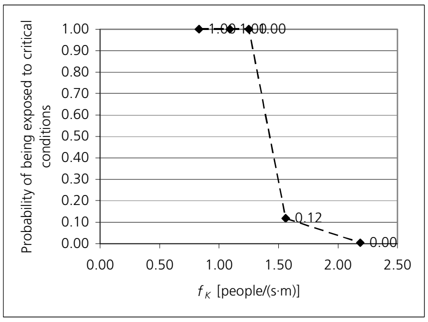


Figure G48. The individual risk to the most exposed person in the building, P_{worst}.

Variable: *w* (2_9)

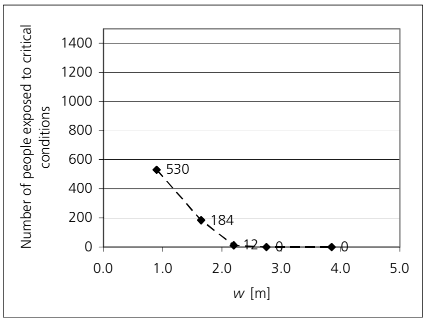


Figure G49. The consequence when all system work, $C_{all\ work}$.

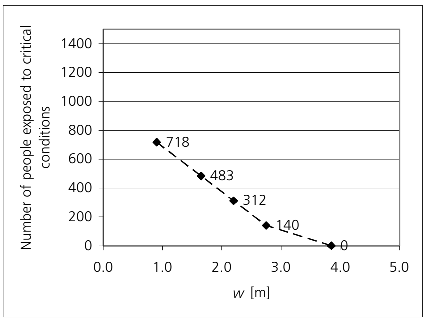


Figure G50. The maximum consequence of a single source failure, $C_{max\ ssf}$.

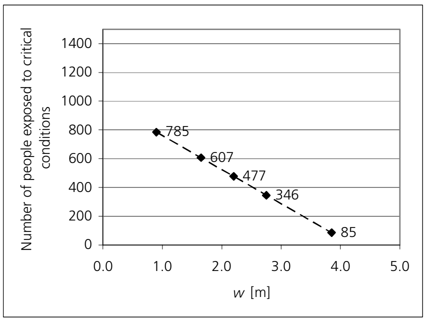


Figure G51. Konsekvensen av "the wors case scenario".

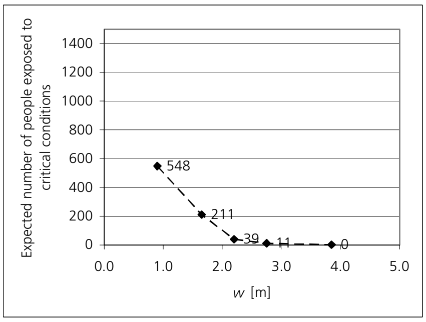


Figure G52. The mean risk, R_{mean}.

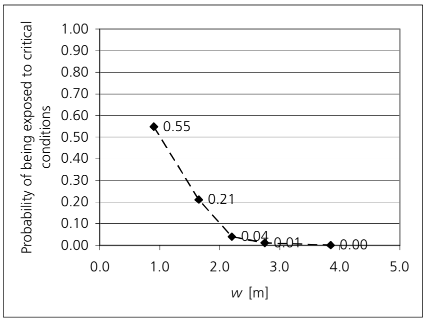


Figure G53. The individual risk, P_{ind}.

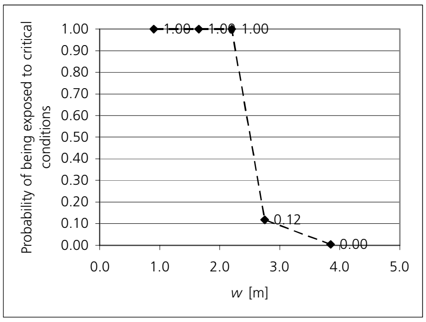


Figure G54. The individual risk to the most exposed person in the building, P_{worst}.

Variable: *A* (2_10)

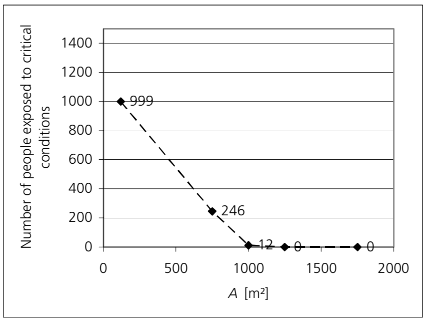


Figure G55. The consequence when all system work, $C_{all\ work}$.

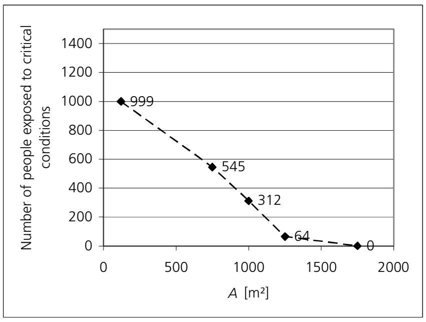


Figure G56. The maximum consequence of a single source failure, $C_{max\ ssf}$.

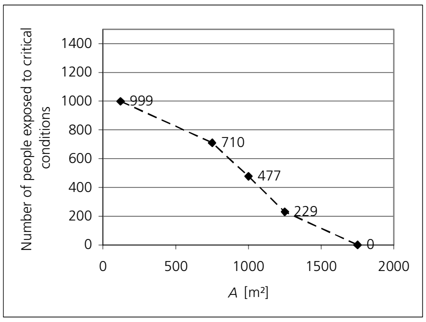


Figure G57. The consequence of the worst case scenario, $C_{worst\ case}$.

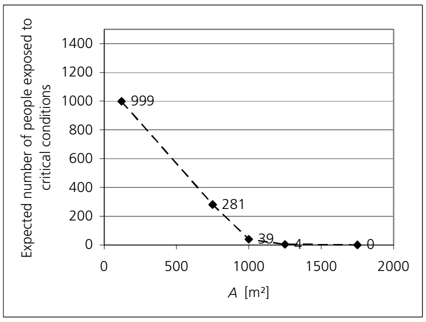


Figure G58. The mean risk, R_{mean}.

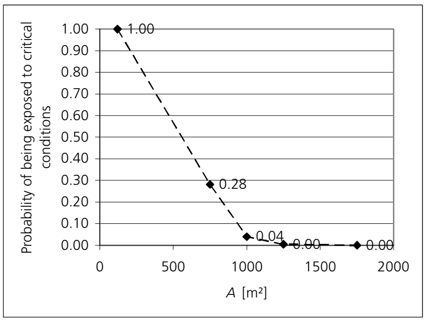


Figure G59. The individual risk, P_{ind}.

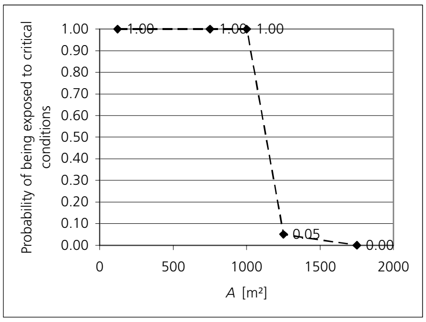


Figure G60. The individual risk to the most exposed person in the building, P_{worst}.

Variable: *h* (2_11)

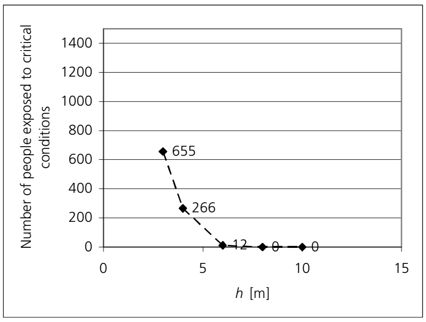


Figure G61. The consequence when all system work, $C_{all\ work}$.

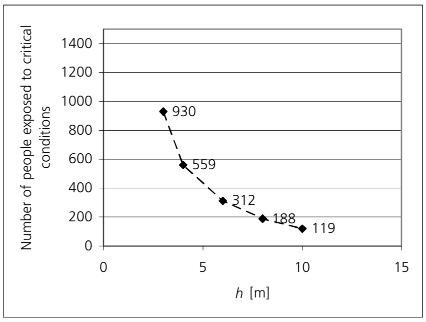


Figure G62. The maximum consequence of a single source failure, $C_{max\ ssf}$.

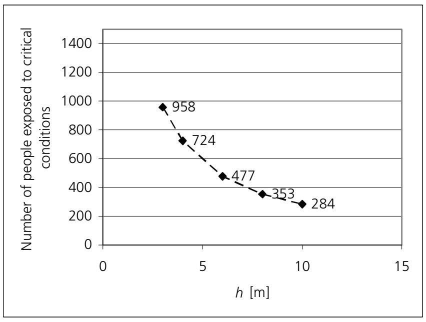


Figure G63. The consequence of the worst case scenario, $C_{worst\ case}$.

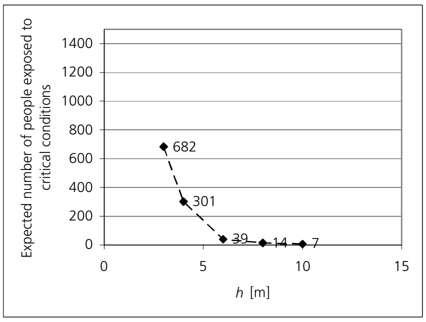


Figure G64. The mean risk, R_{mean}.

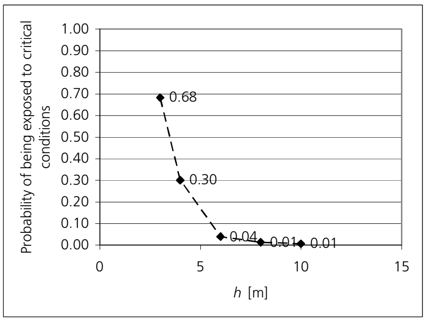


Figure G65. The individual risk, P_{ind}.

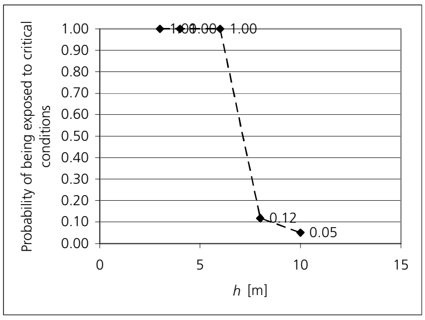
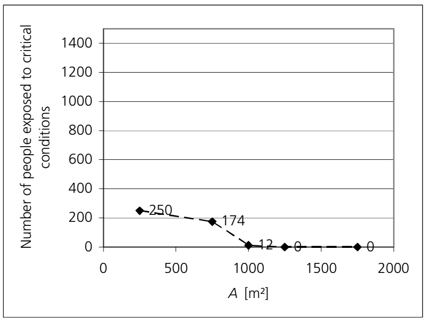


Figure G66. The individual risk to the most exposed person in the building, P_{worst}.

Variable: *A* (2_12), design effect on *N* and *w*



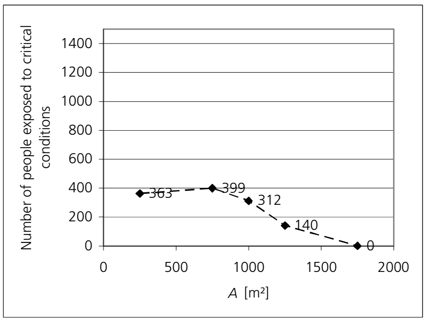
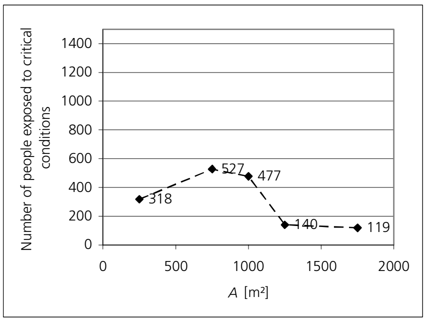


Figure G67. The consequence when all system work, $C_{all\ work}$.

Figure G68. The maximum consequence of a single source failure, $C_{max\ ssf}$.



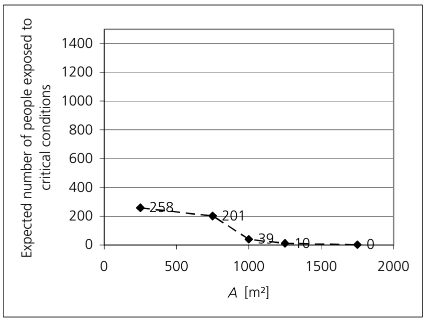
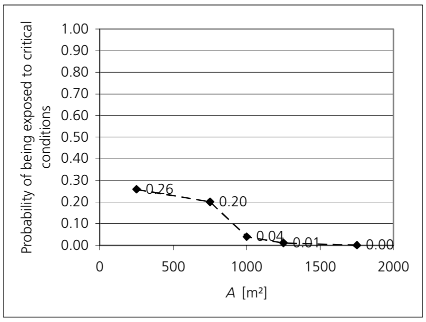


Figure G69. The consequence of the worst case scenario, $C_{worst\ case}$.

Figure G70. The mean risk, R_{mean}.



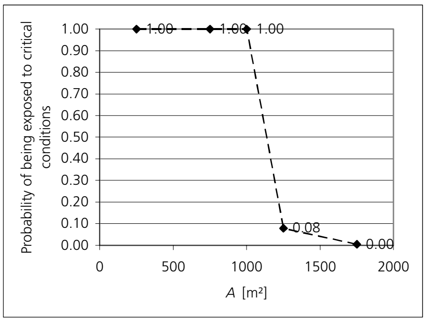


Figure G71. The individual risk, P_{ind}.

Figure G72. The individual risk to the most exposed person in the building, P_{worst}.

Variable: *w* (2_13), design effect on *N*

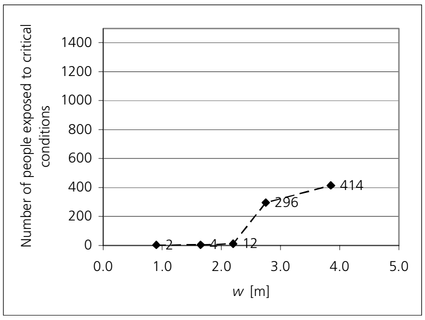


Figure G73. The consequence when all system work, $C_{all\ work}$.

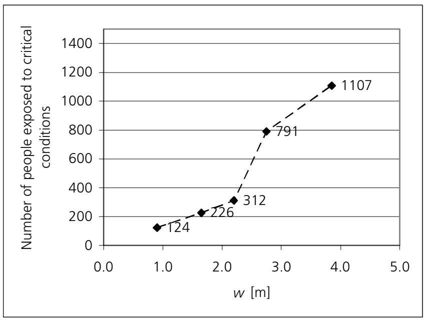


Figure G74. The maximum consequence of a single source failure, $C_{max\ ssf}$.

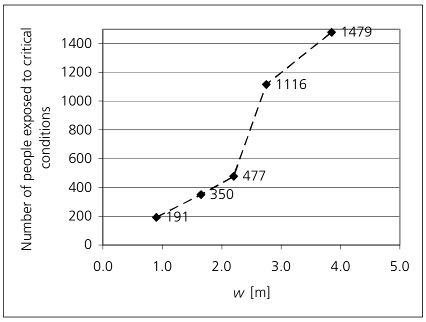


Figure G75. The consequence of the worst case scenario, $C_{worst\ case}$.

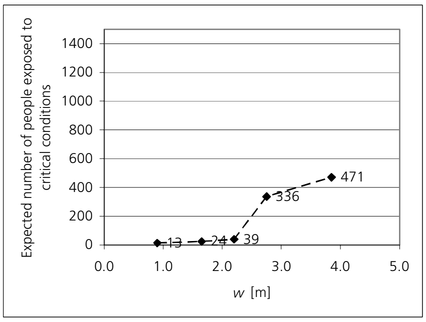


Figure G76. The mean risk, R_{mean}.

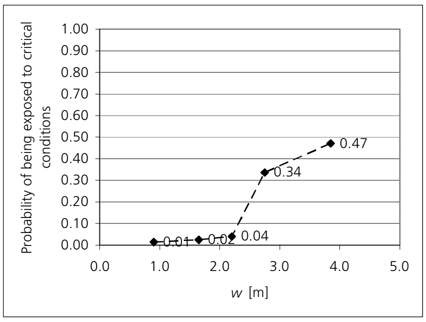


Figure G77. The individual risk, P_{ind}.

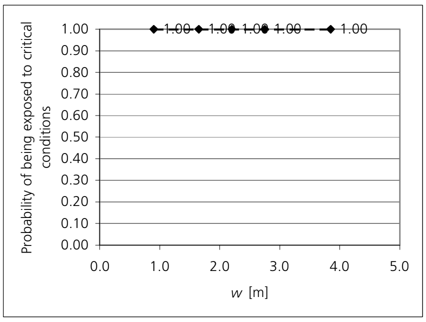


Figure G78. The individual risk to the most exposed person in the building, P_{worst}.

Variable: w_{1a} (2_14)

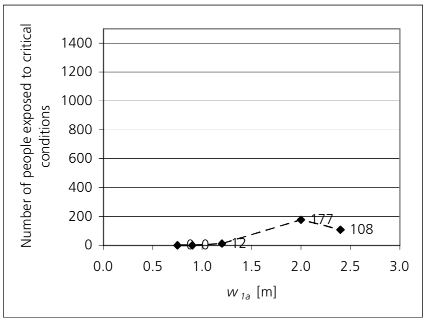


Figure G79. The consequence when all system work, $C_{all\ work}$.

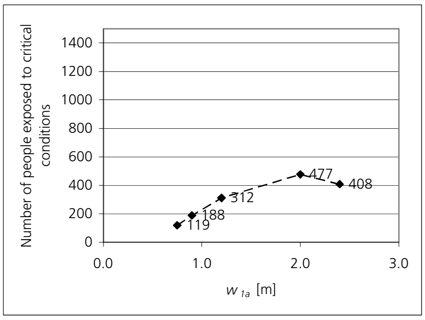


Figure G80. The maximum consequence of a single source failure, $C_{max\ ssf}$.

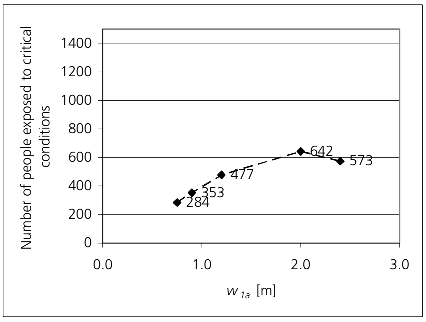


Figure G81. The consequence of the worst case scenario, $C_{worst\ case}$.

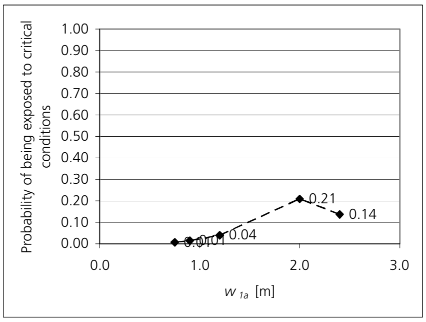


Figure G82. The mean risk, R_{mean}.

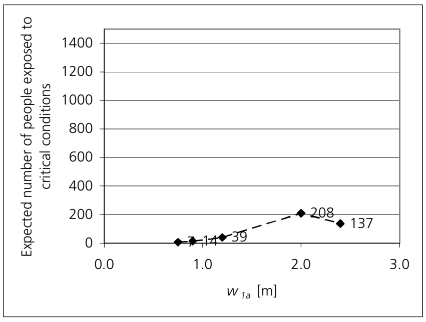


Figure G83. The individual risk, P_{ind}.

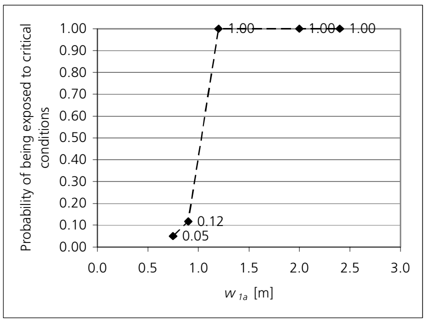


Figure G84. The individual risk to the most exposed person in the building, P_{worst}.

Variable: p_{f_evac} (2_15)

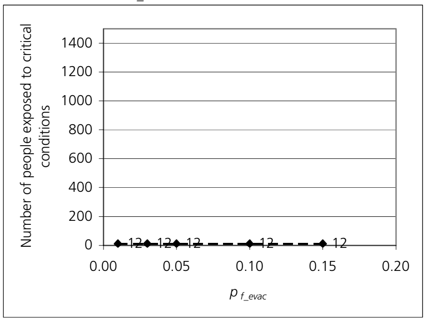


Figure G85. The consequence when all system work, $C_{all\ work}$.

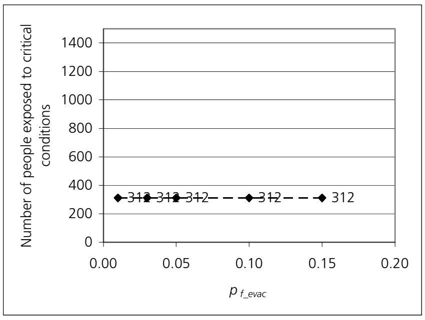


Figure G86. The maximum consequence of a single source failure, $C_{max\ ssf}$.

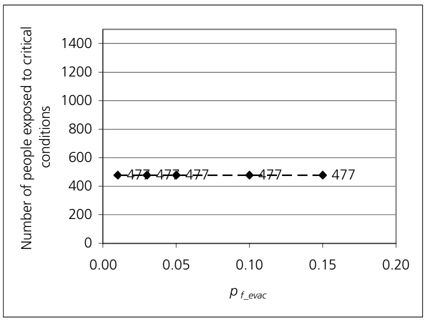


Figure G87. The consequence of the worst case scenario, $C_{worst\ case}$.

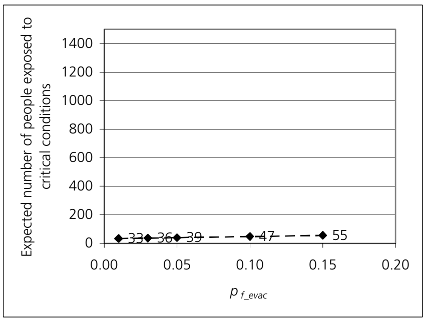


Figure G88. The mean risk, R_{mean}.

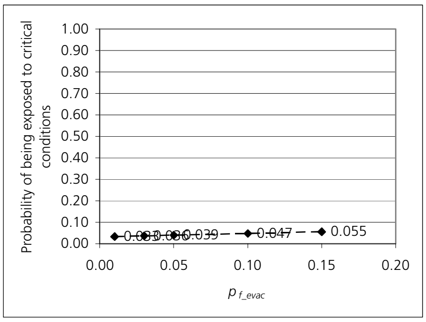


Figure G89. The individual risk, P_{ind}.

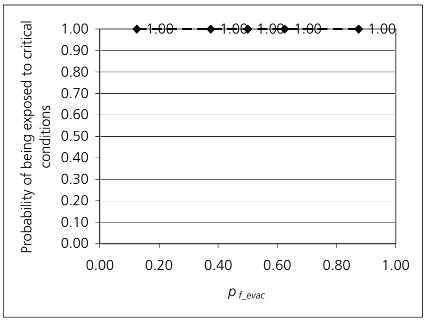


Figure G90. The individual risk to the most exposed person in the building, P_{worst}.

Variable: p_{f_aut} (2_16)

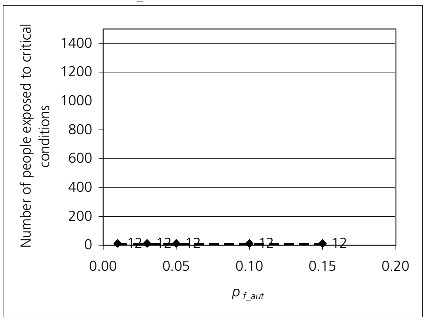


Figure G91. The consequence when all system work, $C_{all\ work}$.

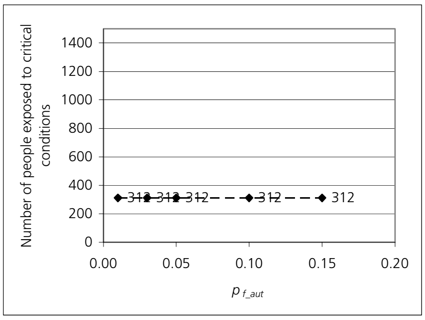


Figure G92. The maximum consequence of a single source failure, $C_{max\ ssf}$.

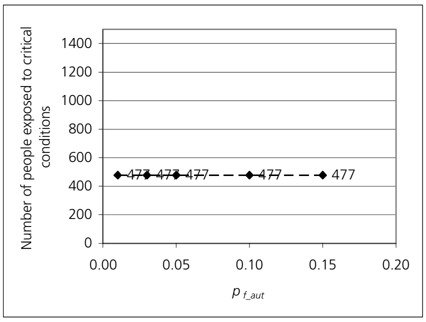


Figure G93. The consequence of the worst case scenario, $C_{worst\ case}$.

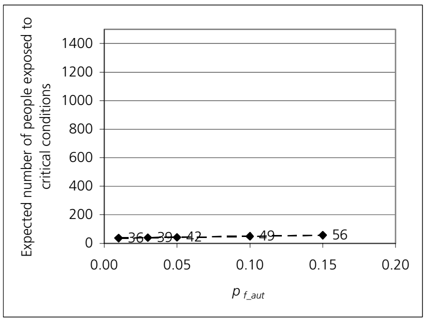


Figure G94. The mean risk, R_{mean}.

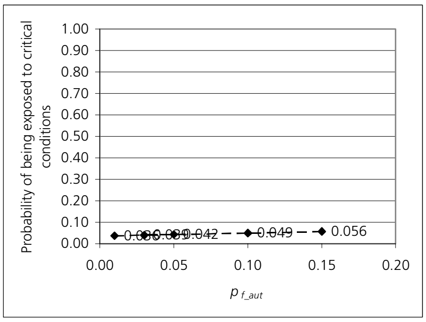


Figure G95. The individual risk, P_{ind}.

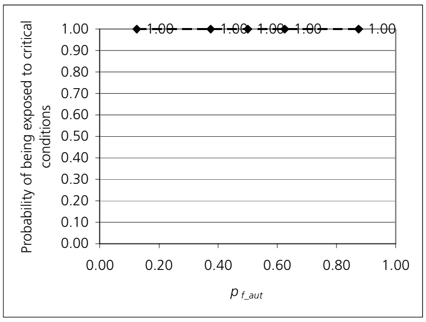
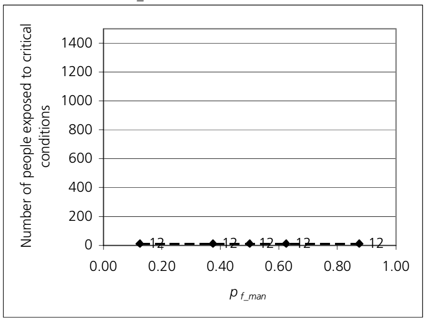


Figure G96. The individual risk to the most exposed person in the building, P_{worst}.

Variable: p_{f_man}(2_17)



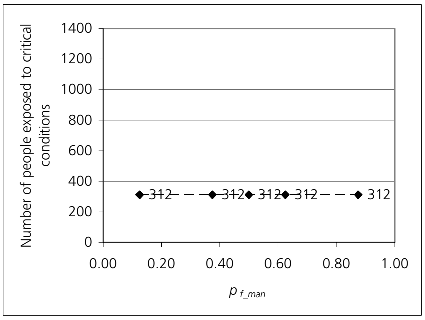
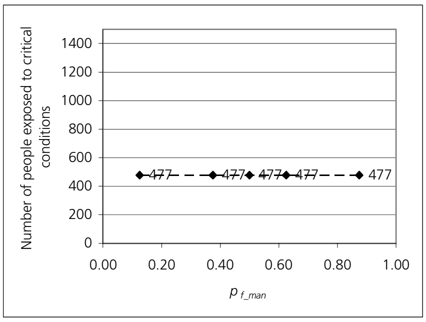


Figure G97. The consequence when all system work, $C_{all\ work}$.

Figure G98. The maximum consequence of a single source failure, $C_{max\ ssf}$.



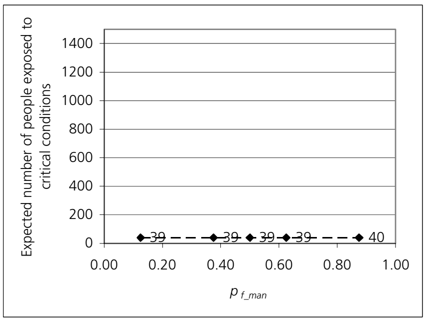
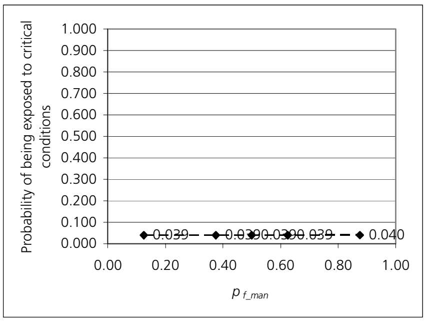


Figure G99. The consequence of the worst case scenario, $C_{worst\ case}$.

Figure G100. The mean risk, R_{mean}.



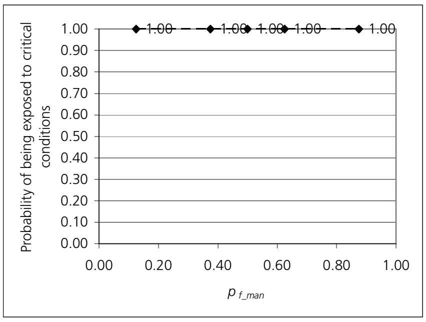
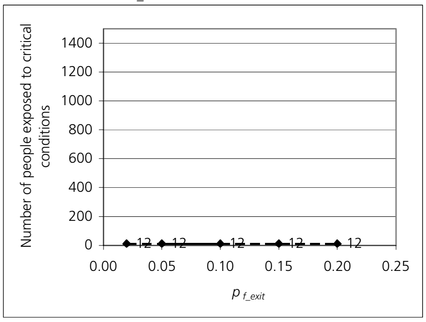


Figure G101. The individual risk, P_{ind}.

Figure G102. The individual risk to the most exposed person in the building, P_{worst}.

Variable: p_{f_exit} (2_18)



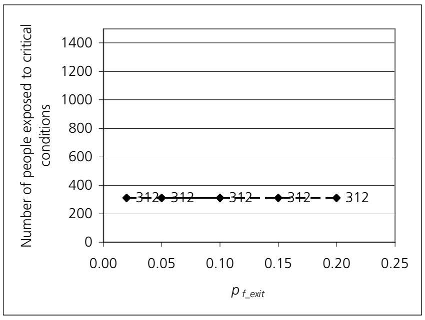
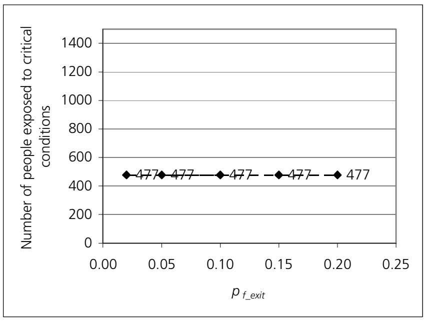


Figure G103. The consequence when all system work, $C_{all\ work}$.

Figure G104. The maximum consequence of a single source failure, $C_{max\ ssf}$.



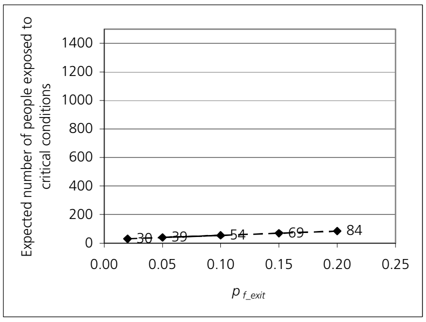
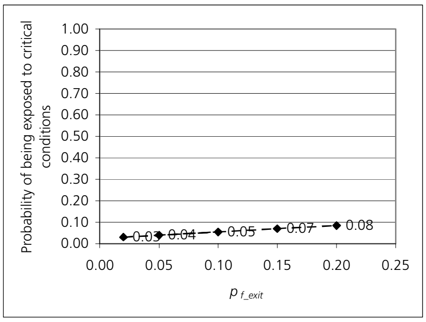


Figure G105. The consequence of the worst case scenario, $C_{worst\ case}$.

Figure G106. The mean risk, R_{mean}.



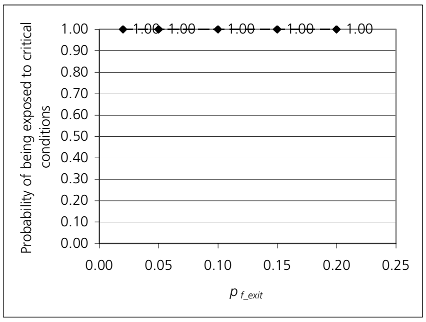


Figure G107. The individual risk, P_{ind}.

Figure G108. The individual risk to the most exposed person in the building, P_{worst}.

Variable: Q_{wv} (2_19)

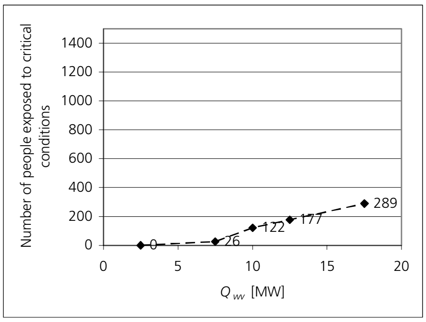


Figure G109. The consequence when all system work, $C_{all\ work}$.

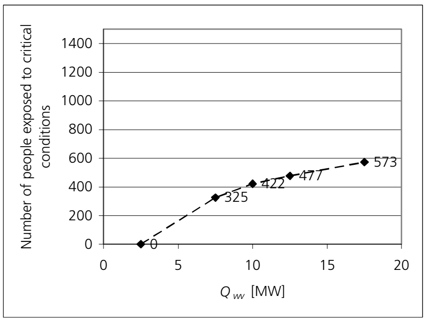


Figure G110. The maximum consequence of a single source failure, $C_{max\ ssf}$.

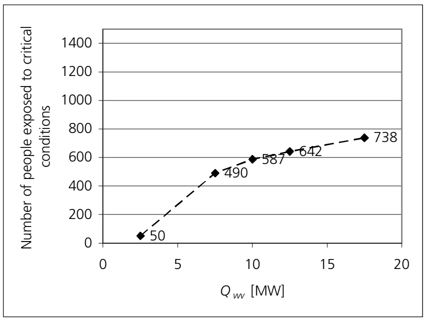


Figure G111. The consequence of the worst case scenario, $C_{worst\ case}$.

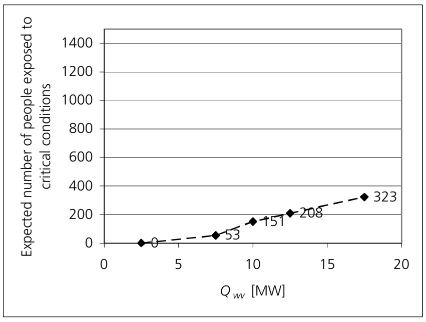


Figure G112. The mean risk, R_{mean}.

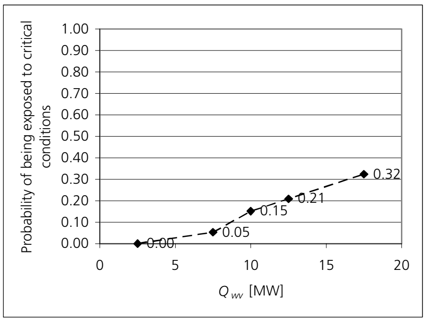


Figure G113. The individual risk, P_{ind}.

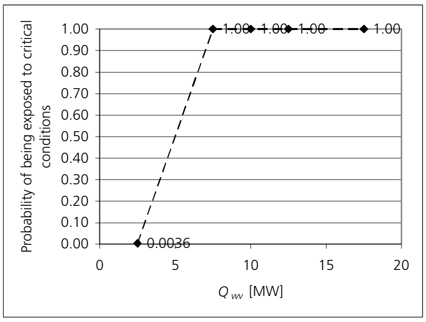


Figure G114. The individual risk to the most exposed person in the building, P_{worst}.

Variable: Fuel type (2_20)

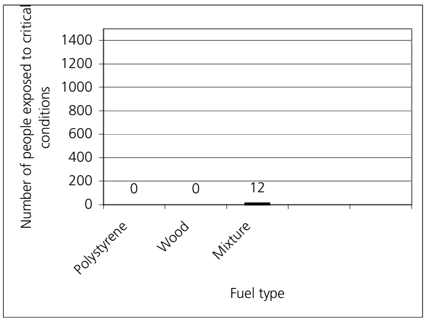


Figure G115. The consequence when all system work, $C_{all\ work}$.

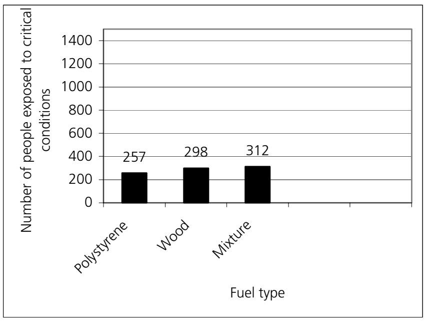


Figure G116. The maximum consequence of a single source failure, $C_{max\ ssf}$.

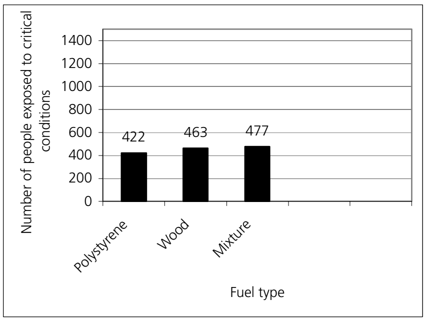


Figure G117. The consequence of the worst case scenario, $C_{worst\ case}$.

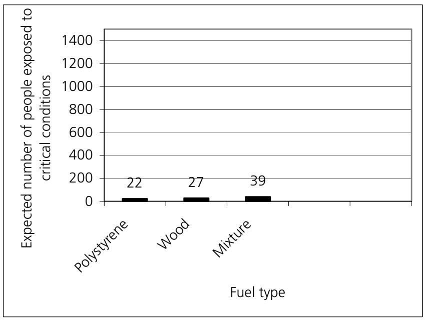


Figure G118. The mean risk, R_{mean}.

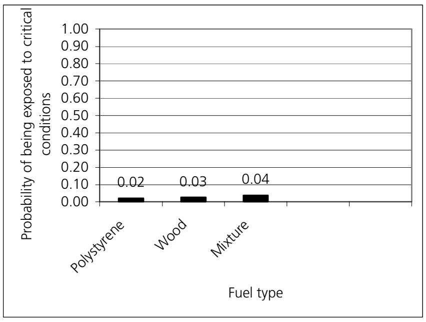


Figure G119. The individual risk, P_{ind}.

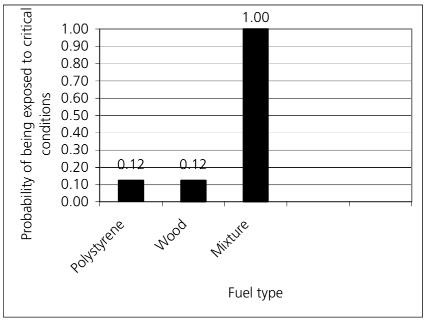


Figure G120. The individual risk to the most exposed person in the building, P_{worst}.

Variable: Definition of critical conditions (2_21)

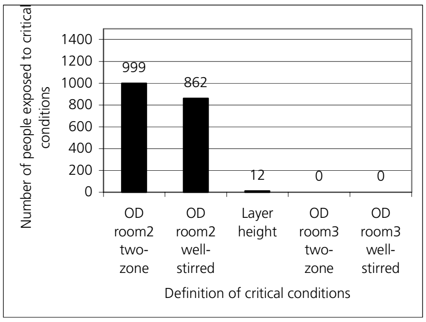


Figure G121. The consequence when all system work, $C_{all\ work}$.

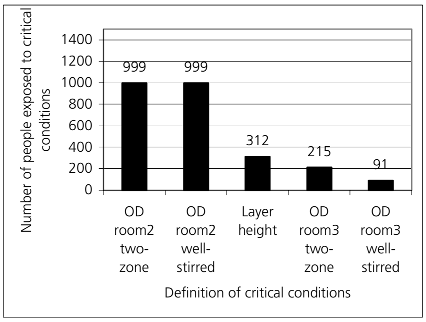


Figure G122. The maximum consequence of a single source failure, $C_{max\ ssf}$.

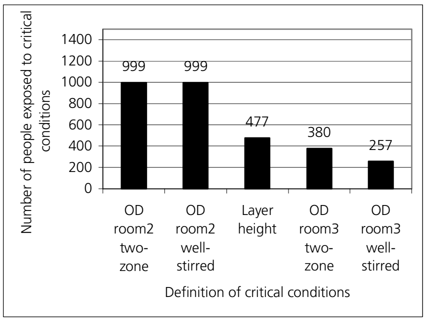


Figure G123. The consequence of the worst case scenario, $C_{worst\ case}$.

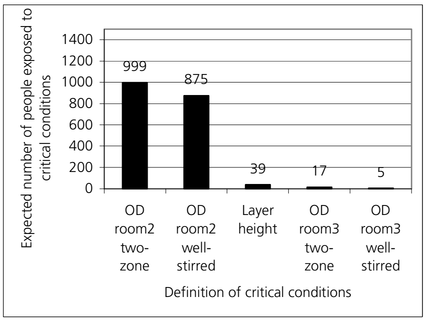


Figure G124. The mean risk, R_{mean}.

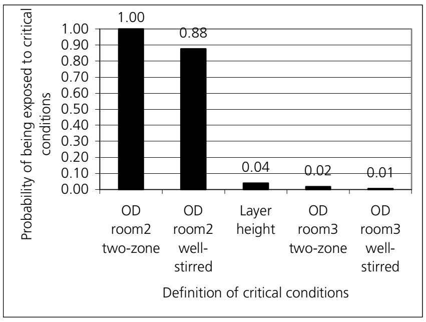


Figure G125. The individual risk, P_{ind}.

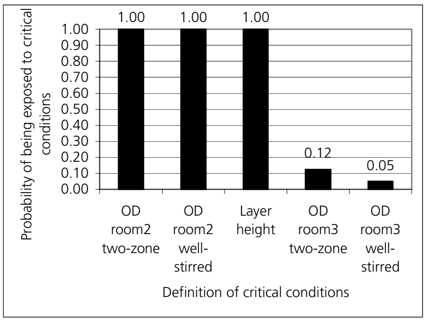


Figure G126. The individual risk to the most exposed person in the building, P_{worst}.

Variable: Definition of critical conditions, well vent. (2_22)

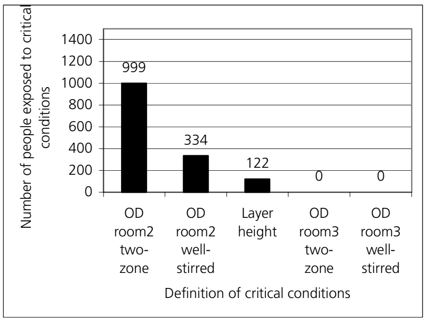


Figure G127. The consequence when all system work, $C_{all\ work}$.

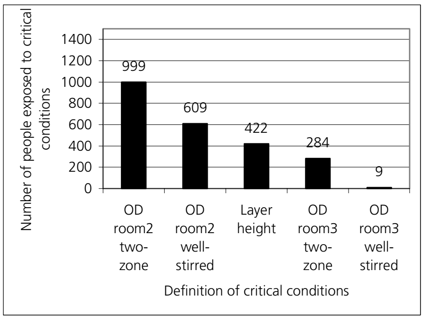


Figure G128. The maximum consequence of a single source failure, $C_{max\ ssf}$.

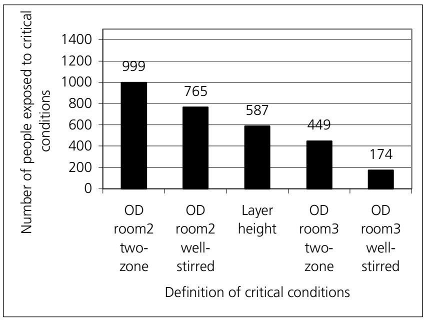


Figure G129. The consequence of the worst case scenario, $C_{worst\ case}$.

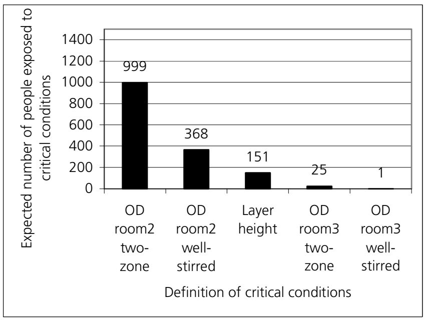


Figure G130. The mean risk, R_{mean}.

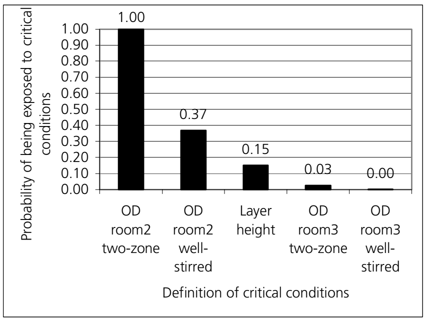


Figure G131. The individual risk, P_{ind}.

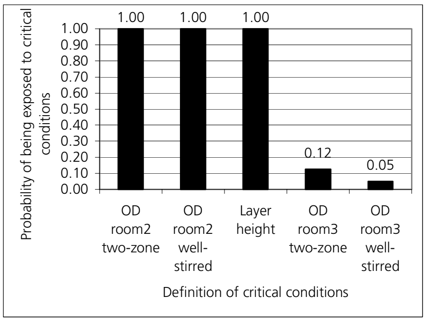


Figure G132. The individual risk to the most exposed person in the building, P_{worst}.

Variable: ΔH_c (2_23)

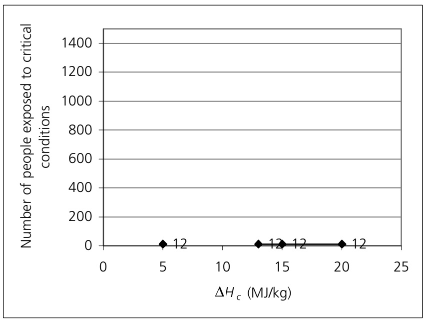


Figure G139. The consequence when all system work, $C_{all\ work}$.

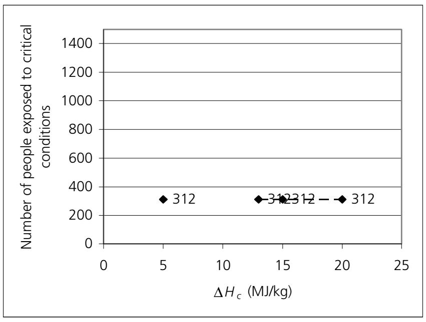


Figure G140. The maximum consequence of a single source failure, $C_{max\ ssf}$.

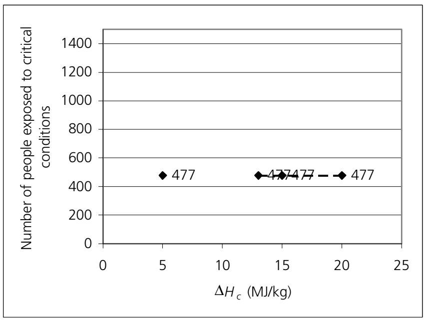


Figure G141. The consequence of the worst case scenario, $C_{worst\ case}$.

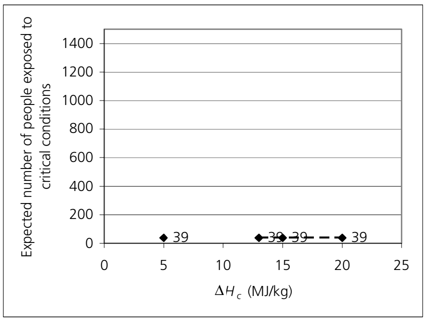


Figure G142. The mean risk, R_{mean}.

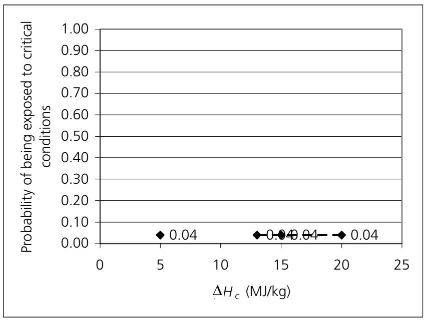


Figure G143. The individual risk, P_{ind}.

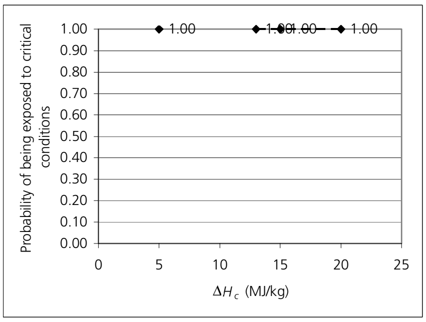


Figure G144. The individual risk to the most exposed person in the building, P_{worst}.

Variable: χ_{rad} (2_24)

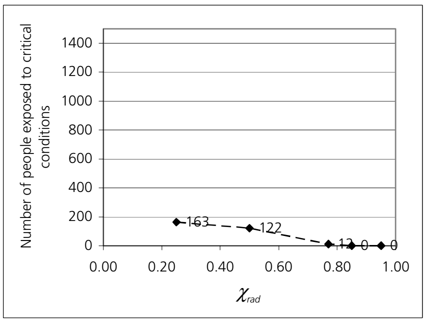


Figure G133. The consequence when all system work, $C_{all\ work}$.

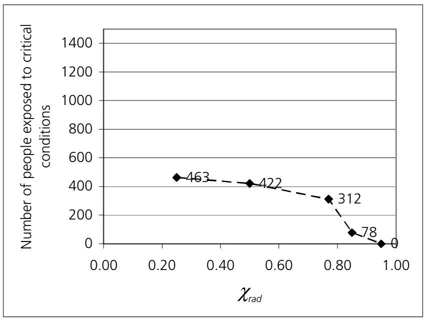


Figure G134. The maximum consequence of a single source failure, $C_{max\ ssf}$.

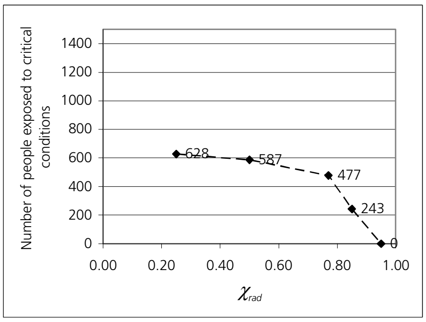


Figure G135. The consequence of the worst case scenario, $C_{worst\ case}$.

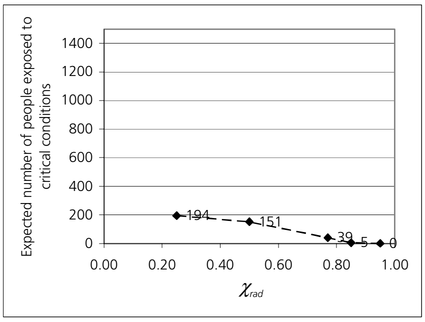


Figure G136. The mean risk, R_{mean}.

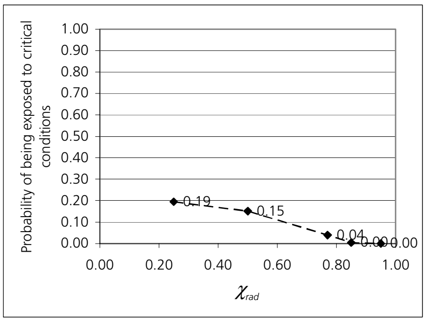


Figure G137. The individual risk, P_{ind}.

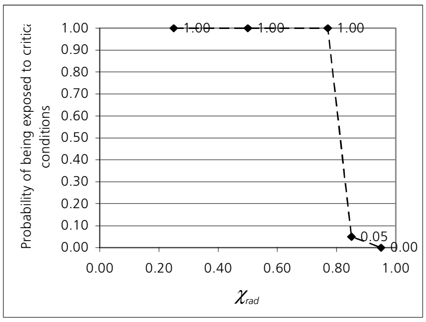


Figure G138. The individual risk to the most exposed person in the building, P_{worst}.

Variable: ρ_{design} (2_25)

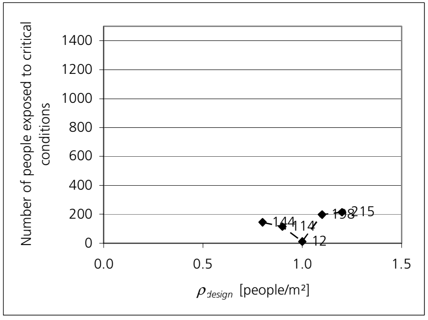


Figure G145. The consequence when all system work, $C_{all\ work}$.

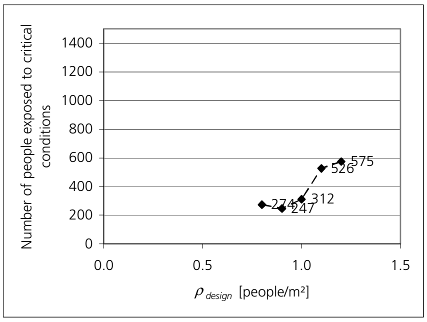


Figure G146. The maximum consequence of a single source failure, $C_{max\ ssf}$.

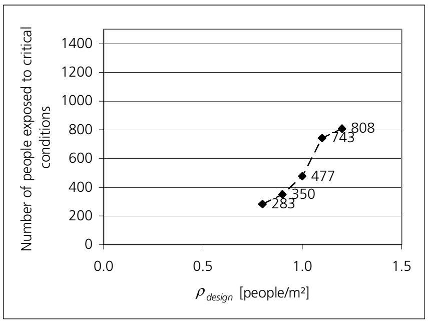


Figure G147. The consequence of the worst case scenario, $C_{worst\ case}$.

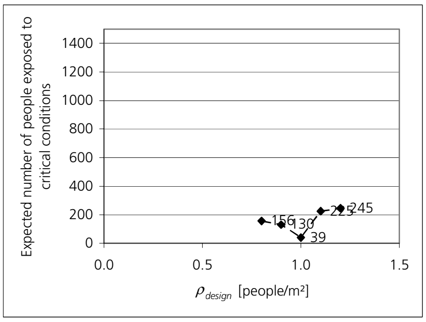


Figure G148. The mean risk, R_{mean}.

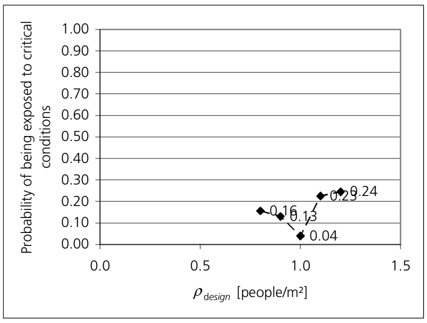


Figure G149. The individual risk, P_{ind}.

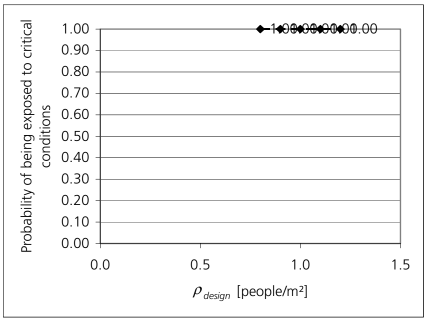


Figure G150. The individual risk to the most exposed person in the building, P_{worst}.