

# **Analysing Fire Risk in Automated High Bay Warehouses**

**-Applying the IEC model for risk  
analysis on high bay warehouse fires**

***Marcus Arvidsson  
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Abstract  
This master thesis presents a framework, aimed at assessing fire risk in large automated warehouses. The International Electrotechnical Commission's (IEC) framework, *Risk analysis of technological systems*, provides the base, as to the functions of a risk analysis framework and this is subsequently adopted and expanded to better suit the fire risk analysis in high-bay warehouses. The framework presented is mainly intended for automated high bay areas, but it is the authors' belief that the methodologies used can be applied to other premises where ignition sources are scarce and not readily analysed. The methodology presented analyses risk in a quantitative manner, and is predominantly based on event tree analysis. The ignition frequency is assumed to be related to floor area and the fire consequence is approximated by utilising damage criteria limits. In order to assess the proposed methodology, a case study was performed at Ikea's high bay warehouse in Älmhult, Sweden.

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## Foreword

This thesis has been conducted to meet the requirements for a Master of Science degree in Risk Management and Safety Engineering and a Bachelor of Science degree in Fire Protection Engineering at the Department of Fire Safety Engineering, Lund University, Sweden.

There are several people who have been involved in the work with this thesis, without the assistance and support of these persons our work would have been much harder, and we would like to show them our greatest appreciation.

At IKEA. Our initial contact Jan Lagerblad and our supervisor Ulrich Mayer, thank you both for taking time out of your busy schedules and helping us in our work providing valuable insight.

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## Sammanfattning

Användandet av centraliserade distributionscentraler och lager har blivit en vanligt förekommande logistisk strategi, framförallt bland multinationella företag. Dessa distributionscentraler täcker ofta vidsträckta marknader och är därför inte sällan av betydande storlek. I takt med en ökande efterfrågan på flexibilitet och effektivisering inom företagen, så har centrallagren växt, både vad gäller golvarea och byggnadshöjd, och i och med en ökande automatisering så tycks lagerlokalerna bli ännu större. Denna strategi medför naturligtvis ett antal logistiska fördelar, i form av minskade administrationskostnader och en ökad kontroll över lagernivåerna, men tyvärr medför denna strategi också en ökad sårbarhet. Det finns endast ett fåtal riskkällor som potentiellt skulle kunna förstöra stora delar av lagret eller på andra sätt slå ut distributionscentret över en längre tid. Dessa riskkällor innefattar främst naturkatastrofer, såsom jordbävningar och översvämningar, men även bränder faller in i denna kategori. I händelse av en brand så är naturligtvis en totalbrand det värsta tänkbara scenariot, men öppenheten (stora volymer utan brandteknisk avskiljning) i dessa lagerlokaler gör att även mindre bränder potentiellt skulle kunna förstöra stora mängder av gods genom rök- och värmepåverkan.

Trots att en brand i ett automatiserat höglager potentiellt kan ha katastrofala följder för en organisation så har påfallande lite forskning utförts inom detta område. Å andra sidan så finns det väldigt få, om några, dokumenterade bränder i dessa anläggningar. Detta samband leder till att man kan anta att brandfrekvensen i automatiserade höglager är väldigt låg. Ett antagande som stärks av bristen på tändkällor i dessa lager.

I ett försök att belysa problematik kring brandriskanalys i automatiserade höglager, samt utveckla en metodik för att utvärdera densamma, så har detta examensarbete utförts i samarbete med IKEA och Institutionen för Brandteknik vid Lunds Tekniska Högskola. Examensarbetet presenterar ett ramverk ämnat för brandriskanalys i stora automatiserade höglager. Ett ramverk framtaget av The International Electrotechnical Commission har använts som en bas för det nya ramverkets uppbyggnad, men har under arbetets gång omformats för att bättre lämpa sig för brandriskanalys i höglager. Vidare så har de olika delarna av IEC ramverket utvärderats för deras förmåga att uppfylla följande tre kriterier; enkelhet, expanderbarhet och kvantitet.

Det nya ramverket har utformats genom att arbetssätt har identifierats för följande delsektioner i IEC,

- IEC 5.3 Hazard identification
- IEC 5.4.1 Frequency analysis
- IEC 5.4.2 Consequence analysis
- IEC 5.4.3 Risk calculations

Vidare så har karakteristika för automatiserade höglager identifierats och dessa har också spelat in i valet av metodologier. Bland annat så har det antagits att inga signifikanta tändkällor finns i ett automatiserat höglager och brandfrekvensen har därför fastställts med hjälp av golvareberoende modeller. Vidare så har konsekvensanalysen utförts genom att en modell för kritiska värden för olika brandskador använts.

Det föreslagna ramverket, eller arbetsgången, för brandriskanalys i höglager är summerad nedan;

- Använd en checklistemetod för att upptäcka uppenbara och signifikanta tändkällor.
- Om signifikanta tändkällor påträffas så skall dessa avlägsnas från höglagret innan analysarbetet kan fortsätta. Detta för att fastställa att de antaganden som modellen grundats på är giltiga för fallet i fråga.

- 
- Brandfrekvensen fastställs med hjälp av det tidigare nämnda sambandet mellan brandfrekvens och golvarea.
  - All tillgänglig byggnadsspecifik data sammanställs och används för att uppdatera den generiska datum från föregående steg.
  - Ett händelsetråd med bashändelsen ”brand uppstår” ställs upp. Händelsetrådets grenar skall representera olika brandscenarion och innefatta olika framgångsgrader av eventuella brandskydd.
  - Fastställ till vilken grad brandrelaterade fenomen kan påverka godset. Detta bör innefatta värme, strålning rök etc.
  - Fastställ vilka nivåer som godset kan antas utsättas för, med hänsyn till de brandskyddsåtgärder som finns närvarande, och deras respektive effektivitet.
  - Fastställ vilka nivåer av ovan nämnda fenomen som godset kan antas motstå.
  - Beräkna konsekvensen för varje slutscenarion i händelsetrådet.
  - Sannolikhetsfördelning för skadan av en inträffad brand kan nu fastställas.
  - Den förväntade årliga brandskadekostanden kan fastställas genom att kombinera den förväntade skadan med brandfrekvensen. En sannolikhetsfördelning skall användas för att illustrera brandrisken.

En fallstudie har utförts för att utvärdera det föreslagna ramverket. Fallstudien utfördes vid IKEA:s distributionscentral i Älmhult. Resultatet av utvärderingen fann att;

- På det hela taget, så var det föreslagna ramverket lättarbetat och ett kvantitativt mått på brandrisken kunde fastställas för studieobjektet.
- Att använda checklistor för att identifiera tändkällor är hållbart. Det framkom dock att vissa förkunskaper inom branddynamik och en gedigen kunskap om systemet ifråga krävs för att resultatet skall bli trovärdigt.
- Användandet av golvareberoende modeller för att fastställa brandfrekvensen var en framgång. Författarna anser dock att brandfrekvensen har överskattats på grund av bristande statistiskt underlag. En förfinad analys med ett större statistiskt underlag skulle sannolikt bidra till avsevärt lägre uppskattad brandfrekvens.
- Brukandet av en kontinuerlig sannolikhetsfördelning, som initieellt valdes på grund av den enkla uppdateringsmetodik den förknippas med, visade sig komplicera slutresultatets känslighetsanalys så till den grad att ingen känslighetsanalys kunde utföras.
- Den goda detaljnivå som konsekvensanalysens datormodeller kunde erbjuda blir aningen tillintetgjorda av bristen på tillförlitliga skadekriterier för palleterat gods.
- Användandet av händelsetråd, Monte Carlo-analys och sannolikhetsfördelningar anses vara framgångsrika, och uppfyller studiens syfte.



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## Summary

The use of centralized distribution centres and warehouses has become an accepted logistic strategy among larger retail corporations. These distribution centres often cover demands in a wide geographic area and they are sized accordingly. Due to the increased demand for warehouse flexibility the trend has been to utilize larger and larger fire compartments and with the introduction of unmanned automated high-bay warehouses compartment sizes are growing even bigger. Although this particular logistic approach brings many advantages such as decreased handling costs and increased control, it unfortunately also comes with the downside of increased vulnerability. Few hazards, such as flood and earthquakes, threaten the entire stock but also fires are among these hazards.

In case of fire, a large fire is of course the worst imaginable scenario, but the openness of these warehouses mean that also smaller, more probable, fires still could affect a great amount of goods through the buoyancy driven transport of smoke and heat.

Although potentially disastrous, there has been little research done about the fire hazards connected to automated high-bay warehouses. At the same time, there are few, if any, documented fires reported. This leads to the assumption that the fire frequency in these kinds of premises is exceptionally low. An assumption that is reinforced by the scarcity of ignition sources in these warehouses.

In an effort to shed some light on and provide tools for the analysis of fire risk in automated high-bay warehouses, this thesis has been written in collaboration with IKEA and the Department of Fire Safety Engineering, Lund University, Sweden. The thesis presents a framework, aimed at assessing fire risk in large automated warehouses. As an inspiration, as to the functions of a framework for risk analysis, The International Electrotechnical Commission framework, *Risk analysis of technological systems*, has formed the base and has been adopted and expanded to better suit fire risk analysis in high-bay warehouses. Furthermore the different elements of the framework were evaluated based on their ability to comply with the following three criteria; *simple, expandable and quantitative*.

The framework has been constructed by finding tools for the following sections of IEC, based on the three criteria mentioned above and the characteristics found for high bay warehouses. The framework is based around an assumption that no significant ignition sources exist within the warehouse, and as such uses floor area dependency as a factor for fire frequency. The amount of damaged goods is assessed by using Threshold Damage Limits- a type of damage criteria for fire induced damage for goods.

- *IEC 5.3 Hazard identification*
- *IEC 5.4.1 Frequency analysis*
- *IEC 5.4.2 Consequence analysis*
- *IEC 5.4.3 Risk calculations*

The suggested mode of procedure, or framework, for fire risk analysis of high-bay warehouses is briefly presented below:

- Perform a checklist analysis to expose apparent and significant ignition sources.
- If any significant ignition sources are discovered these should be attended to before commencing on the later stages of risk analysis. This is to ensure that the assumptions of this work are valid for the case in question.

- 
- The frequency of a fire is determined using the aforementioned correlation between fire occurrence and the type of occupancy and building size.
  - All available plant specific data is collected and the generic data derived from the previous step is updated using Bayesian updating.
  - Construct an event tree the first event being “fire started”, the branches of the event tree should represent different degrees of function of fire protection, i.e. sprinklers activates and controls the fire.
  - Determine what phenomena that threaten stock in case of a fire, i.e. radiative heat, convective heat and combustion species (smoke).
  - Determine what levels of exposure to these phenomena the stock may end up being subjected to in the event of a fire with a certain degree of involvement from fire protective measures.
  - Establish the threshold damage limits for these exposures.
  - Calculate the consequences of the end scenarios by combining the threshold damage limits with the predicted exposure levels.
  - The probability distribution of an occurred fire can now be determined.
  - The expected yearly loss due to fire can now be calculated by multiplying the expected value of an occurred fire with the frequency of a fire. This should be expressed as a probability distribution.

A case study, using this proposed framework, was then carried out at the IKEA DC, Älmhult, to assess the methodology. It was found that;

- In all, the proposed framework was a success as it proved to be reasonably easy to work with and did provide a quantitative estimate of the fire risk in the studied automated high bay warehouse.
- The use of a checklist to identify ignition sources is viable. It was however found that it does require that the end-user needs to have some knowledge in fire dynamics and an intimate knowledge of the compound.
- The use of an estimate of fire frequency based on compartment size proved successful. It is however the authors’ opinion that the generic estimation of fire frequency overestimates the fire frequency in automated high bay warehouses and that more accurate results could be produced using a larger statistical basis.
- The use of a continuous probability distribution, initially chosen for its simplicity when being updated, proved to complicate the sensitivity analysis to such an extent that it lost its purpose.
- Regarding the consequence analysis; the accuracy provided by the CFD modelling was somewhat diminished by the lack of good, reliable Threshold Damage Limits for palletised goods.
- The use of event trees, Monte Carlo analysis and illustrating risk with risk profiles was successful and deemed sufficient for the purposes of the study.

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# 1 Introduction

This thesis forms part of the Masters of Science in Risk Management and Safety Engineering education given at Lund Institute of Technology in Lund, Sweden. This thesis has been written in collaboration with the Department of Fire Safety Engineering and IKEA.

## 1.1 Background

The use of centralized distribution centres and warehouses has become an accepted logistic strategy among larger retail corporations. These distribution centres often cover demands in a wide geographic area and they are sized accordingly. Due to the increased demand for warehouse flexibility the trend has been to utilize larger and larger fire compartments and with the introduction of unmanned automated warehouses compartment sizes are growing even bigger. Although this particular logistic approach brings many advantages such as decreased handling costs and increased control, it unfortunately also comes with the downside of increased vulnerability. Due to the scarcity of warehouses a disturbance at one warehouse can not easily be alleviated by other warehouses. Another issue that contributes to the increased vulnerability is the large amounts of goods that are being risked in the ever increasing compartment sizes. Although there are few conceivable scenarios that threaten the entire stock, such as structural collapse due to earthquakes, floods or heavy snowfall, the immense consequence of even a partial damage scenario justifies analysis of the risk exposure that is affiliated with these large compartments. As mentioned, there is a possibility for high consequence scenarios in automated warehouses and especially one scenario could potentially ruin large quantities of stock; an uncontrolled fire. Other hazards such as the natural disasters mentioned earlier seldom threaten the entire stock and the risk is not as dependent on compartment size as the fire risk. In case of fire, a large fire is of course the worst imaginable scenario, but the openness of these warehouses mean that also smaller, more probable, fires still could affect a great amount of goods through the buoyancy driven transport of smoke and heat. At the same time the layout in this type of buildings doesn't lend to manual fire fighting and therefore a fire that isn't controlled by automatic suppression during its early stages will be very hard, or impossible, to suppress. These fire scenarios are documented to be potentially catastrophic and thus arises the need for proper analysis of these hazards as for the determination of what magnitude of risk a corporation takes when choosing to store vast quantities of goods in one compartment. As drastic as these scenarios might sound it must also be stated that fire frequency in unmanned warehouses is assumingly very low due to the scarcity of fire sources and the low human activity.

The process of identifying, assessing and controlling risk is called the risk management process and there are plenty of different risk management frameworks available to different industries, activities and organisations.<sup>1 2</sup> These frameworks are often based on variations of the basic risk management process steps and as such are quite similar in context, although not always in phrasing. Frameworks for analysing and managing fire risk are no exception and there are frameworks suitable for different entities. The absolute majority of these fire risk frameworks are aimed at public areas and as such focus more on personal safety rather than economic effects, although studies has been carried out in this field too.<sup>3</sup> The number of fire risk analysis tools available for largely unmanned buildings is small, although there have been a few frameworks developed, for example regarding telecommunications facilities.<sup>4</sup> However, their applicability when trying to analyse fire risk in a high bay area is highly questionable. Thus, a new framework is needed.

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<sup>1</sup> *Enterprise Risk Management-Integrated Framework* (2004), Committee of Sponsoring Organizations of the Treadway Commission(COSO).

<sup>2</sup> *Risk analysis of technological systems* (1995), International Electrotechnical Commission.

<sup>3</sup> Johansson, H. (2003), *Decision Analysis in Fire Safety Engineering-Analysing Investments in Fire Safety*.

<sup>4</sup> Parks, L., et al. (1998) *Fire Risk Assessment for Telecommunications Central Offices*.

One of the frameworks mentioned earlier, the International Electrotechnical Commission (IEC) framework<sup>5</sup>, has a general description on how a risk management process regarding a technical system could be carried out, whilst the risk analysis part is particularly detailed. This readily available framework has already been used to engulf other activities or buildings than for which it was originally intended<sup>6</sup>. Thus the thought arises that perchance the generally expressed IEC theories can be adapted to form part of a simple framework aimed at assessing and managing fire risk in automated high bay warehouses.

## 1.2 Problem Statement

The IEC framework is a general description of a risk management process and as such the phrasing is highly unspecific and vague. Interpreting the theories found in the IEC framework and finding the most appropriate way of applying them in practical fire risk management strategies specifically aimed at unmanned high bay warehouses might not be a straightforward task. Hence, the main problem of this thesis becomes;

- How can the IEC framework function as a basis for fire risk management in unmanned high bay warehouses, providing guidelines for the choice of methods as well as structure as to how to work with them?

The total fire risk in a high bay warehouse depends on the frequency of fires that affect the warehouse and the likely consequences given that a fire occurs. However, neither one is easily assessed. The fire incidence is heavily dependant on the activities in, and the contents of, the fire compartment and therefore very specific for each entity. Likewise, the damage inflicted given that a fire occurs is also associated with large variability. To determine and communicate the total fire risk in a high bay warehouse, these two questions have to be addressed and answered;

- How can the fire frequency in an unmanned fire compartment be quantitatively estimated?
- How can the property loss of a fire in a high-bay warehouse be quantitatively estimated?

## 1.3 Objectives

The main objective of this master thesis is to adapt the theories in the IEC into an operational framework for analysis of the fire risk in any given automated high bay warehouse.

The thesis will compile methods for analysis of both the probability and the consequence of different fire accident scenarios, with regards to the fire related characteristics of high bay areas.

## 1.4 Limitations

High-bay warehouse - a high bay warehouse is usually a part of, and hence connected to, a larger traditional warehouse. Although the risk analysis methods used in the report could be used for the entire distribution centre the thesis will focus on the high bay area. The possibility that a fire in an adjacent compartment spreads to affect the high bay compartment will be briefly discussed but not thoroughly evaluated.

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<sup>5</sup> *Risk analysis of technological systems* (1995), International Electrotechnical Commission.

<sup>6</sup> Jansson, T.; Nilsson, H. (2003) *Riskhantering vid sjukvårdsverksamhet-ett underlag för förbättring*.



Personal safety - This thesis will only evaluate the economic consequences of fires and fire safety measures, and thus not personal safety. It is assumed that all the fire safety solutions evaluated satisfy the applicable building code.

Human factors - The causes of ignition can be divided into two broad groups; human and non-human. As the name implies, an unmanned automated warehouse is associated with a very low level of human activity and therefore this thesis will not in detail deal with the human factors.

Material damage - The economic consequences of a fire is often far more widespread than just the goods and buildings involved in the actual fire. The loss of production capacity, market shares and reputability can mean far bigger economic losses than the initial fire damage. As this thesis will only focus on material damage it is highly important that the end-user of the model adds the financial and immaterial consequences of a fire when analysing their respective fire risks.

## 1.5 Method

The IEC-*Risk analysis of technological systems* model is very generally expressed and in the following four areas the risk analyst needs to choose which tool is most appropriate for the activity being analyzed;

- *IEC 5.3 Hazard identification*
- *IEC 5.4.1 Frequency analysis*
- *IEC 5.4.2 Consequence analysis*
- *IEC 5.4.3 Risk calculations*

To fulfil the main purpose of this thesis, the appropriate tools in regards to fire risk analysis in high bay warehouses will have to be found in all the above framework parts. To be able to determine which tools that might be of interest firstly the characteristics of fire risk in high bay areas will have to be determined and secondly a compilation of tools available to the above mentioned framework parts will need to be produced.

The characteristics of fires in high bay areas will be determined through studies of existing research carried out on the subject. The studies will focus on two subjects; *Fire behaviour in high rack storage* and *Smoke movement in high ceiling spaces*.

To be able to suggest appropriate risk analysis tools for the framework parts mentioned above, a study of different tools will be carried out in the following areas: *Hazard Identification Methods*; *Frequency Analysis Methods*; *Consequence Analysis Methods* and *Risk Calculation Methods*.

The theoretical background gained in the studies of high bay fire characteristics and risk analysis tools will be combined to form the basis for choosing tools suitable for assessing fire risk in automated high bay warehouses. The tools utilised will be examined for their ability to foremost cope with the characteristics of high bay warehouse fire risk, but shall also be examined based on the following criteria:

1. **Simple.** The tools used shall, to a reasonable extent, be simplistic and demand little training from the end user.
2. **Expandable.** The tools shall be able to provide means of incorporating new information and constant updates.
3. **Quantitative.** As the analysis is intended to be used in an investment process it is decided that the results of the analysis should be quantitative. Tools will be chosen to comply with this requirement.

The proposed framework's applicability will be examined through a case study where the framework is implemented in an existing organisation. The case study will be performed at Ikea's automated high bay warehouse in Älmhult, Sweden.

## 2 The Risk Management Process

Risks in different types of businesses, social structures etcetera differ greatly in terms of type, consequence and other characteristics. But even though risk can take many forms, the process of managing these risks is often quite similar. Common to all risks is that the total risk cost is the sum of the expected damage costs and the costs of safety measures as seen in Figure 2-1. When making risk reducing investments the intention should be to minimise the total risk cost<sup>7</sup>.

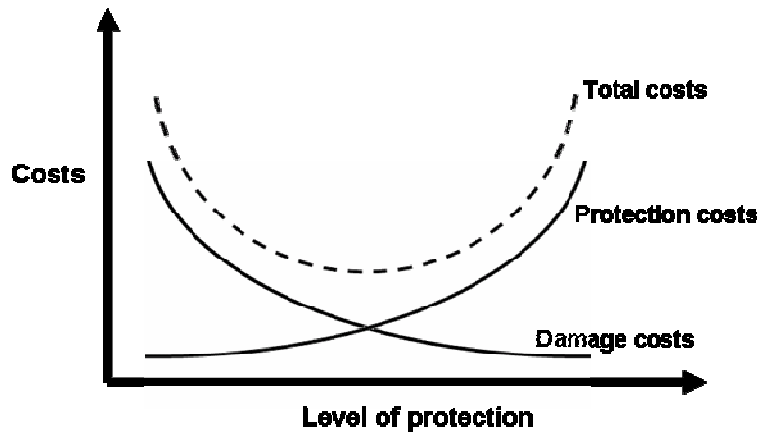


Figure 2-1. The total risk cost.<sup>8</sup>

The risk management process generally starts with an ambition to investigate which risks are affiliated with an activity and how significant they are to the organisation. Furthermore the consequences of these risks have to be evaluated to address how human life, environment, property etcetera might be affected by the risks and also how likely these consequences are. As a concluding part of the risk management process, suggestions on how to control the risks should be investigated and evaluated. Figure 2-2 shows a schematic model of the risk management process. The model has been brought forward by the International Electrotechnical Commission<sup>9</sup> and this is the framework that has been chosen to provide the basic structure of methodology for fire risk analysis developed in this thesis. This illustration is however just one example of how the risk management process can be structured.

<sup>7</sup> Nystedt, F., (2000), *Risikanalysmetoder*.

<sup>8</sup> Ibid.

<sup>9</sup> *Risk analysis of technological systems* (1995), International Electrotechnical Commission

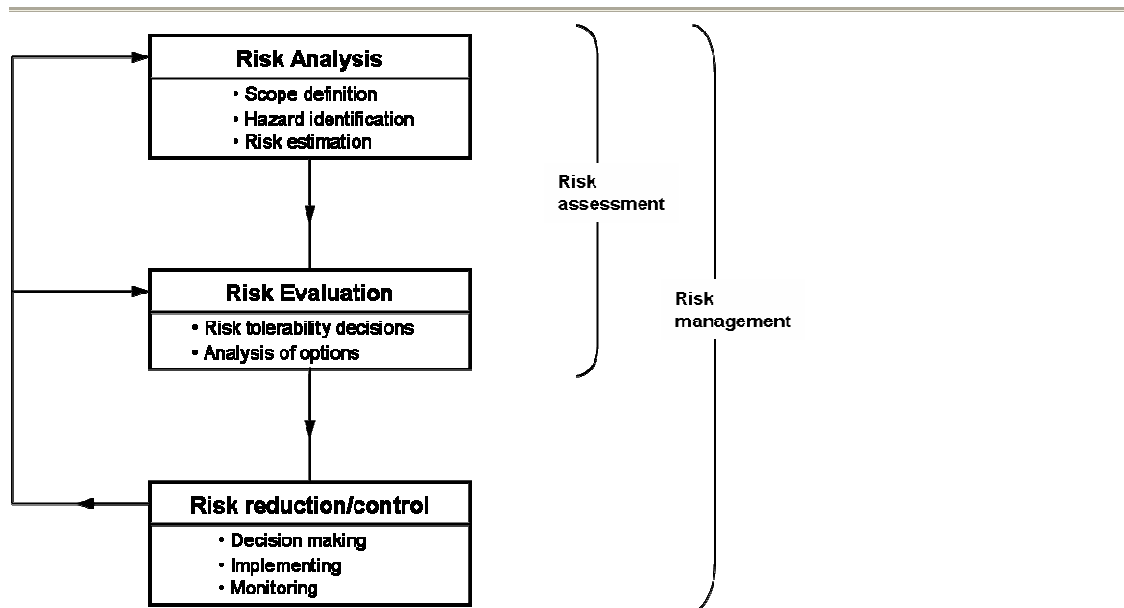


Figure 2-2. A simplified relationship between risk analysis and other risk management activities<sup>10</sup>

## 2.1 Risk Analysis

As an initial part of the risk management process, the risk analysis means to set the risk management ambitions and thereafter identify and evaluate risks that are relevant to the risk management process. This is done by analysing the risk's two main elements; the probability and the consequence. Risk analysis methods are often categorised into three levels of quantitiveness;

- Qualitative methods
- Semi-quantitative methods
- Quantitative methods

The level of quantitiveness chosen for the risk analysis depends on how detailed the analysis is required to be and on the labour resources available. During risk analysis, all three levels can be used in sequence. The more basic methods are used to determine which scenarios are relevant to continue with in the quantitative risk analysis.<sup>11</sup>

There are several risk analysis techniques available and they can be divided into groups depending on their quantitiveness;<sup>12</sup> Figure 2-3 illustrates a number of available risk analysis tools sorted by level of quantitiveness.

<sup>10</sup> *Risk analysis of technological systems* (1995), International Electrotechnical Commission.

<sup>11</sup> Frantzieh, H. (1998), *Uncertainty and Risk Analysis in Fire Safety Engineering*.

<sup>12</sup> Nystedt, F., (2000), *Risikanalysmetoder*.

Qualitative methods	Semi-Quantitative methods	Quantitative methods
HazOp	Gretener	Consequence analysis
What-If	NFPA	QRA/ PRA
Check lists	Index methods	Uncertainty analysis

Figure 2-3. A list of available risk analysis tools, sorted after their respective quantitiveness.<sup>13</sup>

A *qualitative* approach to risk analysis is sometimes used to roughly estimate risks accompanied to a specific operation or building. Qualitative methods are the least advanced type of risk analyses but as the methods are quick and simple, they are often used in the first stages of an extensive risk analysis to point out which risks are especially interesting and therefore should be considered for more detailed investigation.

The *semi-quantitative* approach allows for numerical values to be used when assessing probability and consequence in the risk analysis, and by doing so it also provides for the possibility to rank different risk sources. The method is more detailed than the qualitative methodology but is not as detailed as the quantitative analysis, for instance the consequences or probabilities could be given ranges of values rather than point estimates.

The most advanced risk analysis method available is the *quantitative* risk analysis. In this method all variables are expressed in numerical terms, such as expected fatalities per year or expected monetary value of an investment. There are two types of quantitative risk analysis approaches; the deterministic approach and the more common probabilistic approach. The deterministic approach is often a consequence analysis which delivers a single point estimate on the outcome of an event, with no regards to probability whereas the probabilistic approach combines the consequences and probabilities to a risk estimate. Quantitative methods allow for numerical treatment of uncertainties.

### 2.1.1 Scope Definition

The scope of the risk analysis should be defined and documented to create a plan at the start of the project. The scope definition should involve;

- The reasons or problems that originated the risk analysis.
- The objective of the risk analysis.
- Defining the criteria of the success/failure of the system being analysed.
- Defining the system being analysed.
- Identifying sources giving information relevant to the activity and the problem being analysed.
- Stating the assumptions and constraints governing the analysis.
- Identifying the decisions that have to be made, the required output from the study and the decision-makers.<sup>14</sup>

<sup>13</sup> Nystedt, F., (2000), *Riskanalysetoder*.

<sup>14</sup> *Risk analysis of technological systems* (1995), International Electrotechnical Commission

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### 2.1.2 Hazard Identification and initial consequence evaluation

The scope definition states the criteria for system failure and it is the hazard identification process' purpose to state activities and objects that potentially could lead to system failure. Known risk sources, or hazards, should be clearly stated whilst potential hazards that are previously unknown can be evaluated using qualitative or semi-quantitative methods such as What-if, HAZOP or index methods. To find which of the risk sources are significant for the following risk estimation, the hazard identification also comprises an initial evaluation of how severe the consequences of each scenario might be.

### 2.1.3 Risk Estimation

The hazard identification should now have provided significant risk sources that need further investigation. The risk estimation consists of two parts; the *frequency analysis* and the *consequence analysis*. When choosing which risk analysis methods to use it is extremely important to evaluate the available data as, generally, the more detailed a risk analysis becomes the better the input needs to be.

The frequency analysis means to state how often the unwanted event occurs. This is done by examining the initial event that could lead to a significant realization of the risk. For instance; if fire risk is to be evaluated, an electrical motor that catches fire is an initial event that could lead to a significant fire. The probability that this initial event occurs can be derived from statistical data, through formal methods or through qualitative methods using, for instance, expert analysis.

The purpose of the consequence analysis is to measure the damages inflicted by the unwanted event, given that the initial event occurs. The consequences can of course be very different depending on which risk is being investigated, but generally the damage can be divided into environmental, human and property consequences. Depending on the risk type, the consequence can be estimated by different methods. The use of event trees is an informative way of showing possible end scenarios together with their respective probability and consequence<sup>15</sup>. An event tree shows the possible outcomes of an initial event, such as a fire starting, and shows how the fire might evolve into different sub scenarios depending on a range of alternative events that might or might not occur during the fire.

The results from the two previous parts, the frequency and the consequence analysis, are combined and the resulting *risk calculation* will need to be illustrated in some way to make the result more easily accessible to the decision makers. The most basic way is to illustrate the risks in point estimates, with or without a notation for variance, whilst another alternative is to show the expected outcome as distribution.

## 2.2 Risk Evaluation

Once the risks in question have been identified and possibly quantified, the risk management process continues by examining these risks and deciding on the appropriate response. Enterprise risks are predominantly connected to activities that are valued by the organisation. Therefore the most interesting risk management option is often to reduce the risk in question rather than to completely eliminate it. Nonetheless a corporation can not accept any level of risk even for a highly desired activity or investment, hence decisions have to be made to state the corporation's risk attitude.

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<sup>15</sup> Mattson, B., (2000) *Risikhantering vid skydd mot olyckor*.

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## 2.2.1 Risk Tolerability Decisions

Decision makers are faced with the task of evaluating each risk identified and deciding on the appropriate risk management response. However it is not always clear which risks are negligible and which risks need to be reduced or eliminated. In practice this procedure often means that the numerical values derived from the risk analysis has to be compared with the expected advantages gained through the activity. To weigh expected advantages against uncertain risks is a complicated process and therefore a risk policy can be used as tool for making more rational and consistent risk management decisions.

The Swedish Rescue Services Agency suggests that the following four risk acceptance criteria can be used as a basis when setting a risk policy, given that the organisation is willing to accept some activities associated with risks and that risk reducing resources are not infinite.<sup>16</sup>.

- **The Rule of Reason.** An activity should not incorporate risks that could be avoided with a reasonable effort. This inflicts that risks that could be reduced or eliminated using reasonably large technical and economical efforts should always be attended to (regardless of risk level).
- **The Rule of Proportion.** The total risk brought by an activity should not be disproportionately large to the benefits (income, products, services, etc.) brought by the activity.
- **The Rule of Distribution.** Risks should be reasonably distributed within the society, related to the benefits brought by the activity. This means that individual persons or groups should not be exposed to risks disproportionately large to the benefits brought to them by the activity.
- **The Rule of Catastrophe Avoidance.** Risks should preferably be controlled to result in numerous accidents with limited consequences rather than rare catastrophes that can not be handled by available resources.

The phrasing “ (the risk) *should not be disproportionately large to the benefits* [...]” connects the risk evaluation process to the risk control process, as the risk management decisions made in the latter should be related to the company risk acceptance or risk policy.

## 2.2.2 Analysis of Options

When the risks that are of significance to the organisation have been clearly identified and evaluated, the next step will be to analyse the ways in which these risks could be handled. As there are many conceivable ways to control risks it is important to try to reduce these alternatives to a few viable options that can be further investigated. When doing this it is important to once again refer back to the scope definition to ensure that the risk management options both fulfil the objective of the risk management process and can do it within the resource limits. Even though there might be numerous suggestions of how to control the risk in question these options can be divided into four categories. It is critical that all these categories are discussed to determine their applicability in the present case;

- **Risk Elimination.** Some risks are such that they can only be eliminated by the ending the activity associated to the risk.
- **Risk Transferral.** The most suitable solution is sometimes to sell the risk, either by insuring the risk with an insurance company or to pay a third part to take responsibility for the risk.

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<sup>16</sup> Davidsson, G. et al. (1997), *Värdering av risk*.

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- **Risk Reduction.** Most of the risks fall into this category, with the goal not being to eliminate the risk source but to control the associated risk and keep it under an acceptable level.
  - **Risk Acceptance.** Sometimes the ability to affect the risk source can be limited or the risk reduction is not proportional to the cost of it. In these cases the only available option might be to accept the risk as it is.

## 2.3 Risk Control

The concluding part of the risk management process consists of deciding which risk management strategy to adopt and implementing it into the organisation. This is however by no means the final part of the risk management process as this is to be a continuous process and constant re-evaluation of the organisations risks have to be performed.

### 2.3.1 Decision Making

Deciding on which risk control measures to adopt and invest in should be done in a consistent manner. To make this possible it is vital that there is a predefined decision theory present which gives the organisation the ability to compare investment options in a rational way. There are many different decision criteria available but these can be divided into three categories<sup>17</sup>;

- Technology based criteria
- Right based criteria
- Benefit based criteria

The *Technology based criteria* inflicts that the latest and best technology should always be used to reduce risks. If the organisation does not use the best technology, the organisation is not doing enough to reduce risks.

A *Right based criteria* either states that the risk should, ideally, never exceed a given value and this value could in extreme cases be zero. The zero risk approach is inevitably connected to rising margin costs as the risk level is lowered. If the risk can not be eliminated the margin costs will be enormous for the last investments. To reduce the risk so that it does not exceed a given value could also lead to large risk reducing costs.

Examples of methods that utilise the *Benefit based criteria* are Cost-Benefit analysis (CBA), Cost-Effect analysis (CEA) and Multi-Criterion-Decision-Making (MCDM). These methods intend to evaluate different investments against each other by giving monetary values to the investments respective pros and cons. The best investment is either the one that gives the highest expected utility or the one that can fulfil the wanted effect at the lowest cost.

### 2.3.2 Implementation and Monitoring

After a suitable risk reduction strategy has been accepted by the organisation the process of implementing it into day to day business starts. It is important that employees that are affected by this decision are informed of any changes inflicted by the risk reducing investment. The effects of the investment should be monitored as to determine any positive or negative results from it and to allow for further improvements.

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<sup>17</sup> Mattson, B., (2000) *Riskehantering vid skydd mot olyckor.*



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## 3 High Bay Warehouse Fire Dynamics

The rate at which energy is released in a fire depends mainly on the type, quantity, and orientation of fuel and on the effects that an enclosure may have on the energy release rate<sup>18</sup>. The behaviour of fires and smoke movement in large compartments, such as high bay warehouses, differ largely from fires in smaller compartments. This fact, in conjunction with the orientation of fuel in rack storage, leads to the need for a more detailed description of the characteristics of fires in high bay warehouse type buildings.

### 3.1 Basic Fire Dynamics

As a process, fire can take many forms, all of which involve chemical reactions between combustible species and oxygen from the air<sup>19</sup>. As true as this statement is, it is also the fact that, for the mode of burning, the physical state and distribution of the fuel, and its environment, carries great significance. These sets of skills, in fire related chemistry and physics, make up the basis of the area of science known as Fire Dynamics. In Fire Dynamics the development of a fire can be divided into two phases, ignition and combustion. Another distinction that has to be made is the one between smouldering and flaming combustion. Both the type of fuel involved and the conditions regarding the ignition decides whether there will be one or the other.

#### 3.1.1 Ignition

The start of every fire can be described as the process in which a rapid exothermic reaction is initiated, which then propagates and causes the material involved to undergo change, producing temperatures greatly in excess of ambient<sup>20</sup>. In other words, the initiation of a self-sustaining process that develops heat. A general distinction can be made between piloted and spontaneous ignition. In a piloted ignition a 'pilot', such as a spark or an independent flame, sets aflame a flammable vapour/air mixture. A spontaneous ignition on the other hand needs no 'pilot'; instead flaming develops spontaneously within the substance, this phenomenon can be seen where autoxidating substances are stored without the proper care.

Typical ignition sources include the ones listed below.

- Open flames
- Mechanical sparks
- Electrical sparks
- Electrical currents
- Hot surfaces
- Hot air
- Autoxidating substances

When an ignition is a fact there may be two results, smouldering or flaming combustion.

#### 3.1.2 Smouldering combustion

If the fuel is porous and forms a solid carbonaceous char when heated it can undergo self-sustained smouldering combustion. According to studies of the mechanism of smouldering<sup>21</sup> the combustion

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<sup>18</sup> Karlsson, B. et al.. (2000), *Enclosure Fire Dynamics*.

<sup>19</sup> Drysdale, D. (2002), *An introduction to Fire Dynamics*.

<sup>20</sup> Ibid.

<sup>21</sup> Moussa, N.A.al. (1976), *Mechanism of Smoldering Combustion of Cellulosic Materials*.

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process can be broken down to three distinct regions; a pyrolysis zone, where the temperature rises significantly and there is an outflow of visible airborne products from the material. A charred zone, this is where the temperature reaches a maximum (typically 600-750°C) and glowing can be observed, here the production of the visible products stops. And finally, a zone of very porous residual char and/or ash whose temperature is falling slowly, this zone acts as insulation for the heat producing zone. Smouldering combustion is of interest in fire safety engineering for two reasons. First, it typically yields a substantially higher conversion of a fuel to toxic compounds than flaming combustion though at a slower pace, this is a concern when studying occupant safety, especially when occupants may be sleeping. Second, smouldering can lead to flaming, initiated by heat sources much too weak to directly produce a flame.<sup>22</sup>

### 3.1.3 Flaming combustion

Flaming combustion, as opposed to smouldering combustion, involves open flames, and produces much more heat (has a higher heat release rate). A fire scenario involving flaming combustion also generally has a much faster course of events. These characteristics make flaming combustion a much greater threat to the goods stored in the warehouse.

When a solid or liquid fuel is involved in flaming combustion the flame will radiate towards the fuel base and thus pyrolysing the fuel and providing fuel for the continued burning. The flames in turn will act as a pump, the hot air rising toward the ceiling. The buoyant air above is called the plume. The turbulence of the buoyant gases entrains air into the plume through turbulent mixing. This means that the temperature of the hot gases in the plume will decrease the higher the plume rises.

## 3.2 Fire Development in an Enclosure

When the plume flow impinges on the ceiling, the gases spread across it as a momentum driven circular jet. These ceiling jets, as they are called, will continue to spread across the ceiling until it reaches the surrounding walls, where it will be forced to move downward along the wall until the buoyancy will turn the flow upward, creating a layer of hot gases under the ceiling. This is called the stratified case. If, on the other hand, the plume does not have buoyancy enough, the smoke will mix within the enclosure. This is called the well mixed case.

The development of a fire in an enclosure differs to a varying degree from the development of a free burning fire. When it comes to energy released and burning rates, the enclosure will have two effects on the developing fire. Firstly, according to the laws of thermodynamics the hot surfaces and gases will radiate heat toward the fuel surface and by doing so increase the burning rate. Second, windows, doors and other leakages that connect the enclosure to the surrounding environment, called enclosure vents, will dictate the availability of oxygen needed for combustion (1 gram of oxygen will be consumed per 13.4 kJ)<sup>23</sup>. The lack of oxygen will decrease the amount of fuel burnt, thus decreasing the energy release rate and increasing the concentration of unburnt gases. These effects on a developing fire are called enclosure fire dynamics.

## 3.3 Fire Dynamics in High Bay Type Buildings

The enclosure effects accounted for in the preceding section (3.2) are to a large extent dependent on the geometrical prerequisites. A high bay warehouse differ substantially from the typical enclosure (being very large length, width and height wise), thus one needs to re-evaluate what the enclosure effects will be in this particular case.

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<sup>22</sup> DiNenno, P.M. et al. (1995), *SFPE Handbook of Fire Protection Engineering*.

<sup>23</sup> Ibid.

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### 3.3.1 Rack Storage Fire Dynamics

Rack Storage fires, and especially high ceiling rack storage is something that, from a fire safety engineering viewpoint, long has been considered a necessary evil. The reason for this is that fire spread is to a very large extent governed by the orientation and spacing of the fuel. In rack storage there will be concurrent-flow flame spread (the flame spreads with the flow of gases), and the spacing between the racks and individual pallets will facilitate the supply of oxygen to the fire<sup>24</sup>. Ingason and De Ris formulate themselves as follows;

*The physics of the burning of single walls is reasonably well understood, particularly for situations in which the flow is constrained by side-walls to remain two-dimensional. Considerably less is known about fire growth in more general three-dimensional situations. Warehouse geometries are a particularly important example. Warehouses typically contain huge quantities of goods which are stored to great heights in racks designed for easy access by personnel. Unfortunately such storage arrangements also maximise the fuel surface area accessible to flames. Fires can rapidly spread up between opposing fuel surfaces. Heat from flames burning on one surface augments the heat transfer from the flames burning on the opposing surface. It all adds up to the rack-storage geometry being perhaps the most hazardous of all fire geometries.*<sup>25</sup>

In other words, fuel stacked to a height is more susceptible to a rapid fire growth than fuel that is laid out flat. At the same time the spacing between the fuel packages also facilitates a fast fire growth and fire spread. Due to the severity of fires in rack storage there has been studies performed.

Ingason has in his doctoral thesis<sup>26</sup> gathered the results of seven papers, some of which have been published in international symposiums or fire safety journals. The subjects of interest for the thesis were to study high rack fire behaviour and sprinkler response both theoretically and experientially. More accurately, the main objective of his work was to establish a simple in-rack fire plume model that could be used to predict the flow conditions and the flame height inside the vertical flues. The simple in-rack fire plume model is supposed to take into account the variations in flow conditions, flame height and fire spread caused by variations in horizontal as well as vertical flue dimensions. This, in turn, would have a practical use in the predicting of the response time of the first in-rack sprinkler and also how this will vary with varying flue dimensions. The paper include one part (two papers) containing studies of thermal response of glass bulb sprinklers using plunge and ramp tests and numerical simulation of the wind shadow effect on the convective heat transfer to glass bulb sprinklers and one part (five papers) that is based on a series of reduced scale free-burn tests aiming to divulge simple engineering power law correlations for in-rack plume flow and in-rack flame height. Ingason's conclusions are:

- The prediction of sprinkler response in realistic fire scenarios is generally well represented by the two parameter model, i.e. using the RTI and C parameter.
- The orientation of the sprinkler head (yoke arms oriented perpendicular to the flow or aligned with the bulb and the flow) will substantially affect the time to operation of the sprinkler.
- Using ordinary axisymmetric power law correlations to plot the 3D experimental data appeared to yield a better representation of the mechanisms governing the in-rack plume flow than using linear power law correlations.

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<sup>24</sup> Karlsson, B. et al.. (2000), *Enclosure Fire Dynamics*.

<sup>25</sup> Ingason, H., De Ris, J. (1996) *Flame Heat Transfer in Storage Geometries*.

<sup>26</sup> Ingason, H. (1996), *Experimental and Theoretical Study of Rack Storage Fires*.

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- Simple engineering power law correlations for in-rack plume flow and in-rack flame height has been presented and as a consequence, it should be possible to calculate the activation time of the first in-rack sprinkler in similar 3D rack storage configurations.
  - Additionally, correlations for heat flux distributions to storage walls given as a function of the flame height and fuel type, it should be possible to apply these correlations as input to other flame spread models. Thus enabling predictions of flame spread in rack storage fires quite accurately within the near future.
  - As for flue widths, based on the model scale results the tentative recommendation of storage arrangement to keep the fire growth rate as low as possible would be to keep the vertical gaps wide and the horizontal gaps narrow.

### 3.3.2 Smoke behaviour in large compartments

In the case of a small fire in a large enclosure the hot gases in the plume will not have enough buoyancy to form an upper layer. It may have buoyancy enough to reach the roof, but as the enclosure also has a large floor area the smoke will cool as the ceiling jets travels along the roof. Eventually the smoke will loose the buoyancy and start to drop towards the floor and at the same time mix with the ambient air resulting in a well-mixed case, especially if there is forced ventilation or any source of turbulence in the enclosure. Even if the fire is larger and the buoyancy is enough to form a stratified case the temperature of the upper layer will be relatively low. This is due to that the large ceiling area delays the build up of a hot gas layer, a lot more hot gases is required to cause a significant temperature raise.

The radiation from the hot smoke layer is, as mentioned in section 3.2, one of the factors that dictate fire growth. This radiation is dependant of the thickness and even more the temperature of the hot smoke layer. In a small compartment radiation from the smoke layer will be relatively large and fire growth is often very rapid. In a large compartment, the same burning fuel will cause lower gas temperatures, longer smoke filling time, less feedback to the fuel and slower fire growth<sup>27</sup>. Less radiation from the hot smoke layer leads to prolonged time to flashover and in very large compartments flashover might not even occur at all.

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<sup>27</sup> Karlsson, B. et al.. (2000), *Enclosure Fire Dynamics*.

## 4 Fire Hazard Identification Methods

*“The hazards which generate risk in the system should be identified together with the ways in which the hazards could be realized. Known hazards [...] should be clearly stated. To identify hazards not previously recognized, formal methods covering the specific situation should be used.”*

*Hazard identification involves a systematic review of the system under study to identify the type of inherent hazards that are present together with the ways in which they could be realized. Historical accidents records and experience from previous risk analyses can provide a useful input to the hazard identification process. It needs to be recognized that there is an element of subjectivity in judgements about hazards, and that the hazards identified may not always be the only ones which could pose a threat to the system. It is important that the identified hazards are reviewed in the light of any relevant new data. Hazard identification methods fall broadly into three categories:*

*Comparative methods, examples of which are checklists, hazard indices and reviews of historical data; Fundamental methods, examples of this type of methodology are Hazard and Operability (HAZOP) studies, and Fault Modes and Effect Analysis (FMEA); Inductive reasoning techniques such as event tree logic diagrams.<sup>28</sup>*

The IEC lists a number of risk analysis methods, these listings can serve as the starting point for the inventory of potential fire hazard identification methods. Table 4-1 compiles the methods that the IEC considers useful in the hazard identification stage. In this chapter some methods available in the three aforementioned categories will be presented.

Method	Description and usage
Event Tree Analysis	A hazard identification and frequency analysis technique which employs inductive reasoning to translate different initiating events into possible outcomes
Fault Modes and Effects Analysis & Fault Modes, Effect and Criticality Analysis	A fundamental hazard identification and frequency analysis technique which analyses all the fault mode of a given equipment item for their effects both on other components and on the system.
Fault Tree Analysis	A hazard identification and frequency analysis technique which starts with undesired event and determines all the ways in which it could occur.
Hazard & Operability Study.	A fundamental hazard identification technique which systematically evaluates each part of the system to see how deviations from the design intent can occur and whether they can cause problems.
Preliminary Hazard Analysis	A hazard identification and frequency analysis technique that can be used early in the design stage to identify hazards and asses their criticality.
Checklists	A hazard identification technique which provides a listing of typical hazardous substances and/or potential accident sources which need to be considered.
Delphi Technique	A means of combining expert opinions that may support frequency analysis, consequence modelling and/or risk estimation.
Hazard Indices	A hazard identification/evaluation technique which can be used to rank different system options and identify the less hazardous options.

<sup>28</sup> *Risk analysis of technological systems* (1995), International Electrotechnical Commission

Review of Historical Data	A hazard identification technique that can be used to identify potential problem areas and also provide an input into frequency analysis based on accident and reliability data et al.
Sneak Analysis	A method of identifying latent paths that could cause the occurrence of unforeseen events.

Table 4-1. A list of existing hazard identification methods

## 4.1 Comparative Hazard Identification Methods

One comparative Hazard Identification Method will be described.

### 4.1.1 Checklists

Checklists are based on previous experiences and are used to identify known types of risk sources and to control that acknowledged safety measures are being respected.

Checklists are easy to use and can deliver quick results. Checklists is generally one of the most time- and cost efficient methods for safety control in cases where well known techniques are used in conjunction with good common practice to provide satisfactory safety.<sup>29</sup>

## 4.2 Fundamental Hazard Identification Methods

Fundamental hazard identification methods are structured to stimulate a group of people to apply foresight in conjunction with their knowledge to the task of identifying hazards by raising a series of “what if?” questions<sup>30</sup>. In this section two methods will be briefly described; *HAZOP-studies* and *FMEA studies*.

### 4.2.1 HAZOP

Hazard and Operability studies (HAZOP) are a qualitative method of hazard identification and evaluation. A HAZOP is performed by a team of knowledgeable persons who, with the help of guide words, try to assess the consequences if a system component deviates from its normal process conditions. The HAZOP also tries to remedy these deviations by identifying ways to detect or prevent them.

### 4.2.2 FMEA

Fault Mode and Effects Analysis (FMEA) means to identify failure modes in components in technical systems and the effects these faults would inflict on the system. A FMEA team systematically works through the system being analyzed and raises what if?-questions regarding different components likelihood of failure and how a failure would be likely to propagate through the system.

## 4.3 Inductive Hazard Identification Techniques

Event trees and fault trees are examples of inductive reasoning techniques available when performing hazard identification. The use of fault trees and event trees are described in sections 5.2.1 and 5.2.2 respectively.

<sup>29</sup> Nystedt, F., (2000), *Risikanalysetoder*.

<sup>30</sup> *Risk analysis of technological systems* (1995), International Electrotechnical Commission.

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## 5 Fire Frequency Analysis Methods

The probability that a fire arises in a building is one of the two main components of fire risk, the other one being the probability that a fire causes a certain level of damage. The probability of a fire starting depends on the amount of ignition sources in the building and their respective attributes. When the probabilities are very small, the use of frequencies is often a more illustrative way of expressing the likelihood of a fire occurring within a building.

*“Three approaches are commonly employed to estimate event frequencies. They are:*

*a) to use relevant historical data;*

*b) to derive event frequencies using analytical or simulation techniques;*

*c) to use expert judgement.*

*All of these techniques may be used individually or jointly.”<sup>31</sup>*

In this chapter it will be discussed how these different approaches can be used when determining fire frequency and how they can be used in conjunction with each other. Furthermore a number of methodologies available for updating statistical data are described.

### 5.1 Historical data

If possible, it is common practice to check historical records on how often an event of interest has occurred over the past and by that data draw conclusions on how frequent the event will be in the future. There are two sources of incidence data; *generic* event frequencies and *plant-specific* event records. Often these are used in conjunction with each other. When using historical data it is important to ensure that the data is relevant to the activity being considered<sup>32</sup>.

#### 5.1.1 Generic Data

The most readily available data is often generic component failure values from data bases, literature and previous risk studies or fire incidence statistics from for instance the fire service. The applicability of this data to a specific plant or building has to be confirmed before it can be put into use and hence the quality of the generic values is utterly important. Regarding component failure data, the *Committee for the Prevention of Disasters* lists a number of requirements that characterise quality data, the more of these requirements that are fulfilled the better the quality of the data<sup>33</sup>. The requirements are shown below.

- Component type
- Clear description of the failure mode
- Description of the component boundary
- Mean value
- Median value
- Uncertainty bound
- Description of component population

Another subject of relevance to fire frequency determination is the use of statistics from observed fires in different building types and deducing mean fire frequencies that are dependant on floor area

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<sup>31</sup> *Risk analysis of technological systems* (1995), International Electrotechnical Commission.

<sup>32</sup> *Ibid.*

<sup>33</sup> *Methods for determining and processing probabilities*, (1997), Committee for the Prevention of Disasters.

or building type. Studies have showed that fire frequency is dependant on floor area and that the dependency is linear for large floor areas (exceeding 1000m<sup>2</sup>).<sup>34</sup>

### 5.1.2 Plant-specific Data

It is common nowadays for industries or organisations of a certain size and complexity to systematically collect data regarding incidents in different activities. This data, called plant-specific data, can later be used to increase knowledge about risks within the organisation. Although time-consuming if used to determine failure rates for all types of equipment, the collection of plant-specific data provides a valuable input in regards to the robustness of the operations. Due to the potential severity of a fire all types of fire initiating incidents should always be reported and investigated.

## 5.2 Analytical techniques

When historical data is unavailable or insufficient, it is necessary to derive event frequencies using analytical models for example *fault tree analysis* and *event tree analysis*. Numerical values are given to all relevant events, including equipment failure and human error. The values can be derived both through operational experience and through published data sources<sup>35</sup>. In this section the workings of fault tree analysis and event trees will be described.

### 5.2.1 Fault tree analysis

To estimate the probability of for instance a fire starting in a piece of electrical equipment a fault tree analysis could be utilised. The fault tree analysis is a risk identification tool that means to find the underlying reasons for a specific incident, assign probabilities to the respective reasons and by doing so estimate the probability of the incident. The fault tree analysis utilises *logical gates* to construct the fault tree. A gate always has one outgoing connection and at least two incoming connections. In an *or-gate*, the outgoing event will occur if at least one of the incoming events occurs. In an *and-gate* the outgoing event will occur if all the incoming events occur.<sup>36</sup> Two schematic fault trees are illustrated in Figure 5-1. The top event is a system failure. The system on the left will fail if at least one of the base events occurs, whereas the system on the right only fails if the two base events occur simultaneously.

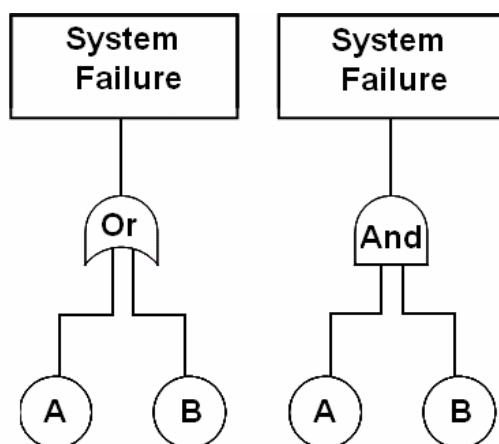


Figure 5-1 Schematic fault trees models.

<sup>34</sup> Rahikainen, J. et al. (1998) *Determination of Ignition Frequency of Fire in Different Premises in Finland*.

<sup>35</sup> *Risk analysis of technological systems* (1995), International Electrotechnical Commission.

<sup>36</sup> Nystedt, F., (2000), *Risikanalysetoder*.



## 5.2.2 Event Tree Analysis

Event trees illustrate the different possible outcomes with regards to their respective probability. The event tree method is quantitative in its nature and is also very informative as it can incorporate consequences and show how the end results are affected by the initial conditions and by any mitigating or worsening events. A brief example of how event tree analysis can be used to determine fire consequence will be performed in this section. The event tree as described here is illustrated in Figure 5-2.

An event tree is constructed through the use of an initiating event, in this case a fire, and a number of branch events that affect the outcome of a fire, given that a fire occurs. The initiating event can, although not necessarily, be assigned a frequency and the branch events are assigned point estimates or probability distributions. The end results are here denoted sub scenarios.

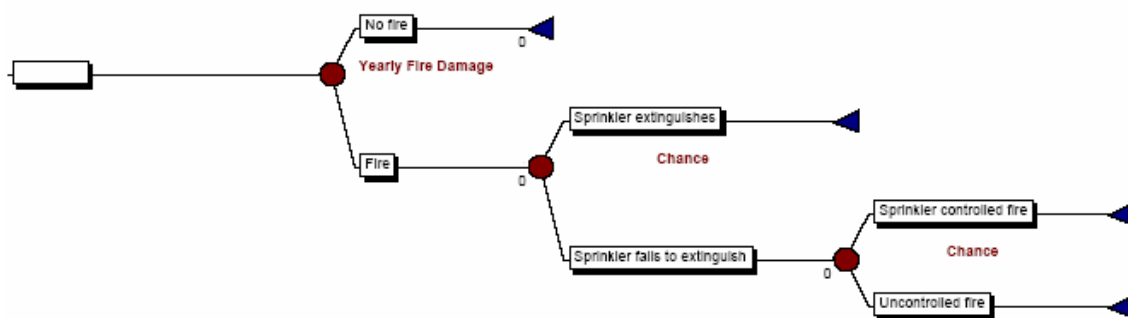


Figure 5-2. Event tree

At each branch point, different alternatives may occur. For example, an installation such as an automatic fire alarm will either operate or fail. The alternatives at the branch point affect the following parts of the tree. Each event tree outcome is evidence of the chain of events leading to the final event. The event tree structures the scenario so that the relevant questions for the analysis can be identified:<sup>37</sup>

- What can happen?
- What is the probability of each sub scenario
- What are the consequences of each sub scenario?

Each final outcome, or sub scenario, in the event tree has its own set of answers, called the Kaplan and Garrick triplet<sup>38</sup>. A triplet is composed of the three variables,  $(s_i, p_i, c_i)$ , where  $i = 1$  to  $n$  with  $n$  equal to the number of sub scenarios, i.e. the number of branches in the event tree. The term  $s_i$  is the event description and  $p_i$  and  $c_i$  describe the probability and consequence of the sub scenario.<sup>39</sup>

The total risk is the set of all triplets  $R = \{(s_i, p_i, c_i)\}$  for the scenario. In this definition of risk, all information regarding the calculated risk is included. Each sub scenario is defined by its probability

<sup>37</sup> Frantzych, H. (1998), *Uncertainty and Risk Analysis in Fire Safety Engineering*.

<sup>38</sup> Kaplan, S., et al, (1981) *On The Quantitative Definition of Risk*

<sup>39</sup> Frantzych, H. (1998), *Uncertainty and Risk Analysis in Fire Safety Engineering*.

and, possibly, its consequence. The set of triplets can be stored as three vectors, one for each component in the triplet.<sup>40</sup>

### 5.3 Expert judgement

Often, good objective data needed for the aforementioned methods is not readily available and the use of experts to determine fire frequency may then be a viable option. It is inevitable that the quality of the results from an expert judgement is dependant on the quality of the experts and the elicitation process<sup>41</sup>. Great care should therefore be taken in the choice of experts and in conducting the interviews.

Two issues are of utmost importance when using probability distributions derived from expert judgements;<sup>42</sup>

- How good is the knowledge of the expert in the area of concern?
- How capable is the expert in expressing his knowledge, and translating and relating it into probabilities

There are several different methods for deriving probability distributions from expert judgement. The elicitation process can be direct, where the expert states a probability that he believes to be right; or indirect where the expert compares and relates events with other events that have known probabilities. The latter does not require any probabilistic knowledge of the experts. The results from the elicitation process can thereafter be evaluated and combined using different methods, generally these methods can be divided into two group; *consensus techniques* and *mathematical techniques*. Consensus techniques attempt to reach iteratively a mutual point of view of all experts by way of discussions and feedback of the results whereas the mathematical techniques combine the results from the interviews in attempt to find a representative value.<sup>43</sup>

#### 5.3.1 Bias in expert judgements

Subjective estimates of uncertain values will always contain biases. These biases influence the accuracy of the expert's estimate in a negative way. Two different biases can be discerned;

- over/underestimation : The expert tends to underestimate or overestimate (extreme) incidents, resulting in a too optimistic or pessimistic value of the estimated median value.
- Over/under confidence : The tendency of the expert to estimate the confidence interval too narrowly. Underconfidence is of course also possible.<sup>44</sup>

The possible biases are illustrated graphically in Figure 5-3.

<sup>40</sup> Frantzych, H. (1998), *Uncertainty and Risk Analysis in Fire Safety Engineering*.

<sup>41</sup> *Methods for determining and processing probabilities*, (1997), Committee for the Prevention of Disasters.

<sup>42</sup> Ibid

<sup>43</sup> Ibid

<sup>44</sup> Ibid

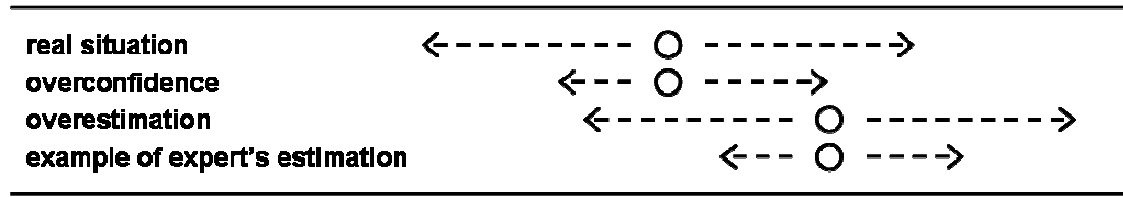


Figure 5-3. Illustration of biases in expert judgement.<sup>45</sup>

### 5.4 Bayesian methods of updating information

In the cases where little plant-specific data is available or little confidence in the plant specific data exists there is a need for a method that can enhance the information base.

For these cases Bayesian methods for updating of information can be very useful, as it allow combining information from different sources. In other words, using Bayesian methods, available plant-specific data can be used to improve available generic data, data derived through analytical techniques or data derived through expert judgments.

The Bayesian update process consists of the following steps<sup>46</sup>:

- For each basic event group, the plant-specific data and the mean and error factor of the generic distributions are collected. The generic distribution can be assumed to be lognormal or for example a gamma distribution.
- From this input data a new failure rate and error factor, or variance, for the basic event group are calculated.

The result is that the Bayesian update process changes the generic (prior) uncertainty distribution into a “posterior” distribution by incorporating the plant-specific data. Both the mean value of this distribution and its spread (the uncertainty) might change during the update process. This is illustrated in Figure 5-4.

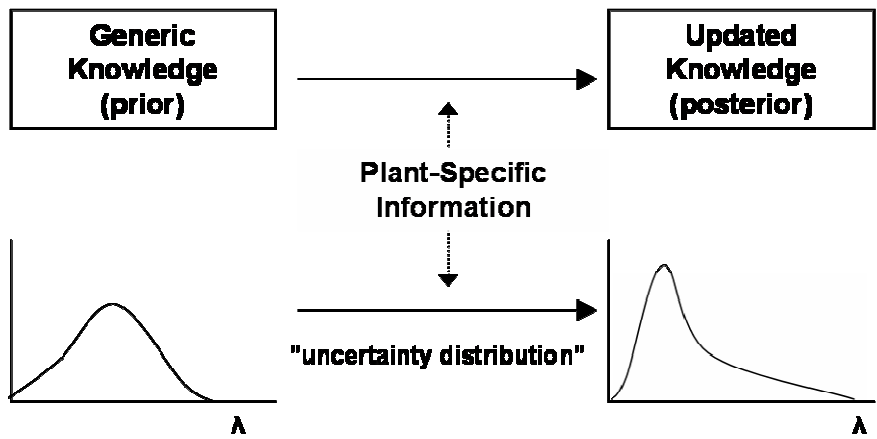


Figure 5-4. Illustration of the updating process.<sup>47</sup>

<sup>45</sup> *Methods for determining and processing probabilities*, (1997), Committee for the Prevention of Disasters.

<sup>46</sup> Ibid

### 5.4.1 Bayes Theorem

Bayes theorem states that, if one starts with a particular belief (expressed in the form of a probability distribution) regarding some parameter and receives additional information that one wants to incorporate into the previous body of knowledge, this can be done through the following expression;

$$P(\theta_i | E) = \frac{P(E | \theta_i) \cdot P(\theta_i)}{\sum P(E | \theta_i) \cdot P(\theta_i)}$$

Where

$P(\theta_i)$  = The probability that the state assigned - prior to obtaining the new information – to  $\theta_i$  is the correct state.

$P(E | \theta_i)$  = The probability that the new information  $E$  would have been observed given that the state of the parameter of interest was in fact  $\theta_i$ .

$P(\theta_i | E)$  = The probability assigned to  $\theta_i$  being the correct state, given that the new information observed is  $E$ .

### 5.4.2 Updating Continuous Distributions

In the discrete form of Bayes theorem presented above, the input prior distribution needs to be discrete. However when using Bayes theorem for applications such as fire frequency analysis, various continuous distributions can be highly useful. These continuous distributions are the Gamma distribution, the Beta distribution and the Dirichlet distribution. When updating continuous distributions the following inputs are required.

- Generic failure data : Failure rate  
Error factor (EF)
- Plant-specific data : Number of failures  
Exposure (operating time or calendar time)

The generic error factor (EF) is a measure of the uncertainty in the generic information and is expressed as the square root of the ratio of the 95:th and the 5:th percentile.

$$EF = \sqrt{\frac{P_{95\%}}{P_{5\%}}}$$

There are other possible representations of the generic data. What is least required however, is an estimate of the parameter (failures and exposures) plus an uncertainty indicator of some sort.

The posterior density function for  $\lambda$ ,  $f(\lambda | E)$ , combining the generic and specific information, is calculated using the Bayesian update formula.

$$f(\lambda | E) = \frac{f(\lambda) f(E | \lambda)}{\int_0^{\infty} f(\lambda) f(E | \lambda) d\lambda}$$

<sup>47</sup> Ibid

The prior distribution  $f(\lambda)$  reflects the generic knowledge. The function  $f(\lambda|E)$  is called the likelihood function. This function expresses the probability of observing  $E$ , the plant specific failure data, given that  $\lambda$  is the true value. The likelihood is the Poisson function, as  $\lambda$  is the parameter of a Poisson process (continuously operating with constant failure rate).

To establish the resulting posterior distribution  $f(\lambda|E)$  the denominator needs to be numerically integrated. To avoid this numerical integration an approximation using a Gamma distribution can be performed.

### 5.4.3 The Gamma distribution

Using the Gamma prior distribution, it is possible to perform straightforward updating, without the complex numerical calculations. The probability density function of a Gamma distribution is:

$$f(\lambda) = \frac{\beta^\alpha}{\Gamma(\alpha)} \lambda^{\alpha-1} \exp(-\beta\lambda) \quad \text{for: } \lambda > 0, \alpha > 0, \beta > 0$$

Where

$a$  = the shape factor

$\beta$  = the scale factor

$a / \beta$  = the mean value

$a / \beta^2$  = the variance

Calculation of the posterior distribution parameters  $\alpha'$  and  $\beta'$  is an addition of the specific data:

$$\alpha' = \alpha + f_T$$

$$\beta' = \beta + T$$

where:

$$f_T = \text{number of time-related failures}$$

$$T = \text{time interval over which } f_T \text{ failures occurred}$$

Thus, in this Bayesian approach, the Gamma parameters  $a$  and  $\beta$  have a very appealing interpretation: the  $a$  represents the number of failures, while the  $\beta$  represents the exposure time.



## 6 Fire Consequence Analysis Methods

*“Consequence analysis is used to estimate the likely impact should the undesired event occur.*

*Consequence analysis should:*

- a) be based on the undesirable events selected;*
- b) describe any consequences resulting from the undesirable events;*
- c) take into consideration existing measures to mitigate the consequences together with all relevant conditions that have an effect on the consequences;*
- d) give the criteria used for completing the identification of the consequences;*
- e) consider both immediate consequences and those that may arise after a certain time has elapsed, if this is consistent with the scope of the study;*
- f) consider secondary consequences, such as those associated with adjacent equipment and systems.”<sup>48</sup>*

To comply with the guidelines of the IEC framework the proposed method for consequence analysis will;

- a) be based on the selected fire scenarios
- b) describe all consequences of interest regarding the economical consequences of the selected fire scenarios
- c) take into account the existing mitigating measures (i.e. fire protection systems) and all other relevant conditions that affect the consequences
- d) be clear in what criteria will be used in determining the consequences
- e) due to the scope of this thesis only consider the direct economical consequences (property loss)
- f) due to the scope of this thesis only consider consequences in the actual enclosure being studied (i.e. not adjoining areas)

Stipulations a) through c) calls for the formulation of plausible fire scenarios and the use of an enclosure fire dynamics model to simulate them. The fire dynamics model as such must be appropriate for the conditions at hand.

Stipulation d) and e) calls for a methodology for deriving economical damages from the results of the enclosure fire model.

### 6.1 Enclosure Fire Dynamics Models

When one wants to study certain events, such as the effect of an enclosed fire, there are different ways to go about doing that. The most accurate would of course be to perform a full scale test, obviously this will for most cases result in unreasonable high costs. When a full scale test is deemed too expensive a scaled model may be used for testing, this, however cheaper, will often still be time consuming as well as expensive. The most commonly used way of analysing events of interest is through the use of models.

Models vary greatly in complexity from simple hand calculations to advanced computer applications. What they all have in common is that they aim to make analysis as effective as possible.

Deterministic models for fire safety engineering make use of existing scientific relations to try to emulate the actual physics and chemistry involved. The models are in turn normally divided into different categories, depending on what parameters they aim to divulge. Examples of problem

<sup>48</sup> *Risk analysis of technological systems* (1995), International Electrotechnical Commission.

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categories are; smoke and heat transfer in enclosures and detector/sprinkler activation. The complexity of deterministic models varies from simple one-line correlations of data to highly complex models requiring a lot of computer resources.

The simple one-line correlations of data are the simplest forms of deterministic models and they are typically represented through hand calculations. Examples of these simple correlations include equations for flame temperature, flame height and plume flow. One-line correlations are, due to their simple and empirical nature, often well evaluated and validated. The down side is, also due to their simple nature, that the one-line correlations will not provide the user with the possibilities to, as with more complex computer simulations, get the whole picture with a high resolution, instead they analyse one phenomenon at a time. This often reduces the one-line correlations to a tool for evaluation of the performance of the more advanced models used for simulations.

The computer based models vary a great deal in complexity among themselves, from relatively simple two zone fire models to the more advanced and demanding field models or computational fluid dynamics models. There are also models based on finite element or finite difference methods used to calculate the thermal and mechanical response of fire exposed building elements. Among the deterministic enclosure fire dynamics models there are two types of computer based models which are used very frequently in research as well as commercial contexts. These are the zone models and field models.

### 6.1.1 Zone Models

Zone models are one kind of computer based models commonly used to model smoke and heat transfer, or movement, in enclosed fires. The basic principle of zone models is to divide the enclosures being studied into two zones, one lower zone consisting of cold (ambient) air, one upper zone in turn consisting of the hot buoyant gases including the plume. The fire acts as a source of energy and mass that through entrainment into the plume “pumps” mass from the lower to the upper zone. It is assumed that the volume of the fire plume is small compared to the zone volumes, and thus its effect is ignored. The zones themselves are assumed to be well mixed, meaning that the physical properties of the upper and lower zones are considered spatially uniform, but can vary with time. Other assumptions being made are as listed below.

- The gas is treated as an ideal gas with a constant molecular weight and constant specific heats:  $c_p$  and  $c_v$ .
- Exchange of mass at free boundaries is due to pressure differences or shear mixing effects. Generally these are caused by natural or forced convection, or by entrainment processes.
- Combustion is treated as a source of mass and energy. No mechanism from first principles is included to resolve the extent of the combustion zone.
- The plume instantly arrives at the ceiling. No attempt is made to account for the time required to transport mass vertically or horizontally in the compartment. Hence, transport times are not explicitly accounted for in zone modelling.
- The mass of heat capacity of room contents is ignored compared to the enclosure wall, ceiling and floor elements; i.e., heat is considered lost to the structure, but not to the contents. Where room contents shields boundary structural surfaces, some compensations can occur in the analysis, but for cluttered rooms this assumption may be poor.
- The horizontal cross section of the enclosure is a constant area,  $A$ . In most cases of zone modelling rectilinear compartments have been considered. However, this is not a



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- necessary assumption, and enclosures in which  $A$  varies with height can easily be handled.
- The pressure in the enclosure is considered uniform in the energy equation, but hydrostatic variations account for pressure differences at free boundaries of the enclosure; i.e.,  $p \gg \rho g H$ . In general, the enclosure pressure,  $p$ , is much greater than the variations due to hydrostatics. For example, for  $p = 1 \text{ atm} = 14.7 \text{ psi} = 102 \text{ kPa}$  ( $\text{kN/m}^2$ ) =  $10^5 \text{ Pa}$ , the hydrostatic variation for a height,  $H = 1 \text{ m}$ , gives a pressure difference of  $\rho g H = 1.2 \text{ kg/m}^3 \times 9.8 \text{ m/s}^2 \times 1 \text{ m} = 10 \text{ kg/m s}^2 = 10 \text{ Pa}$  ( $\text{N/m}^2$ ).
  - Mass flow into the fire plume is due to turbulent entrainment. Entrainment is the process by which the surrounding gas flows into the fire plume as a result of buoyancy. Empirically, the inflow velocity linearly depends on the vertical velocity in the plume.
  - Fluid frictional effects at solid boundaries are ignored in the current models.<sup>49</sup>

The solution process for the layer properties consists of applying conservation equations for mass, species and energy to each zone. The equations for mass and energy permits the determination of the temperature of the two layers, the height of the boundary between the two layers and the compartment pressure. Densities can be found from the ideal gas equation of state, in which  $\rho T$  is approximately constant.

To complete this solution process, each of the source or transport terms in the equation must be given in terms of the above layer properties or auxiliary relationships must be included for each new variable included. The extents to which source and transport relationships are included reflect the sophistication and scope of the zone model. Some source and transport terms are essential to a basic zone model, others can be specified as approximations to reality, and others can be ignored when physically irrelevant. These source and transport relationships can be termed *submodels* and can comprise the subroutines of a zone model computer code.<sup>50</sup>

### 6.1.2 Field Models

Field models or computational fluid dynamics models represent the more complex and advanced deterministic models. Thanks to cheaper computational power, field modelling has become more common. In field modelling, the volume being studied, typically the enclosure containing the fire, is divided into many small volumes, so called control volumes. As opposed to zone modelling, where three to five control volumes may be established, field models may require up to several million control volumes.

Field models are complex fluid mechanical models of turbulent flows derived from classical fluid dynamics theory. The equations governing fluid behaviour consist, in general, of a set of three-dimensional, time-dependent, nonlinear partial differential equations, called Navier-Stokes equations. The Navier-Stokes equations express conservation of mass, momentum and energy. From these equations, five transport equations are formed; one continuity equation; three momentum equations and one energy equation. There are seven unknowns, and to form a closed set, two additional equations obtained from thermodynamic principles are added (the equation of state and the constitutive equation). In the normal case, the Navier-Stokes equations can not be solved by the use of analytical methods, instead solving the equations usually requires the use of numerical techniques. Computer fluid dynamics (CFD) involves the numerical solution of the Navier-Stokes equations using computers. The equations are solved numerically at a discrete moment in time and point in space. Using the aforementioned set of grids, the compartment is divided into many small volume

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<sup>49</sup> DiNenno, P.M. et al. (1995), *SFPE Handbook of Fire Protection Engineering*.

<sup>50</sup> Ibid.

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elements or cells and the difference equations are solved simultaneously in each cell to obtain the parameters of interest. The flows that occur in room fires are turbulent, and generates eddies or vortices of many sizes. The energy contained in large vortices cascades down to smaller and smaller vortices, until it diffused into heat. Eddies exist down to the size where the viscous forces dominate over inertial forces and energy is dissipated into heat. This scale is typically in the order of a millimetre or so. The control volume size used to make the Navier-Stokes equations discrete should be consistent with this scale. Applying this criterion would result in problems with many more control volumes than could possibly be solved with today's computers (or computers in a foreseeable future).<sup>51</sup>

This fact has brought about two distinct disciplines of field modelling in fire engineering. The first one to emerge was based on the conceptual framework provided by the Reynolds-averaged form of the Navier-Stokes equations (RANS), in particular the k- $\epsilon$  turbulence model. The RANS models, however, have a fundamental limitation for fire applications – the averaging procedure at the root of the model equations. The RANS models were developed as a time-averaged approximation to the conservation equations of fluid dynamics. The averaging time, however not specified, is clearly long enough to require the introduction of large eddy transport coefficients to describe the unresolved fluxes of mass, momentum and energy. This means that even the most highly resolved fire simulations will be smoothed out in its appearance. The smallest resolvable length scales are determined by the product of the local velocity and the averaging time rather than the spatial resolution of the underlying computational grid. This feature permits long time steps to be taken and thus can save time. Unfortunately, the evolution of large eddy structures characteristic of most fire plumes is lost with such an approach, as is the prediction of local transient events. The other approach to field modelling of fires is the “Large Eddy Simulation” (LES) technique. The LES technique is aimed at extracting greater temporal and spatial fidelity from simulations of fires performed on the more finely meshed grids allowed by ever faster computers. The phrase LES refers to the description of turbulent mixing of the gaseous fuel and combustion products with the local atmosphere surrounding the fire. This process, which determines the burning rate in most fires and controls the spread of smoke and hot gases, is extremely difficult to predict accurately. The basic idea behind the LES technique is that the eddies that account for most of the mixing are large enough to be calculated with reasonable accuracy from the equations of fluid dynamics, while the small scale eddy motion can either be crudely accounted for or ignored.<sup>52</sup>

## 6.2 Determining Economical Consequences of a Fire

Barry<sup>53</sup> proposes a methodology for the calculation of consequences of industrial fire risk. The methodology is based on the establishing and use of so called Threshold Damage Limits (TDLs). TDLs are measurements of vulnerability, and they are expressed as potential failure limits of the targets subsystems and components (equipment, operators, structure, etc.) when exposed to fire or explosion impact. These TDLs must then be put in relation to predicted levels of exposure. The exposure will be provided in the output from the enclosure fire dynamics model used to simulate the fire scenario. When, as in this case, the target is palletized stock the use of TDLs becomes quite rugged and merely a tool to combine an exposure and a sensitivity to form a consequence.

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<sup>51</sup> DiNenno, P.M. et al. (1995), *SFPE Handbook of Fire Protection Engineering*.

<sup>52</sup> McGrattan, K., (2005), *FDS4 Technical reference guide*.

<sup>53</sup> Barry, T.F. (2002), *Risk-Informed Performance-Based Fire Protection*

## 6.2.1 Establishing Threshold Damage Limits

TDLs provide a vulnerability measurement tool by establishing ranges and limits of target component and system damage potential from fire or other exposure.

TDLs are commonly used when occupant safety is being studied. In those cases, one would specify the limits of exposure to convective heat, radiative heat and toxic combustion products up to which occupants can be expected to manage to egress and thus survive. Examples of such limits for occupants are shown in Table 6-1 and Table 6-2<sup>54</sup>.

Convective Heat Exposure	
127 °C	difficult breathing
149 °C	mouth breathing very difficult, temperature limit for escape
160 °C	rapid, unbearable pain with dry skin
182 °C	irreversible injury in 30 seconds
204 °C	respiratory system tolerance time less than 4 min with wet skin

**Table 6-1. TDLs for occupants with regard to convective heat exposure**

Chemical products	5 – minutes exposure		30 – minutes exposure	
	Incapacitation	Death	Incapacitation	Death
Carbon monoxide	6000 ppm	12000 ppm	1400 ppm	2500 ppm
Low oxygen	< 13 %	< 5 %	< 12 %	< 7 %
Carbon dioxide	> 7 %	> 10 %	> 6 %	> 9 %

**Table 6-2. TDLs for occupants with regard to different toxic products of combustion<sup>55</sup>**

Based on these TDLs and the proposed exposure predictions generated through the simulations of the fire scenario, conclusions regarding how long the conditions are tenable in the building can be made. In other words it will tell you within what time different areas of the building must be cleared in order to avoid damage to occupant health.

In the case of high bay warehouse fires one has to look at the goods that are being stored. Regardless of what commodities are stored in the warehouse at hand we will look at the same primary exposure categories<sup>56</sup> when evaluating component damage potential from fires or explosions:

- Thermal effects (i.e., radiant heat, temperature)
- Explosion overpressure effects
- Products of combustion (i.e., corrosive gases, smoke)

In the case of a fire the exposure categories can be specified a little further. Firstly, heat transfer, from the flame itself, through radiation as well as convection may lead to flame spread or pyrolysis, charring, discolouring and melting. Smoke, or buoyant gases emanating from the fire may cause heat damage through convective/diffusive transfer of heat, discolouring due to soot, fire odour.

For each of these exposure categories the TDL for the proposed target (the commodity stored) must be determined. What the TDL will be dependent on what material(s) the target is made up of. For

<sup>54</sup> Barry, T.F. (2002), *Risk-Informed Performance-Based Fire Protection*

<sup>55</sup> Ibid

<sup>56</sup> Ibid

some exposure categories and target materials TDLs are easily assessed, however for others they are not. For example the establishment of TDLs for exposure to high temperatures and radiant flux for common target materials is pretty well documented and straightforward, see for instance Table 6-3 and Table 6-4. However determining TDLs for other exposure categories might not be as simple as there may be no data available. How vulnerable the targets (stored goods) are in these exposure categories must in the end be up to the proprietor or manufacturer since they will be the ones deciding whether or not to discard the exposed property.

Material	Typical examples	Damage conditions	Approximate temperature (°C)
Polystyrene	Thin wall food containers, foam, light shades, handles, curtain hooks, radio casings	Collapse	120
		Softens	120 – 140
		Melts and flows	150 – 180
Polyethylene	Bags, films, bottles, buckets, pipes	Shrivels	120
		Softens and melts	120 – 140
Polymethyl methacrylate	Handles, covers, skylights, “glazing”	Softens Bubbles	130 – 200 250
PVC	Cables, pipes, ducts, linings, profiles, handles, knobs, house ware, toys, bottles	Degrades	100
		Fumes	150
		Browns	200
		Chars	400 – 500
Cellulose	Wood, paper, cotton	Darkens	200 - 300

Table 6-3. TDLs for a number of different materials with regard to air temperature<sup>57</sup>

Incident heat flux (kW/m <sup>2</sup> )	Damage to equipment	Remarks
35.0 - 37.5	Damage to process equipment	Generally includes steel tanks, chemical process equipment, industrial machinery
25.0	Minimum energy to ignite wood at indefinitely long exposure without a flame	
18.0 – 20.0	Plastic cable insulation degrades	
12.5 – 15.0	Minimum energy to ignite wood with a flame; melts plastic tubing	
* Based on an average 10 min exposure time		

Table 6-4. Example of thermal radiation TDLs<sup>58</sup>

## 6.2.2 Determining destroyed quantities

The process of determining the destroyed quantities, is a process of comparing the, through simulations, predicted exposure levels for the different exposure categories discussed in 6.2.1 with the previously established TDLs. Depending on what model has been chosen for the simulations the output, specifying the predicted exposure levels, can be in different forms.

When the destroyed quantities are known the economical consequences are calculated through straight forward multiplication with the value of the goods.

<sup>57</sup> Barry, T.F. (2002), *Risk-Informed Performance-Based Fire Protection*

<sup>58</sup> Ibid

## 7 Fire Risk Calculation Methods

*"Risk should be expressed in the most suitable terms. [...]It should be stated whether the risk estimate reflects the total risk level, or if only part of the total risk is included."*<sup>59</sup>

To make the risk analysis results understandable to decision makers and risk takers it is very important that the results are expressed in a way that can be easily assimilated and at the same time delivers a good representation of the actual risk. In this chapter the basis of some different risk calculation tools will be described. Furthermore it will be discussed how risk can be illustrated and how attitudes towards risk taking can be implemented in the investment process.

In this section two risk illustration tools will be described; *Expected Values* and *Risk Profiles*. Furthermore two methods of illustrating risk with regards to risk attitude will be presented; *Expected Utility* and *Risk Discounted Value*.

The following methods are used when the risk is to be illustrated without a notation for how the risk is valued.

### 7.1.1 Expected Values

A principal concept of basic investment analysis is the use of Expected Values (EV). The EV is the mathematically expected outcome of an investment decision if it was to be repeated many times, i.e. the sum of the different possible outcomes multiplied with their respective probability. Hence, the investment with highest EV should therefore be the best alternative. The EV method uses the basic investment analysis methods such as the net present value method but also takes the uncertainties of future events into account. The use of expected values is illustrated in Figure 7-1. The model depicts the initial decision, A, to make or not to make an investment and its respective consequences depending on an uncertain market growth. The EV of making the investment exceeds the EV of not making the investment and hence the investment should be made.

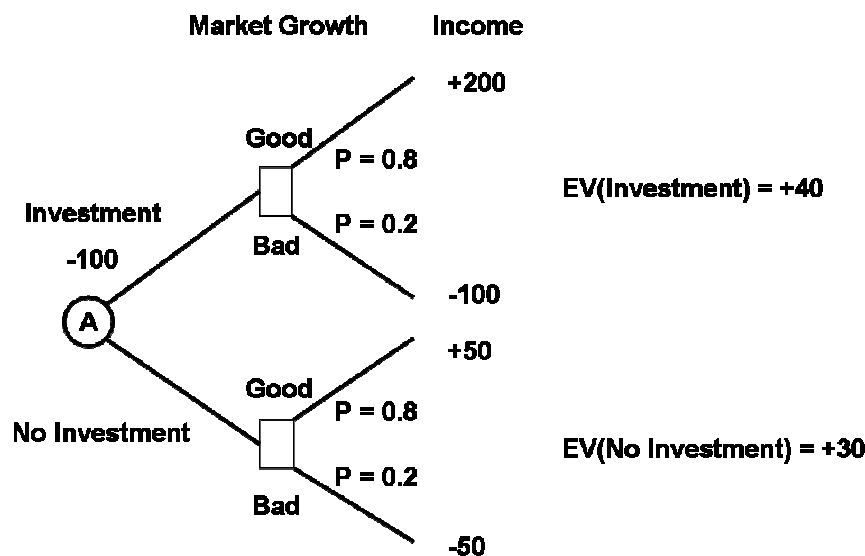


Figure 7-1. Decision tree analysis model.

<sup>59</sup> *Risk analysis of technological systems* (1995), International Electrotechnical Commission.

The use of expected values as a basis for decision making under risk is connected to a bias in such that the EV does not tell how large losses or incomes different alternatives possibly could yield. Therefore, when decisions under risk are to be taken, a more detailed method of illustrating risk is needed to make the right choice.

### 7.1.2 Risk Profiles

Instead of using single values to estimate the outcome of a decision as described in section 5.1.1 one can opt to show all the possible outcomes in relation to their respective probability. The outcomes of the simple decision tree described in Figure 7-1 can be illustrated in a risk profile as shown in Figure 7-2. The profile on the left shows the possible outcomes of making the investment whilst the profile on the right shows the possible outcomes, if the choice is made to turn down the investment. This illustration goes to show that the EV in this case, not only doesn't show the risk involved in the different alternatives but it also shows that the expected value is an impossible outcome.

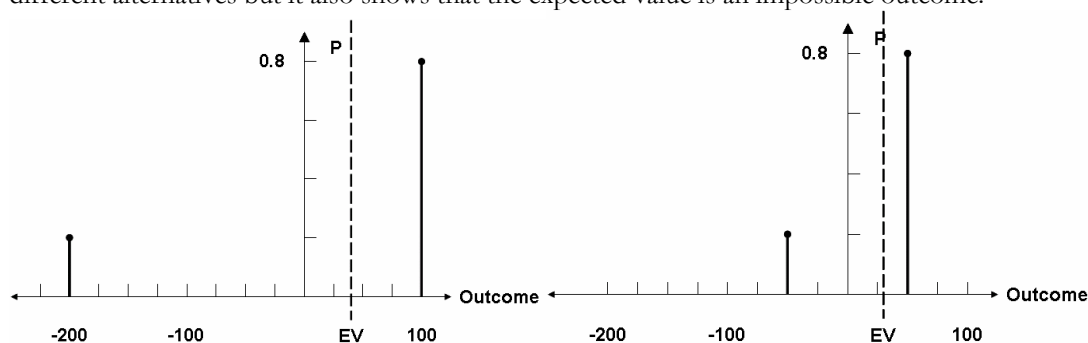
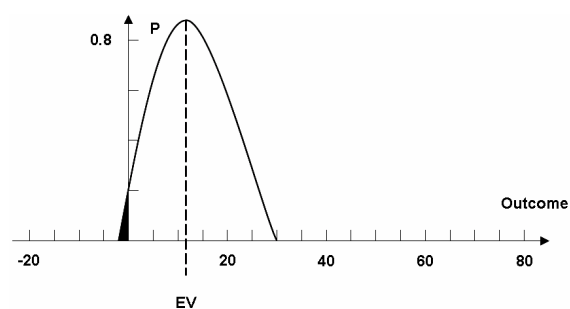


Figure 7-2. Risk profile of the decision tree in Figure 7-1.

The risk profile in this case of course becomes very basic but as a decision tree is expanded by adding further uncertain future events and assigning probability distributions to the events rather than single point estimates, the risk profile becomes more detailed and the inadequateness of using EV becomes more evident. The use of risk profiles, and their advantage over EV is illustrated in Figure 7-3.

Traditional use of EV would recommend alternative no. 2 as this has the highest EV. By using risk profiles, decision makers can get the whole picture of the alternative's respective risk.



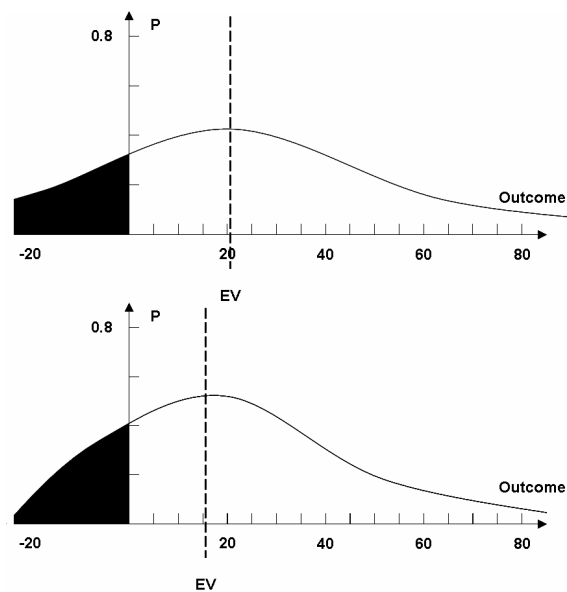


Figure 7-3. Three different investment options.

## 7.2 Methods of Illustrating Risk with Regards to Risk Attitude

One factor that is significant to most investment analysis methods (barring CEA) is the requisite to determine how much the risk reduction is worth, both to the risk takers and to the ones who pay for the risk reduction. As described above observations have been made where people have turned down gambles even though a profit was the expected outcome. A legitimate question related to this kind of behaviour observations might be: How much would the persons be willing to pay to avoid the gamble? This section will describe some methods available when trying to assess risk attitude.

### 7.2.1 Expected Utility

After studies of gambling situations where gamblers were reluctant to take part in certain games, even though the expected value was larger than the investment, Daniel Bernoulli (1700-1782) introduced the idea that the marginal utility decreases with increasing wealth<sup>60</sup>. Losing a great amount of money would therefore inflict greater marginal utility loss than would be gained through winning an equal amount. This was to be considered as one of the earliest ideas regarding expected utility (EU) as a basis for decision making. Neumann & Morgenstern developed these ideas and proved that utility could be measured, presented in a utility scale and compared if the decision makers could make simple judgements of preference between alternatives involving risk. If a decision maker fully follows these axioms in all situations, it will lead to always choosing the alternative with the highest EU. In the aforementioned situation a person turns down a gamble, although the expected outcome is profitable. A situation like this has to be considered as an example of risk adverse behaviour. On the contrary, a person who is willing to pay more than the expected value to take part in the gamble would be a risk seeking individual. For some reason these two types value the gamble in completely different ways, the winnings of the gamble is not large enough to convince the risk avert person to wager his money whilst the risk seeking person might be interested in paying to still be allowed to play. Obviously the utility of the wagered money versus the utility of the winnings is valued differently between the two types of gamblers. For every person or company a utility function can be deduced and this function shows the persons or company's attitude towards risk taking. A schematic

<sup>60</sup> Mattson, B., (2000) *Risikhantering vid skydd mot olyckor*.

illustration of utility curves is shown in Figure 7-4. The Utility Function shows the experienced utility of certain amounts of money depending on the person's or organisation's attitude to risk. The straight line is a risk neutral utility function

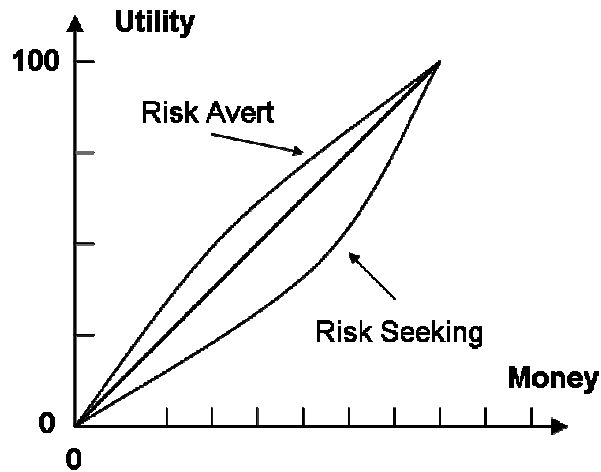


Figure 7-4. A schematic utility function

Another illustrative way of presenting risk attitude is to place the organisation or person somewhere along the dotted line in Figure 2-1. A risk neutral organisation would place it self where the total costs are at the lowest, while risk seeking and risk avert organisations would be placed to the left, respectively the right on the total cost curve.

### 7.2.2 Risk Discounted Value

Utility functions incorporate the company's attitude towards risk taking into the investment analysis process and can be used to re-evaluate investment options with regard to risk attitude. The function could be used directly to calculate EU of the alternative investments and the best alternative would be the one that delivers the highest EU. However, the expected utility value has one major drawback as a final criterion- it is a value on an arbitrary scale<sup>61</sup>. It might therefore be more appropriate to use the *certainty equivalent* (CE). The CE is defined as the single (sure) monetary amount that has the same utility as the expected utility of the investment<sup>62</sup>. Using CE allows for the alternatives to be ranked on an absolute scale with regards to the company risk attitude, the deduced value is called the *risk discounted value* of the investment.

<sup>61</sup> Spetzler, C. S. (1977), *Establishing a corporate risk policy*

<sup>62</sup> Ibid.



## 8 High Bay Warehouse Description

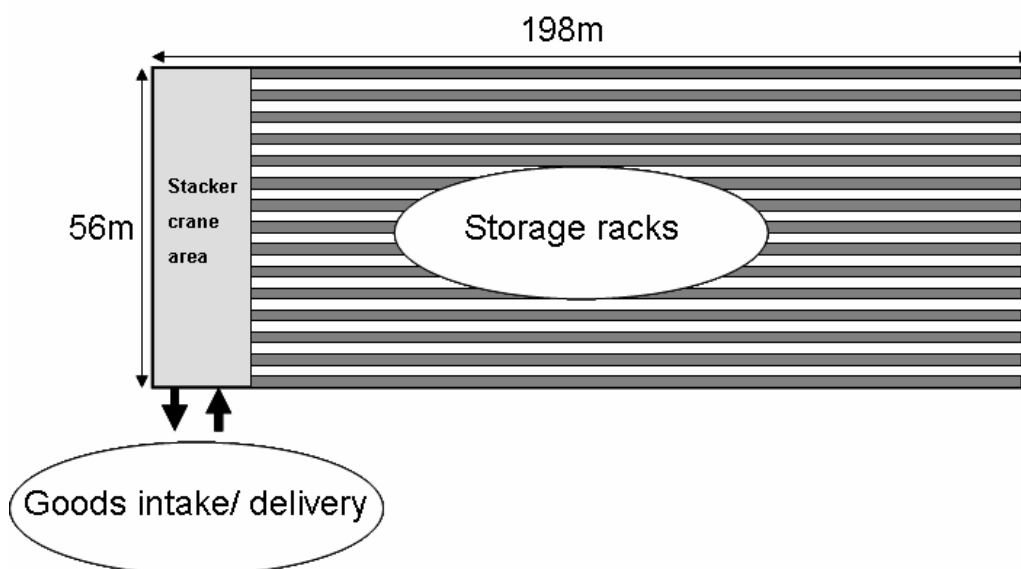
In order to gain a certain degree of knowledge of high bay warehouses and to possibly determine some features that are characteristic to high bay warehouses, two site visits was carried out at Ikea's automated high bay warehouse in Älmhult, Sweden. Fire incidence statistics was also collected along with some personal opinions of the IKEA staff regarding High bay warehouses.

### 8.1 IKEA High Bay Warehouse, Älmhult

The distribution centre in Älmhult was Ikea's first and it was built in 1953. In 1980 a section of the warehouse became automated and in 2000 the automated high bay at *Älmhult South* was taken into use and it is this high bay warehouse that will be described in this section.

#### 8.1.1 Site Description

The automated high bay area is a single fire compartment that is roughly 11 000 m<sup>2</sup> (198 m x 56 m) and the ceiling height varies between 23 and 25 meters. The warehouse interior mainly consists of pallet racks and the automatic system that handle the pallets. There are 18 pallet racks, most of which are located back-to-back thus creating double deep pallet racks. The storage capacity is 38,000 m<sup>3</sup> which, in other terms, corresponds to 33 250 European standard pallets and 7500 IKEA long-pallets. See Figure 8-1 for a plan view of the warehouse. The warehouse is heated by water radiators. Illumination is provided by halogen ceiling lights and leading lights that are mounted to the pallet racks. Lights are only on when there are workers or visitors in the warehouse. Doors leading into the high bay warehouse are kept locked at all times.



**Figure 8-1. Plan view of the automated high bay warehouse in Älmhult.**

The goods in the warehouse are a mix of wooden, metal and plastic furniture, kitchen appliances, textiles and paper wares. IKEA has chosen not to store their most flammable and fire hazardous goods in the automated high bay warehouse, i.e. candles, linseed oil based paints and goods with an expanded plastic content exceeding 15%. The goods are exclusively stored on wooden pallets.

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The automatic pallet loader system consists of 9 fully automatic stacker cranes. The stacker cranes run on rails that are mounted to the floor and the ceiling. The stacker cranes are propelled by a series of electrical motors and they are provided with power and information through a power strip running along side the floor rail. Goods pallets are brought from the loading bays to the automatic warehouse by a system of automatic conveyor belts and thereafter loaded into the racks by the automatic stacker cranes. Pallets are unloaded in the same fashion. The automatic system can load and unload 400 pallets per hour. The automatic system is in use 16 hours per day and is not in use during weekends and holidays. When not in use, the stacker cranes are in stand-by position by the loading/unloading area.

### **8.1.2 Fire Detection Systems**

Fire detection consists of a sampling system at ceiling height and a flow sensor in the sprinkler system. The aspirating system is divided into six sections. In case the detection detects signs of fire, either from the aspirating system or the flow sensor, a signal is sent to the alarm central in the security control office and evacuation procedures are initiated. The stacker cranes are also stopped by the fire alarm.

### **8.1.3 Fire Suppression Systems**

Fire suppression consists of sprinkler systems, both at ceiling height and at every other level in the pallet rack. The sprinkler systems are provided with water from a diesel driven pump with a capacity of 8000 litres per min at 10 bars pressure, water supply is guaranteed by two water basins of 750 m<sup>3</sup> each.

### **8.1.4 Fire Systems Maintenance and Management**

The fire detection and suppression systems are checked and maintained on a regular basis. For example the sprinkler flow sensors are tested once every fortnight and the detectors are checked once a month. It is the authors' impression that the fire safety systems are well maintained and handled by knowledgeable staff.

There is a crew of fire trained employees at IKEA but their main purpose is not to put out fires, should one occur, but rather to ensure that the distribution centre is properly evacuated and to aid the rescue service with information regarding the premises.

### **8.1.5 Fire Incident Reporting System**

Internal fire statistics show that no fire has ever occurred at Älmhult South. Internal fire statistics for similar high bay warehouses is also available and shows that no fire incidence has been reported at any other similar high bay area either. A complete list of fire statistics for similar high bay warehouses is shown in Appendix A5.

## **8.2 Other IKEA High Bay Warehouses**

IKEA has some 30 automated high bay warehouses across the world. Some of them are similar to the Älmhult South warehouse in terms of size and layout while others rather are semi-automatic, with regular, manned, pallet loaders providing the automatic stacker cranes with goods. Interviews and correspondence with knowledgeable IKEA staff strongly indicates that IKEA has never encountered even the smallest of fire incidents in any of its 30 high bay warehouses. The general opinion seems to be that, apart from the odd false alarm from the detection system, the automated high bay warehouse is an exceptionally reliable system.

## 9 Choosing Fire Risk Analysis Tools for High Bay Warehouses

In this chapter the theoretical knowledge of risk analysis and high bay warehouse fire dynamics gained in the theoretical study of this thesis will be combined with the theories and advices presented in the IEC. This chapter will analyse which risk analysis methods that are applicable when analysing fire risk in high bay warehouse type buildings. As set out in Section 1, risk analysis tools will be chosen for these four parts of the IEC framework:

- IEC 5.3 - Hazard identification
- IEC 5.4.1 - Frequency analysis
- IEC 5.4.2 - Consequence analysis
- IEC 5.4.3 - Risk calculations

In addition to the IEC's constraints and recommendations, the risk management methods and tools that are suggested in this chapter have also been examined in regards to their ability to comply with a number of characteristics, as identified by the authors, for high bay warehouses;

- Well defined system- In terms of technical complicity, the automated high bay warehouse is regarded as rather simple. The pallet loader and stacker cranes are, at least mechanically, easy to understand and describe. Fuel load and configuration is known.
- Low fire frequency- There is little doubt that fires in automated high bay warehouses are rare. This stems from the fact that the automatism itself eliminates many of the common fire starters, such as human negligence.
- Unknown Fire Behaviour- The fire dynamics in high bay areas are hard to determine.
- Unknown Damage Criteria- The resistance of pallet goods towards smoke, heat and water is unknown.

In addition to these characteristics, the tools will also be examined for their ability to comply with the criteria stated in Section 1:

- Simple. The tools used shall, to a reasonable extent, be simplistic and demand little training from the end user.
- Expandable. The tools shall be able to provide means of incorporating new information and constant updates.
- Quantitative. As the analysis is intended to be used in an investment process it is decided that the results of the analysis should be quantitative. Tools will be chosen to comply with this requirement.

### 9.1 Choosing Hazard Identification Tools

When choosing which hazard identification method to use the IEC's three different categories has been examined in terms of applicability. The categories mentioned in the IEC are;

- Comparative methods
- Fundamental methods
- Inductive reasoning techniques

The concept of choosing tools based on their quantitativity is set aside for the hazard identification stage, partly because the hazard identification in itself should be simple and straightforward, but mostly because the simplicity of the system lends itself to a brief hazard identification. It is therefore decided that the hazard identification tool chosen very well can be qualitative.

The fact that the system to be analysed, i.e. the high bay warehouse, is easily understandable and all technical components are known in the system is an incentive to use either Fundamental Methods or Inductive Reasoning Techniques. The system could be illustrated in detail and the hazard identification could be performed using for instance HAZOP or fault trees to determine in which ways fire could occur within the system. The downside to this is the cost of such studies, as even though the system is uncomplicated a full description of it would still demand a considerable effort.

A fire requires fuel and an ignition source and warehouses are almost inherently connected to an abundance of fuel. Thus the thought arises that the hazard identification could be focused on finding ignition sources rather than combinations of ignition sources and fuel sources. This argumentation is considered to be a strong incentive for using comparative methods, as the system is easily understood in conjunction with the fact that ignition only occurs in so many ways. A negative aspect of checklists is that they normally rely on normal process conditions and not necessarily will be able to handle deviations from the normal or hazards that arise from failures etcetera. This fact might induce the need for knowledgeable personnel to use the checklists, even though checklists are intended to be simple to use.

The results from the hazard identification should ideally be used in the following steps of the risk management process. This is however complicated by the fact that the way the ignition sources can induce a substantial fire in a high bay warehouse is highly abstract. The practical use of attempting to specify fire scenarios based on the ignition sources discovered is therefore ruled out, partly because of its inherent complexity but mainly because the results of such a study would be connected to a great deal of subjectivity. It is therefore suggested that the results from the hazard identification could be disconnected from the risk analysis process, and that the hazard identification should be kept simple as long as no other ignition sources are introduced.

The use of Inductive Reasoning Techniques and Fundamental Methods are therefore ruled out, partly due to the unnecessary level of detail these but also due to their inability to comply with the Simplicity requirement given in Section 1 of this work. The conclusion is that Comparative method should be used as it is simple and well suited for situations where the characteristics of safe practice are well known.

As it is one of the presumptions to this work that the fire occurrence is very low and random, it can be assumed that there are no significant ignition sources within the high bay warehouse. If this should prove to be incorrect, the methodologies chosen later in the risk analysis process might not be valid. It is therefore suggested that a checklist should be chosen as to prove that the assumptions of this work are correct.

In conclusion a checklist is thought to be appropriate to use in the hazard identification process. The checklist shall emphasise on finding ignition sources and be based on basic fire chemistry and heat transfer relations. The checklist should be used by a group of persons with an insight in heat transfer or fire chemistry and in the system being analysed. An example of how such a checklist could look is shown in Table 9-1.

Ignition Source	Presence? (Yes/No)	Possible? (Yes/No)	Location
Open flames			
Mechanical Sparks			
Electrical currents			
Hot surfaces			
Hot air			
Autoxidating substances			

**Table 9-1. Example of ignition source checklist**

Furthermore, in compliance to the IEC, a brief consequence analysis should be carried out at this stage to determine if any of the ignition sources found could lead to such consequences that further evaluation of the risk is needed.

## 9.2 Choosing Frequency Analysis Tools

As fires in automated warehouses are very rare and, presumably, have extreme consequences, it is very important that the results from the risk analysis are accurate and trustworthy of basing decisions on. Therefore, it is advised that plant specific data is used as much as possible, and that methods that provides for formal treatment of uncertainties are utilised. The IEC recommends that one or more of these techniques should be used to determine the frequencies needed in the risk analysis;

- Historical data
- Analytical techniques
- Expert judgement

Basically, the frequencies needed for the risk analysis are two; the fire occurrence and the failure frequencies of the technical and physical events involved in the chain of events that arises once ignition has occurred.

### 9.2.1 Fire Occurrence

The use of expert judgements to directly state the fire occurrence is not recommendable as the fire occurrence is, presumably, very low and uncertainties in this technique are hard to determine. Furthermore the use of experts to determine fire frequency relies on a number of experts working together to arrive at a conclusion. In reality very few organisations, if any, posses such expertise. It is therefore suggested that expert judgement in this case neither can provide more accurate results nor is more work efficient than any other technique.

As the system to be described, i.e. the high bay warehouse, is fairly simple the use of network such as fault trees models to calculate the fire occurrence must be evaluated. However, setting up a network model for determining fire occurrence implies that all the respective ignition sources ability to ignite nearby fuel should be determined. In an automated high bay area the fire occurrence is so low that it is not envisaged that there are any particularly significant ignition sources, but that the fire frequency is of a more random character than that. Furthermore these early fire scenarios are not easy to quantify and it is likely to be difficult to find all the probabilities needed to establish a viable fire occurrence. The use of network models is therefore ruled out due to its inherent need for reliable failure data and the potential absence of significant ignition sources.

Another analytical method for determining fire occurrence is available; it is based on a correlation between occupancy, building size and fire occurrence. A number of studies have been performed<sup>63,64,65</sup> and although the results are not entirely applicable to automated high bay warehouses the results might be viable as a baseline number. This method is also very quick to perform and it can easily be updated if more information is collected. Another positive aspect of this approach is that the method engulfs all reasons for fire occurrence, something that is highly desired in a risk analysis of an automated high bay warehouse, as there is not an abundance of significant ignition sources. The negative fact that it is based on generic data is alleviated by the possibility of employing site specific data in the analysis. Another obvious negative effect of this method is that it lacks transparency; it cannot be deduced which ignition sources add to the fire risk as the numbers is based on generic fire statistics rather than statistics for special ignition sources, such as human causes or faulty electric installations etc. This makes any measurements of any ignition risk reducing investments impossible. The method can however still serve as a measurement of the present ignition risk and as such give guidance in an investment process, when analysing post-ignition risk reduction measures.

In conclusion, it is appreciated that generic fire frequencies based on floor area and occupancy, with as good applicability as possible should be utilised in the fire occurrence analysis, and that plant specific data is used to update the generic data. The proposed method is simple, expandable, and quantitative and it is envisaged that it can be used to handle the random nature of fire occurrence present in an automated high bay warehouse.

### 9.2.2 Fire Scenario set-up

When establishing the likely propagation of a fire, it is necessary to designate probabilities of different events, such as the likelihood of successful extinguishing by sprinklers and the probability of a fire spreading from one object to another.

The failure frequencies of fire protection systems have been the subject of a great deal of research and the use of available generic historic data is considered as a viable option. The reliability of other technical systems present in the high bay warehouse can likely also be determined with a combination of generic data and fault tree analysis. It is therefore recommended that generic data is used to establish the reliability of the fire protection systems.

As the system is so simple it should not pose a problem to model the system with a network model. Network models are illustrative and provide good means for combining different scenarios and their respective probabilities and consequences.

The conclusion is that plant specific data should be used wherever possible, even if it is only to update generic data. Analytical techniques are appropriate to determine the frequencies needed for the risk analysis. However, sound generic data can be used where the characteristics of high bay warehouses have been addressed when compiling the generic data, such as fire sprinkler efficiency in rack storage.

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<sup>63</sup> Rahikainen, J. et al. (1998) *Determination of Ignition Frequency of Fire in Different Premises in Finland*.

<sup>64</sup> Sandberg, M. (2004), *Statistical Determination of Ignition Frequency*

<sup>65</sup> *Competitive steel buildings through natural fire safety concept – Part 4: Statistics*. (1999) Profil Arbed

## 9.3 Choosing Consequence Analysis Tools

### 9.3.1 Choosing Enclosure Fire Dynamics Model

In Section 6.1 three different approaches to fire scenario modelling was mentioned, hand calculations, computer zone models and computer field models. In this section these three different methods for enclosure fire dynamics modelling are to be evaluated according to the ability to comply with the criteria stated in Section 1.

Field modelling is the most powerful and complex method for simulating an enclosed fire, but it is also the most demanding in terms of time and knowledge. In other words, for the sake of simplicity hand calculations or zone modelling would be the better choices. Regarding the expandability of the models the field model stands out as it can resolve the simulated enclosure to a much higher degree, and thus take every alteration into account. All three suggested approaches are quantitative by their own rights in the sense that they all return numerical values, the field model however can return much more information at a (as previously stated) higher resolution, and thus must be considered the “most” quantitative.

Before these criteria can even be applied to our different approaches, we must first know if all of them are appropriate for simulations of warehouse fires. To establish which one of these approaches is the most suitable for modelling fires in high bay warehouse type buildings one must consider the geometry of a high bay warehouse. With regards to the large proportions of the building type, both regarding floor area and ceiling height, the hot smoke may not have the buoyancy to form a stratified case, as mentioned in Section 3.3.2. This fact should point us in the direction of some kind of field model since the zone models, by definition, only can be used to model the stratified case. One should as well consider the interference of the pallet-racks on the fire plume, as discussed in Section 3.3.1. The flow through vertical and horizontal flues should contain turbulence that might be poorly represented by a time-averaged turbulence model (RANS). Based on these two observations it is the author’s opinion that the first option should be to evaluate the possibility of LES modelling of the fire scenarios. The by far most accessible and well documented LES fire model is *Fire Dynamics Simulator 4* (FDS 4). To evaluate the appropriateness of this option literature on the subject has been studied. A compilation of work done on the subject as well as brief conclusions follows.

In *Comparison of fire model predictions with experiments conducted in a hangar with a 15 meter ceiling*<sup>66</sup> the purpose was to alleviate an existing lack of verification studies for computer models for fire protections problems at heights in excess of 10 meters. This analysis deals primarily with temperature comparisons as a function of distance from the fire centre and depth beneath the ceiling. Some velocity measurements in the ceiling jets were available and were compared with the models capable of velocity prediction. The models included in the study were the plume correlations of Heskestad and McCaffrey, the ceiling jet correlation of Alpert, the zone models CFAST, FPEtool, and LAVENT, and the CFD models CFX (RANS) and NIST-LES (LES). The fire experiments were conducted in a Navy hangar with the ceiling height of 15 meters, the fires tested were, one 500 kW fire and one 2.7 MW fire. The conclusions of the comparison were that, first of all, all but FPEtool provided good predictive results for the plume centreline temperature. When it came to model predictions of radial temperature variation, ceiling jet velocity and foremost temperature variations as a function of depth beneath the ceiling all models provided more or less poor comparisons with the experimental data. The poor results in predicting the temperature variations as a function of depth beneath the ceiling may be in part accounted for by mixing caused by ceiling beams. Moving on, the

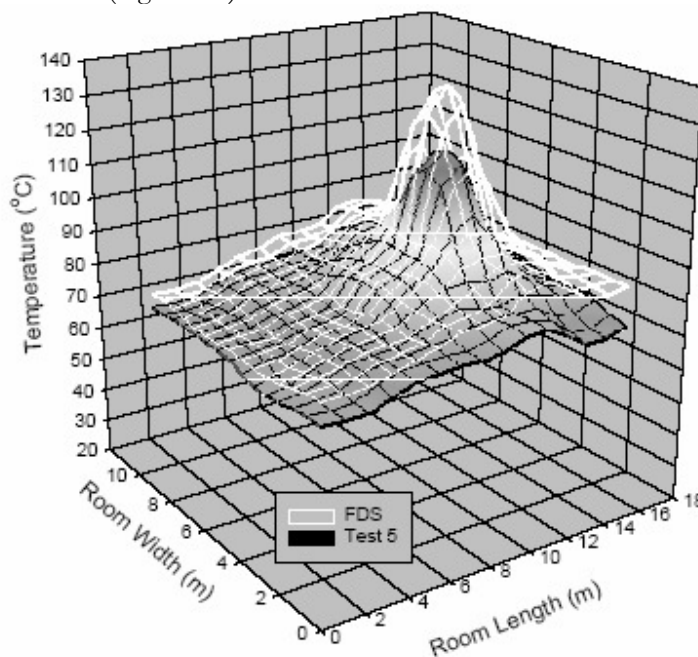
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<sup>66</sup> Davis, W. et al., (1996), *Comparison of fire model predictions with experiments conducted in a hangar with a 15 meter ceiling*.

CFD models performed better than the zone models in some areas, but in other areas no advantage was gained by the use of CFD models.

In writing *Comparison of FDS Model Predictions with FM/SNL Fire Test Data*<sup>67</sup> the authors wanted to provide feedback to the model developers regarding use of the FDS model and to compare FDS model predictions with large-scale fire test data for a mechanically ventilated enclosure. Comparisons were made between the FDS model and 7 full-scale fire tests. The test enclosure was 18.3 m long by 12.2 m wide by 6.1 m high. The tests had fire intensities of 500 kW, 1000 kW and 2000 kW placed at the room centre or along the wall, with ventilation rates varying from 1 to 10 air changes per hour. The conclusions regarding the quality of the predictions offered by the FDS model was that the model in many cases showed agreement within 10 to 20 °C. Plume temperature had the worst agreement with differences, in the worst case, as large as 100°C. The authors also present the following observations:

- In general, improvement in the predictions is observed from the 2 ft (0.61 m) to 1 ft (0.30 m) cases, but not from the 1 ft to the 8 in. (0.20 m) cases.
- Increasing the grid resolution around the fire plume seems to cause more scatter in predicted temperatures
- Transforming the area around the plume to 6 in. (0.15 m) or 4 in. (0.10 m) (for a 1 ft case) did not improve plume temperature predictions
- FDS correctly predicts temperature trends within the FM/SNL enclosure. As is displayed below (Figure 9-1)



**Figure 9-1. 3D Surface plot of FDS Predictions vs. test 5 Measurements (at 0.98H, t=540s, grid=1 ft.)**

In *Large Eddy Simulations of Fire Tests in a Large Hall*<sup>68</sup> the authors give further comments for the evaluation simulations performed for the International Collaborative Project to Evaluate Fire Models

<sup>67</sup> Friday, P. A. et al., (2001), *Comparison of FDS Model Predictions With FM/SNL Fire Test Data*

<sup>68</sup> McGrattan, K. et al. (2001), *Large Eddy Simulations of Fire Tests in a Large Hall*.



for Nuclear Power Plant Applications<sup>69</sup>. The main study's aim was to evaluate different fire models performance compared to a series of test fires, the so called Benchmark Exercise #2. The test setup was 2 – 4 MW fires in an enclosure measuring 27 m long by 14 m wide by 19 m high. The simulations were carried out with grid resolution of 0.13 m cells for the 4 m x 4 m x 10 m grid surrounding the fire and the rest of the space at a resolution of 0.40 m cells. In total 216.000 cells were used in the simulation. The results of the three calculations agreed well with the measurements. For the small fire simulation the 5 upper thermocouple locations in each array are within 10 °C of the measured. The lower 5 temperature locations showed good agreement as well. The only major deviation from the measured results was in the lower thermocouple location in the fire plume where the predicted temperatures were about 100 °C higher than the measurement. For the larger fire simulation the agreement between model and experiment is better. All predicted and measured temperatures within the plume are within 10 °C of one another. The better agreement for the larger fire is due to the fact that, for a given level of grid refinement, a larger fire is easier to model than a smaller one, as in this instance. They found that very good agreement with experiment is achieved when the fire is spanned by roughly 6 to 8 grid cells, this was according to the authors in line with previous findings.

The temperature of the hot gases and how those hot gases spread through the enclosure, thus burning and/or contaminating more and more stock, are the two most interesting parameters when looking at a potential fire. These two parameters are also two of the best verified in the examples of model verification work summarized above. Thus, the findings in these reports are, in the authors' opinion, enough to justify the use of the LES model FDS 4 for the simulations of the high bay warehouse fire scenarios

### 9.3.2 Method for Determining Economical Consequences of a Fire

Once the warehouse fire has been modelled using the enclosure fire dynamics model settled for in the previous section, exposure levels for the contents of the warehouse should be available. The only conceivable way of converting this information into consequences in the form of destroyed goods is to somehow match the exposure levels to the resilience of the goods towards the exposures suffered. One methodology that does just that was presented in Section 6.2, this mode of procedure will be followed, there may be other methodologies that do the exact same thing, but the mode of procedure will be exactly the same.

In this consequence analysis Threshold Damage Limits (TDLs) for the goods in the high bay warehouse in question will be established for the exposure categories listed<sup>70</sup>:

- Thermal effects (i.e., radiant heat, temperature)
- Explosion overpressure effects
- Products of combustion (i.e., corrosive gases, smoke)

Depending on the type of goods stored and the resolution of analysis required the TDLs will differ from case to case.

However, as briefly mentioned in Section 9.3.1, the immense sizes normally associated with high bay warehouse type buildings can help us in directing our interest to the forms of exposure that may threaten the largest amount of stock. Considering the large sizes, one can come to the conclusion

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<sup>69</sup> Dey, M. K.; Hamins, A.; Miles, S, 2003

<sup>70</sup> Barry, T.F. (2002), *Risk-Informed Performance-Based Fire Protection*

that a large, but limited, fire (perhaps sprinkler controlled) can cause a great deal of direct damage in the area directly involved in the fire through the convective heat transfer from the flame and plume, as well as in the area directly surrounding the involved area through heat transferred through radiation. But the sum of the damage done in those two areas will, taking the size of the warehouse into account, be small in comparison to damage sustained by stock through heat and smoke contamination brought about through the transport of hot smoke.

Thus, the most interesting exposures, when determining TDLs to utilise in conjunction with an enclosure fire dynamics model, are the exposures that can damage stock over a great distance. Thus, the temperature and spread of the hot smoke layer becomes the, by far, most important parameters to study in fire scenarios in high bay type buildings.

This means that the potential damage due to radiant heat and direct flame exposure is assumed small in comparison to the potential quantities of stock damaged by the temperature and contaminants of the hot smoke filling the enclosure, and thus will be ignored. This will be assumed to be covered through conservative choices of TDLs for heat and smoke exposure through the hot smoke layer.

These TDLs are then to be matched to predictions of exposure levels of smoke and heat, and conclusions regarding the amount of damage inflicted can be made. In the case of high bay warehouses with fairly symmetrical pallet configurations the damage can be specified as fractions of the total stock.

#### **9.4 Risk Calculation Methods**

In Section 7 two risk calculation methods were described, *Expected Value* and *Risk profiles*. The use of expected values is generally more applicable when the statistical sample is large and there is more certainty of the validity of the EV. As there is a great deal of uncertainties involved in analysing small frequencies and large consequences the use of EV as a single denotation to illustrate for instance yearly expected loss is not recommendable. It is therefore suggested that a risk profile should be used to illustrate the findings of the analysis.

In Section 7, two methods for integrating risk attitude into the results were also described. This is often more of interest later in the risk management process and not an essential part for the risk analysis. It should however, in line with the expandability criterion of this work, be possible to incorporate the results in these later stages too. The results should therefore be possible to express in monetary terms. Depending on the organisations risk attitude the use of expected utility or risk discounted value might be appropriate. Whichever risk calculation method is chosen the uncertainty of the analysis should be made visible.

As the cost of each goods pallet may vary from year to year and is likely to rise over time, it is proposed that the result should be expressed in terms of damaged goods per time period. This value could be used in conjunction with an estimate of average pallet value to derive a monetary value. This also lends the result to indicate how significant for the result the estimate of goods value is.

In conclusion a risk profile should be used. The risk profile should depict an estimate of damaged goods per time period. If necessary this value can be used in conjunction with an estimate of the average goods value to enable risk management decisions to be made.

## **9.5 The proposed methodology**

In this chapter the proposed methodology for each of the different segments of the fire risk analysis are presented, as are the reasons as to why that particular methodology was deemed most suitable. To sum up what now can be regarded as a prototype for a collected methodology for fire risk analysis of high-bay warehouses the suggested mode of procedure is presented below:

1. Perform a checklist analysis to expose apparent and significant ignition sources.
2. If any significant ignition sources are discovered these should be attended to before commencing on the later stages of risk analysis. This is to ensure that the assumptions of this work are valid for the case in question.
3. The frequency of a fire is determined using the aforementioned correlation between fire occurrence and the type of occupancy and building size.
4. All available plant specific data is collected and the generic data derived from the previous step is updated using Bayesian updating.
5. Construct an event tree the first event being “fire started”, the branches of the event tree should represent different degrees of function of fire protection, i.e. sprinklers activates and controls the fire.
6. Determine what phenomena that threaten stock in case of a fire, i.e. radiative heat, convective heat and combustion species (smoke).
7. Determine what levels of exposure to these phenomena the stock may end up being subjected to in the event of a fire with a certain degree of involvement from fire protective measures.
8. Establish the threshold damage limits for these exposures.
9. Calculate the consequences of the end scenarios by combining the threshold damage limits with the predicted exposure levels.
10. The probability distribution of an occurred fire can now be determined.
11. The expected yearly loss due to fire can now be calculated by multiplying the expected value of an occurred fire with the frequency of a fire. This should be expressed as a probability distribution.

When this is known the decision of whether or not the level of risk taken is acceptable or not can be made with greater confidence.



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## 10 Case Study – IKEA DC, Älmhult

To assess the applicability of the tools chosen in Section 9 with respect to fire risk analysis in automated high bay areas a case study has been performed at the IKEA distribution centre in Älmhult. This is the same warehouse that was described in Section 8.

The task of this risk analysis is to determine the fire risk in the high bay area.

### **10.1 Hazard Identification**

A hazard identification was carried out in accordance with the suggestions shown in Section 9.5. A checklist was used to ensure that no significant ignition sources were present in the high bay warehouse at the initiation of the risk analysis.

The hazard identification was performed during an interview and a site visit that took place in Älmhult on December 6<sup>th</sup> 2005. The IKEA staff attending the interview was; Leif Edforss, Risk Manager; Åke Nilsson, Maintenance Manager and Kjell Lindblad, Property Engineer.

The hazard identification was done during the interview with the IKEA staff but the authors solely determined the correct way of action based on the results. Firstly the attendants were asked to recall any fire incidents that had occurred in the high bay area, thereafter if they were asked to state if they knew of fire incidents in similar warehouses and finally an ignition source checklist, as seen in Table 9-1 was utilised.

The IKEA staff present stated that no fire incidents have ever been reported in the IKEA high bays. During the interview it was also reassured that no fire incidents had occurred in the high bay area of Älmhult South or Älmhult North.

The result of the checklist interview is shown in Table 10-1.

<b>Fire Hazard Identification Checklist</b>			
<b>Älmhult South High Bay</b>			
<b>20051206</b>			
<b>Attending:</b> L. Edfors, Å. Nilsson, and K. Lindblad.			
<b>Ignition Source</b>	<b>Present? (Yes/No)</b>	<b>Possible? (Yes/No)</b>	<b>Location</b>
Open flames	NO	NO	
Mechanical Sparks	NO	YES	Stacker crane rails
Mechanical Sparks	NO	YES	Conveyor chains
Electrical Sparks	NO	YES	Electrical motors in cranes
Electrical sparks	NO	YES	Fluorescent ceiling lamps
Electrical currents	YES	NA	Stacker crane motors
Electrical currents	YES	NA	Stacker crane control stations
Electrical currents	YES	NA	Conveyor chains
Electrical currents	YES	NA	Leading lights in racks
Electrical currents	YES	NA	Ceiling lamps
Hot surfaces	NO	UNKNOWN*	
Hot air	NO	NO	
Autoxidating substances	UNKNOWN*	YES	Linseed oil based paint
*not an initial option. The term “Unknown” was introduced during the hazard identification process. See Section 10.1.1 for details			

**Table 10-1. Result of the hazard identification.**

### 10.1.1 Hazard Identification Conclusion

Based on the information gained in the project familiarisation and the hazard identification, it was decided that a more detailed study was needed to achieve the risk analysis' goal of determining the high bay warehouse fire risk. This fact does not however cancel out the opportunity to reduce or eliminate some fire hazards at this stage

It was concluded that, assuming that linseed based products are not present in the high bay warehouse, there were no ignition sources that were of such significance that a more detailed analysis of them is justified. It was therefore assumed that the ignition pattern in this warehouse is of a more random nature and that the assumptions of this work apply to this warehouse.

If a linseed oil based fluid was to spill onto a piece of stored furniture or even onto the cardboard packaging it might lead to an autoxidating process and self ignition. It is therefore advised that the presence of linseed oil based products in the high bay area should be investigated and if it is found that these products are in fact stored in the high bay area it is suggested that they should be moved to the conventional warehouse, where a spillage is more likely to be detected.

## 10.2 Frequency Analysis

In accordance with the argumentation provided in Section 9.2 the fire frequency was determined using generic data depending on building size. Furthermore the likely fire scenarios given that a fire has started were described using an event tree.

### 10.2.1 Constructing the Event Tree

The chain of events that dictate the outcome of a fire, given that ignition has occurred was set out in an event tree. It was assumed that only the sprinkler system could affect the outcome of a fire. Three scenarios were chosen:

1. The sprinkler system works as designed and extinguishes the fire.
2. The sprinkler system fails to extinguish the fire but controls it so it doesn't spread.
3. The sprinkler system fails and the fire spreads uncontrollably.

The event tree of these possible scenarios is shown in Figure 10-1 and in Appendix A3.

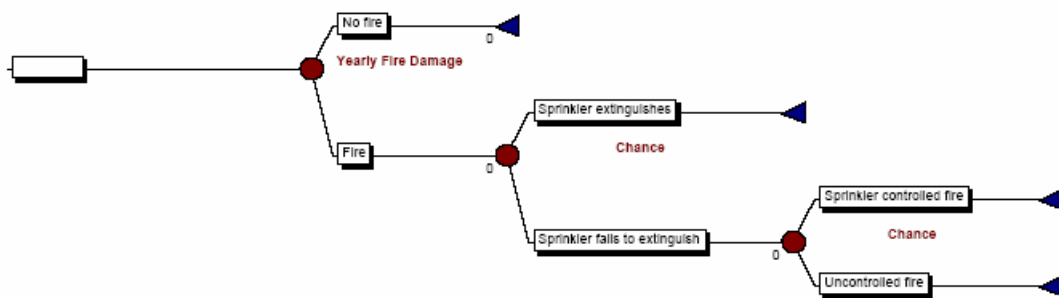


Figure 10-1. The event tree used in the analysis.

### 10.2.2 Determine Fire Occurrence

In accordance with the methodologies set out in Section 9.5, the fire frequency was to be determined using a model based on building size, and if possible update this with plant specific data. IKEA has been collecting fire incident statistics regarding its different sites since the first IKEA warehouse was built in the early 1950s and the statistics show that no fire incident has ever been reported in any IKEA high bay area. However, as Ikea's high bays vary from each other, it was advised from IKEA (see Appendix A5) that the fire incident reports from a number of selected high bay areas during the period September 2003 through October 2005 should be used, as the results then would be directly applicable at Älmhult South. This data could be considered as nearly as good as plant specific data. Except for the storage capacity, there was no information regarding the aforementioned warehouses. The complete list of high bay facilities used in the analysis can be found in Appendix A5. It was decided that this extensive data had to be used in the analysis to determine the fire frequency at Älmhult South.

The mean value of the gamma distribution was chosen between three values that have been presented in studies regarding fire frequency as a variable depending on building type and floor area. A Finnish study<sup>71</sup> based its estimated fire frequency on warehouse fire incidents that had caused fire service intervention and the results can be seen in Figure 10-2. The fire frequency tends to even out around  $1 \cdot 10^{-6}$  per square meter and year for warehouses exceeding 10 000 m<sup>2</sup>. Similar studies has been carried out in Sweden and France, where the results for warehouses have been a slightly higher  $1.6 \cdot 10^{-5}$  and  $2 \cdot 10^{-5}$ , respectively<sup>72,73</sup>.

<sup>71</sup> Rahikainen, J. et al. (1998) *Determination of Ignition Frequency of Fire in Different Premises in Finland*.

<sup>72</sup> Sandberg, M. (2004), *Statistical Determination of Ignition Frequency*

<sup>73</sup> *Competitive steel buildings through natural fire safety concept – Part 4: Statistics*. (1999) Profil Arbed

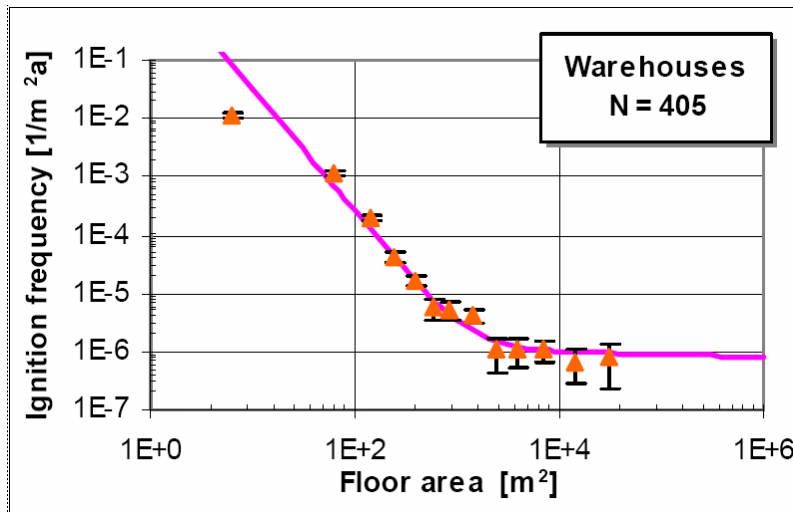


Figure 10-2. Correlation between floor area and fire frequency<sup>74</sup>.

As the total floor area of the IKEA high bays listed in Appendix A5 was not known, an estimate had to be derived. This was done by assuming that all high bays were configured like Älmhult South where both the floor area and the storage capacity are known. The total storage volume is 1 201 900 m<sup>3</sup>, with the assumption that all warehouses are created equal the total floor area would be roughly 350 000 m<sup>2</sup>. As the fire incident statistics were collected over the course of two years, the total annum floor area is roughly 700.000 m<sup>2</sup>a (square metre annum).

The three fire frequencies mentioned above was tested with a Poisson probability distribution test to determine the likelihood of zero fire incidents during the time period, given the tested frequency. The equation used is shown below.

$$P(X = x) = \frac{\mu^x * e^{-\mu}}{x!}$$

Where  $\mu$  is the expected value.

The results of the Poisson testing can be seen in Table 10-2.

Poisson Testing of Fire Frequencies		
	Frequency [m <sup>-2</sup> *a <sup>-1</sup> ]	P(0), n=700.000 [m <sup>2</sup> *a]
Finland <sup>75</sup>	1*10 <sup>-6</sup>	0,5
Sweden <sup>76</sup>	1,6*10 <sup>-5</sup>	0,000014
France <sup>77</sup>	2,2*10 <sup>-5</sup>	0,0000002

Table 10-2. Poisson testing of the fire frequencies.

Based on the results of the Poisson tests it was decided that the likelihood of zero fire incidents, given the two higher frequencies, was too low to consider any of these frequencies as a realistic

<sup>74</sup> Rahikainen, J. et al. (1998) *Determination of Ignition Frequency of Fire in Different Premises in Finland.*

<sup>75</sup> Ibid.

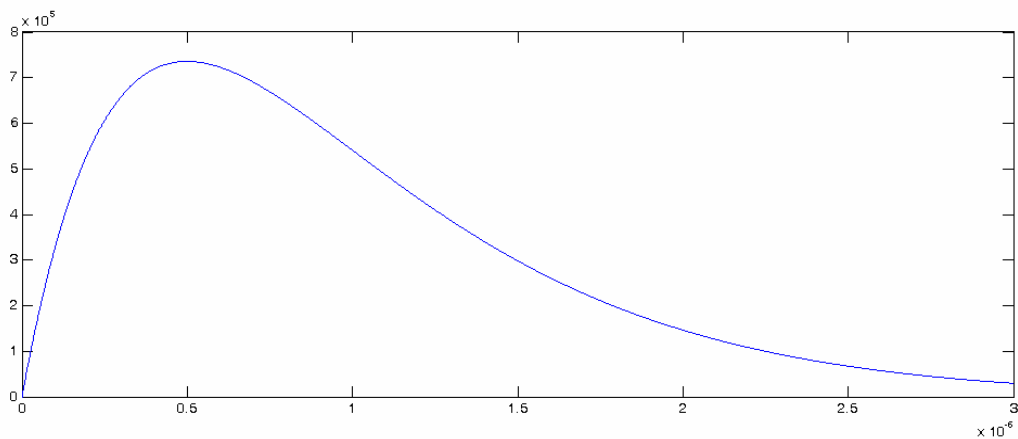
<sup>76</sup> Sandberg, M. (2004), *Statistical Determination of Ignition Frequency*

<sup>77</sup> *Competitive steel buildings through natural fire safety concept – Part 4: Statistics.* (1999) Profil Arbed



estimate at an IKEA high bay. The lowest fire frequency,  $1 \cdot 10^{-6} \text{ m}^{-2} \cdot \text{a}^{-1}$ , was therefore chosen as a probable value.

To model the probability distribution, a Gamma distribution was used for its ease when updating with additional information regarding occurred fires. A number of Gamma distributions were tested, all with a mean value of  $1 \cdot 10^{-6}$ . The choice of which gamma distribution to use as an apriori distribution was based on the shape of the probability density function. The criteria for choosing the Gamma distribution were that the probability density function should be concentrated on frequencies around and below  $1 \cdot 10^{-6}$  but not completely disregard higher frequencies and that the parameter  $\alpha$  should exceed 1, as  $\alpha \leq 1$  inflicts a descending gamma distribution. The chosen apriori gamma distribution is shown in Figure 10-3. The gamma parameters are;  $\alpha=2$  and  $\beta=2000000$ . The mean value is  $1 \cdot 10^{-6}$  fires per  $\text{m}^2$  and year. Other gamma distributions were also considered and these are documented in Appendix A4.



**Figure 10-3 Apriori Gamma probability density distribution. Operating parameters;  $\alpha=2$  and  $\beta=2.000.000$ .**

The updating process was made using the methodologies described in Section 5 with  $f_T=0$  and  $T=700.000$ . The resulting gamma distribution is shown in Figure 10-4. The posteriori mean value is  $7.4 \cdot 10^{-7} \text{ m}^{-2} \cdot \text{a}^{-1}$ .

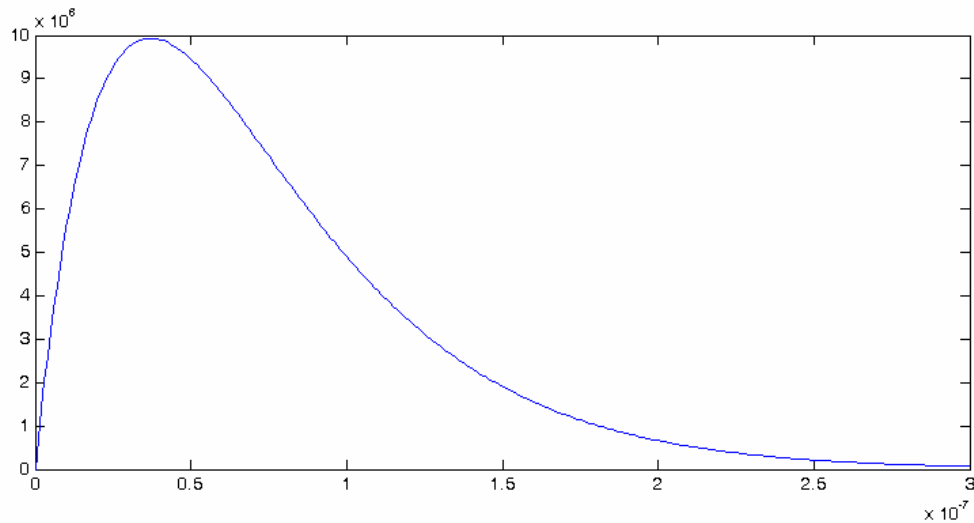


Figure 10-4 Posteriori Gamma probability density distribution. Operating parameters;  $\alpha=2$  and  $\beta=2.700.000$ .

### 10.2.3 Determine Branch Probabilities

The branch probabilities needed for the analysis was;

- Probability of sprinkler succeeding to extinguish the fire
- Probability of sprinkler managing to control the fire, given that extinguishing fails.

The probability of sprinklers succeeding to extinguish a fire was collected from Johansson<sup>78</sup>, who has made a compilation from a number of studies regarding sprinkler reliability. The probability of a sprinkler controlled fire given that the sprinkler fails to extinguish the fire was chosen to be a fifty-fifty draw, i.e. it is equally likely that the fire grows uncontrollably given that the fire has not been put out by a sprinkler as it is that the sprinkler will manage to control the fire and limit its growth.

Probability	Min	Most likely	Max	Distribution type
The probability that the sprinkler system will succeed in extinguishing a fire if one starts	0.94	0.96	0.98	Triangular
The probability that the sprinkler system will control the fire, given that extinguishing fails	0	0.5	1	Triangular

Table 10-1 Branch probabilities.

<sup>78</sup> Johansson, H. (2003), *Decision Analysis in Fire Safety Engineering-Analysing Investments in Fire Safety*.

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### 10.3 Calculating the Consequences of the End Scenarios

As determined in Section 9 the consequences of the fire scenarios will be determined through a methodology<sup>79</sup> for the calculation of consequences of industrial fire risk. The information required to determine the consequences is, first the TDLs for the goods being stored in the warehouse, second the predicted exposure levels. The TDLs must then be put in relation to predicted levels of exposure. The exposure will be provided in the output from the enclosure fire dynamics model used to simulate the fire scenario.

The consequences of the scenario where the sprinklers fail to operate will be assumed to be that the whole stock is destroyed. This is due to the facts discussed in Section 3.3.1, where it was stated that the fire growth speed and the severity of the fire, to a large extent is governed by the geometry and orientation of the fuel. Further it was concluded that the way fuel is arranged in high bay warehouses very much facilitates a rapid fire growth, and thus a fire allowed to freely grow in an environment as in this case, safely can be considered to ruin the entire stock.

#### 10.3.1 Fire Model Input Parameters

In Section 9.3.1 the conclusion after literature studies was to model the fire scenarios with the Large Eddy Simulator model FDS. The model will be used to predict the impact of the end scenarios in the event tree specified in Section 10.2.1.

The input parameters that are needed to run the FDS simulations of the specified fire events are:

- Physical characteristics: geometry, position of the fire, openings, materials
- Characteristics of the fire: heat release rate, fire growth rate, type of fuel
- Impact of fire protection systems: sprinklers, ventilation
- Computational grid: the computational grid must be chosen with care, for the model to give the best possible predictions.
- Specification of desired output: temperature, species concentration, radiation

The physical dimensions are very large, 196 m long by 56 m wide by 23-25 m high. This poses a problem, a prerequisite when using LES modelling is that the resolution of the underlying grid must be high enough to resolve the large eddy mixing that takes place. There is a feature built in to FDS 4 called *MIRROR*. The mirror-function allows for the entire domain including everything in it, prescribed fires, vents, obstacles, to be mirrored around an axis. The point of doing this is that only one half of the resulting domain needs to be calculated, the other half behaves exactly symmetrically. In our case of a fire in a large warehouse, we can assume the fire to be positioned in the exact centre of the warehouse. This makes it possible to mirror the domain around two axes resulting in a computational domain one fourth of the actual domain size. Thus, in practice, giving a computational grid four times as resolved. The principle of mirroring is shown in Figure 10-5. This procedure results in a computational domain of 98 m long by 28 m wide by 23-25 m high, but the modeled domain is still 196 m long by 56 m wide by 23-25 m high.

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<sup>79</sup> Barry, T.F. (2002), *Risk-Informed Performance-Based Fire Protection*

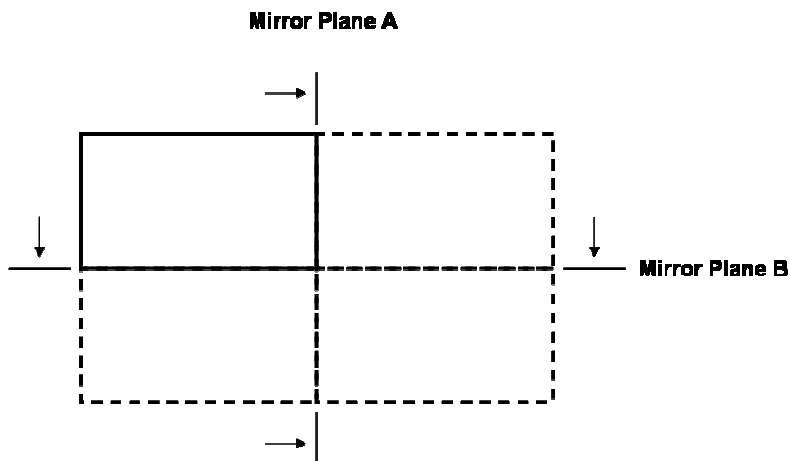


Figure 10-5. The computational domain (shaded) in relation to the resulting domain after mirroring around two planes.

To account for leakages in the enclosure an open vent of 2 m<sup>2</sup> will be prescribed along one of the walls.

The materials of the walls, ceiling and pallets inside of the domain will be modelled as inert to produce the worst temperature conditions.

The fire used for the simulations will be modelled from the Y3.3/60 Pallet system fire test<sup>80</sup>, the test setup consisted of 8 pallets in a 2 x 2 x 2 array with a water sprinkler, for full specifications of this test see Appendix A2. In the test a very slow growth phase can be observed for approximately 300 s, at which time the heat release rate (HRR) is around 800 kW. Then the HRR rises very suddenly and at 330 s the HRR is 4200 kW, at which time the sprinkler activated and the measurements was stopped, which can be observed in Figure 10-6.

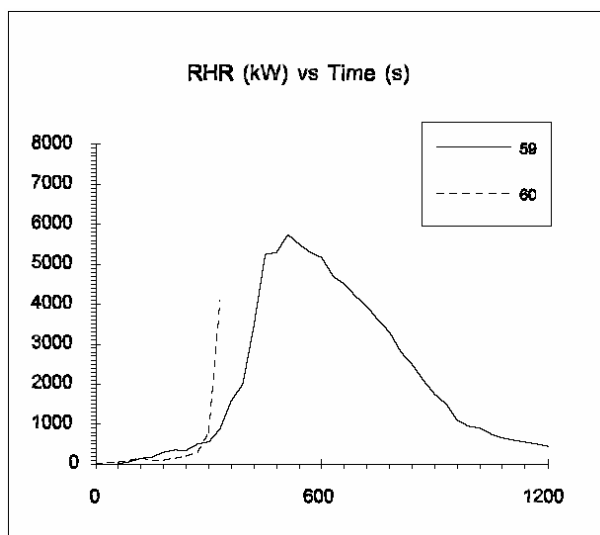


Figure 10-6. The Rate of Heat Release measured in the Y3.3/60 test (the dashed line).

<sup>80</sup> Särndqvist, S., (1993), *Initial Fires*

To apply this heat release rate curve to the scenarios to be simulated, some adjustments will be made:

- In the scenario where the sprinkler system activates and controls the fire the heat release rate is kept constant at 4200 kW until 720 s, where it descends and hits 0 kW at 1200 s. This way the total heat released fairly well matches the total heat released in the single pallet fire test Y3.3/59<sup>81</sup> (the solid line in Figure 10-6), thus represents a scenario where, due to some kind of malfunction, one pallet is allowed to burn out, but no spread occurs. The heat release curve for this scenario is shown in Figure 10-7.
- In the scenario where the sprinkler system activates and extinguishes the fire: The heat release rate immediately descends linearly, and hits 0 kW at 600 s. This thus represents a crude extinction model, with a linear descent. The heat release curve for this scenario is shown in Figure 10-8.

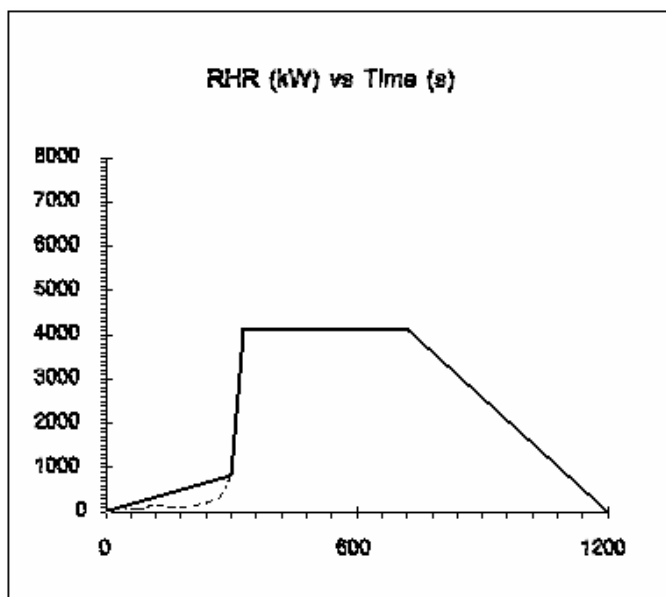


Figure 10-7. The HRR curve used to simulate the sprinkler controlled case.

<sup>81</sup> Särqvist, S., (1993), *Initial Fires*

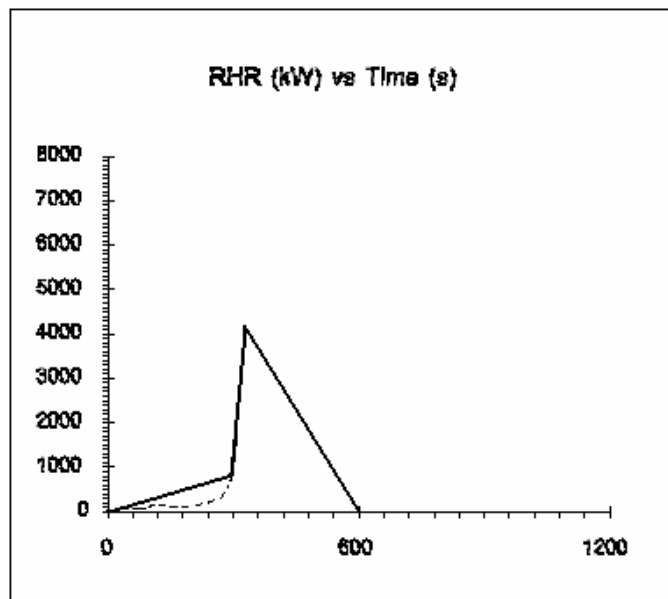


Figure 10-8. The HRR curve used to simulate the sprinkler extinguished case.

FDS has built in models for calculating the effects of sprinkler suppression, but these functions generally need even finer grid resolutions and increase calculation time. To, as done above, specify the HRR with regard taken to the effect of fire protection in the form of sprinklers is common way to handle these issues.

The fire will be modeled as 4 m<sup>2</sup> fire with a maximal HRR of 1050 kW/m<sup>2</sup>, totaling 4200 kW.

The type of fuel used in the simulations should reflect the type of fuel that is stored in the warehouse. The goods being stored is a mix of cellulose materials such as paper, textiles and wood and plastic materials of different kinds. To accurately model the actual different materials burning, would demand very much of both the model and the quality of the data basis. A much more applicable solution is to go with a conservative choice, meaning a fuel that most likely is worse than the real case. In this case Polyurethane was chosen from the FDS 4 database. This will represent the real-case mixture of materials.

Regarding the computational grid, the finer the resolution, the more accurate the predictions. But the more cells the longer runtime, sometimes much longer runtimes. In the case of these simulations, the computer resources were limited to regular PCs (Pentium 4 2.8 GHz with 1.0 Gb of memory) and the only way to get an acceptable resolution was to use as many cells as the model would run. The computational grid ended up being constructed as three separate meshes, with one fine mesh (0.2 m x 0.2 m x 0.2 m) resolving the fire and plume region. Then two meshes (approx 0.8 m x 0.8 m x 0.8 m) bordering to the fire mesh. Grid verification simulations with a 0.1 m x 0.1 m x 0.1 m fire and plume grid and 0.4 m x 0.4 m x 0.4 m grids bordering the fire grid was also run to assure that the solution is grid independent. This mesh compares nicely to the mesh used with good results By McGrattan et al.<sup>82</sup> the fire (2 m x 2 m) is spanned by 2 / 0.2 = 10 cells respectively 2 / 0.1 = 20 cells which is much more than the 6 – 8 cells they had found to suffice for very good agreement.

Finally, one must specify what information one wants from the model, this is called output. In FDS 4 there are many different types of output files measuring many different quantities. There are 3D

<sup>82</sup> McGrattan, K., Floyd, J. (2001), *Large Eddy Simulations of Fire Tests in a Large Hall*

isosurface files, planar slices (slice files), boundary files, particle tracers and 3D smoke. Before the simulation is started one needs to establish which exposures are the greatest threats to the stock. If we go back to Section 6.2.1 there was a list of primary exposure categories to be used when evaluating component damage potential from fires or explosions<sup>83</sup>:

- Thermal effects (i.e., radiant heat, temperature)
- Explosion overpressure effects
- Products of combustion (i.e., corrosive gases, smoke)

In our case we will prioritize the prediction of exposure levels of temperature in the form of hot smoke, and the exposure levels of contaminants in smoke. The damage through radiative heat and direct flame exposure will be ignored as discussed in Section 9.3.2.

So we know that we want to predict exposure levels for temperature and smoke. Temperature exposure can be accurately visualised with both 3D isosurfaces and slice files. The exposure of smoke and soot can also be adequately determined from visibility slice files or isosurfaces, the accuracy in these judgements will be considered sufficient, as the consequences will be modelled with uncertainties in the event-tree model.

### 10.3.2 Establishing Threshold Damage Limits

As mentioned in the previous section, the exposure categories that are to be studied are the temperature and the smoke concentration.

The temperature TDL is quite easily assessable; looking at Table 6-3 again we see that the stock, being a mix of cellulose and plastic materials should have a combined TDL of something like 150 °C. However it is not unthinkable that, based on the temperatures stated in the table, even lower temperatures might cause cosmetic damage to certain materials, rendering the goods un-sellable, thus in effect destroyed. A TDL of 100°C will thus be used as a conservative value.

As for the TDL with regard to odour and discolouring from smoke exposure no facts or numbers have been found, neither through studies of literature or searches online, nor has IKEA been able to provide this information. For the sake of this thesis a TDL for smoke exposure corresponding to a visibility of 10 meters will be used. This will be considered to correspond, roughly, to exposure to the buoyant smoke layer.

In conclusion, the TDLs to be used in the case study of Ikea's Distribution Centre in Älmhult are; for temperature, 100 °C. And for smoke contamination, all stock exposed to smoke concentrations corresponding to 10 meters visibility.

### 10.3.3 Results of the Exposure Analysis

The above determined TDLs will in this section be compared to the predictions made by the FDS 4 model. The temperature exposure will be determined at the point in time where the heat release rate starts to decline which in the sprinkler controlled case is at 720 s and in the sprinkler extinguished case at 330 s. The smoke exposure will be determined at the time the heat release rate reaches zero which in the sprinkler controlled case is at 1200 s and in the sprinkler extinguished case at 600 s

#### ***The sprinkler controlled case***

<sup>83</sup> Barry, T.F. (2002), *Risk-Informed Performance-Based Fire Protection*

The temperature slice file shown in Figure 10-9 show that the temperature exposure through hot gases will only destroy the stock placed directly inside the plume. This effectively means that only a very small portion of the damage will come from exposure to high temperature.

The visibility slice file shown in Figure 10-10 illustrates that the upper layer will be well-defined, thus which visibility limit used as TDL is of lesser importance. However, according to the established TDL regarding smoke exposure, about 2/5 of the palletized stock will be destroyed through smoke exposure.

Smokeview 4.0.7 - Mar 12 2006

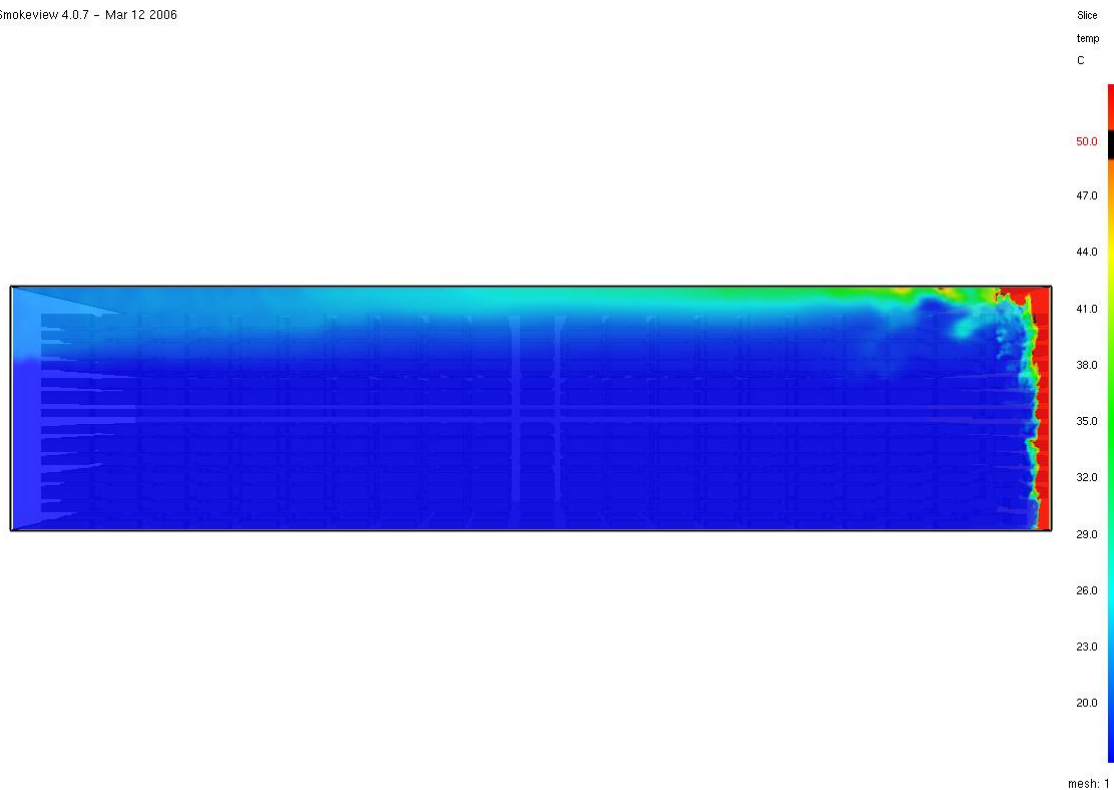
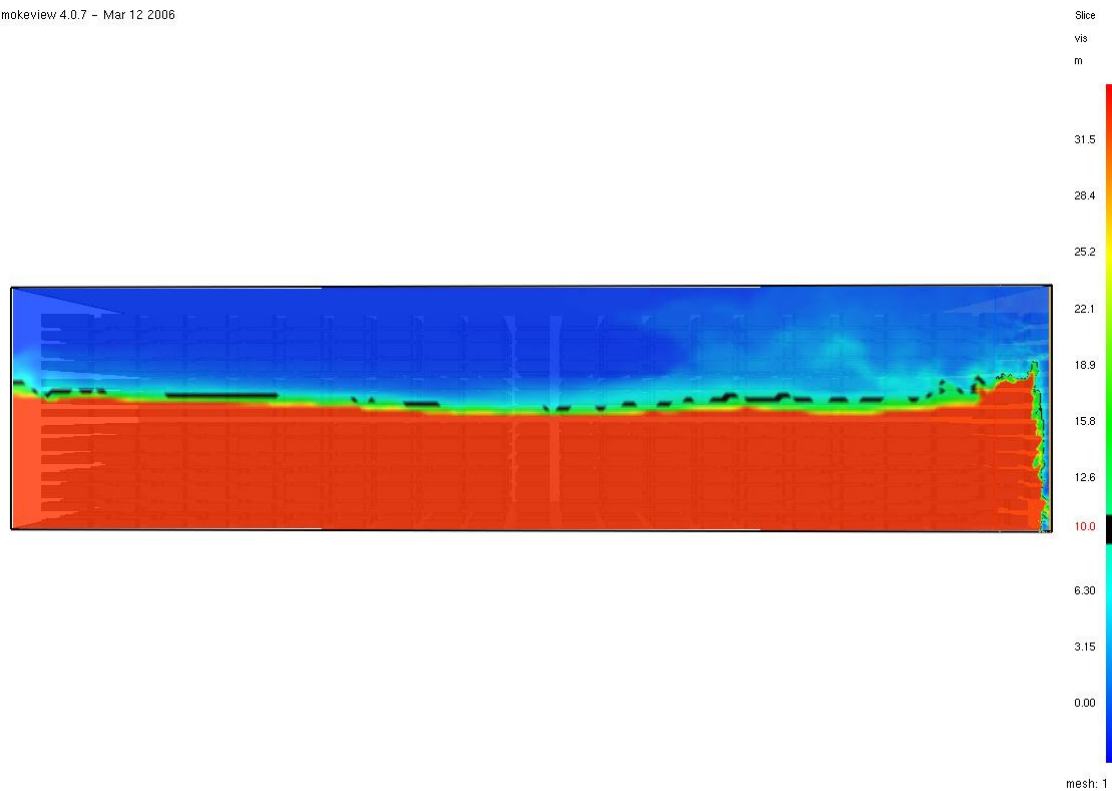


Figure 10-9. Slice file of the temperature exposure for the sprinkler controlled case at 720s.



Smokeview 4.0.7 - Mar 12 2006

Frame: 240  
Time: 1200.0

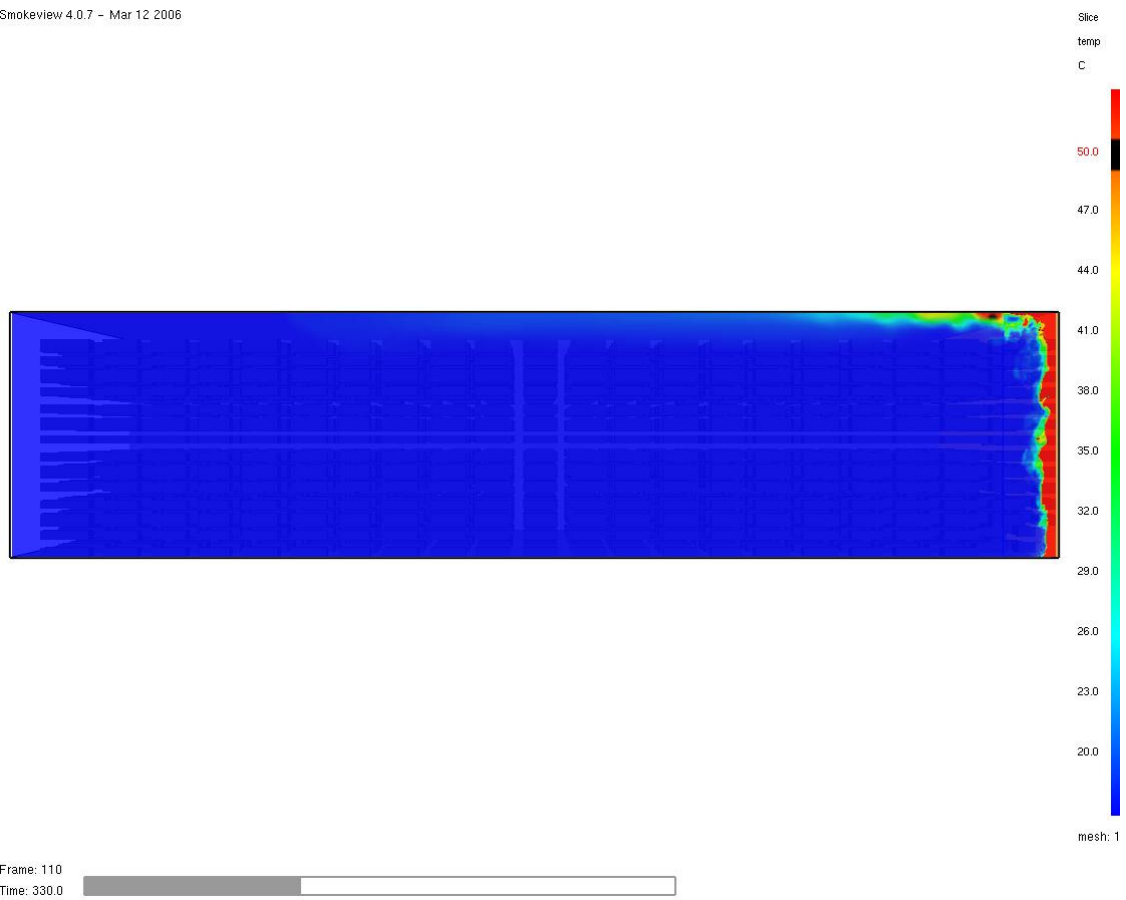
**Figure 10-10.** Slice file of the visibility in the sprinkler controlled case at 1200s, visibility 10m is marked up in black.

### ***The sprinkler extinguished case***

The temperature slice file shown in Figure 10-11 shows that the temperature exposure through hot gases will only destroy the stock placed directly inside the plume. This effectively means that only a very small portion of the damage in this scenario will come from exposure to high temperature.

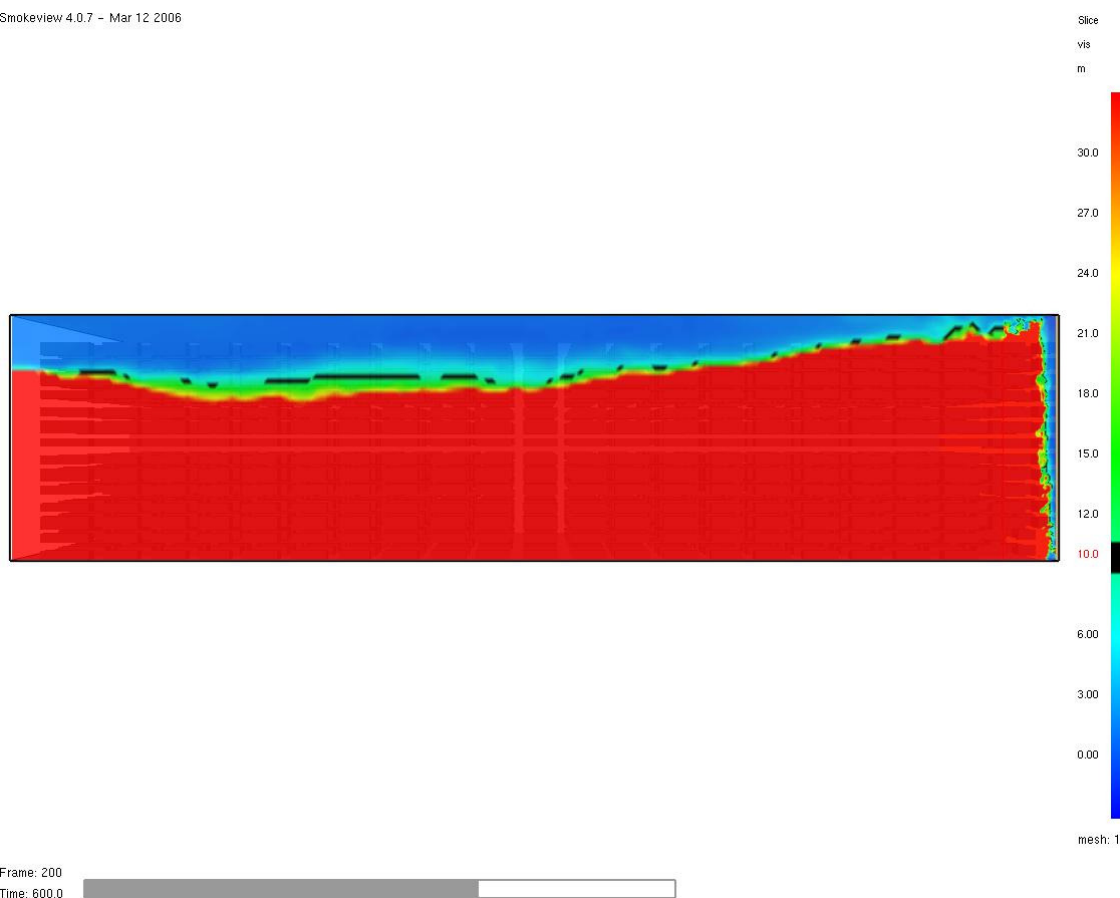
The visibility slice file shown in Figure 10-12 indicates that the upper layer will be well-defined, thus which visibility limit used as TDL is of lesser importance. However, according to the established TDL regarding smoke exposure, about 1/6 or 1/7 of the palletized stock will be destroyed through smoke exposure.

Smokeview 4.0.7 - Mar 12 2006



**Figure 10-11.** Slice file of the temperature exposure in the sprinkler extinguished case at 330s.

Smokeview 4.0.7 - Mar 12 2006



**Figure 10-12.** Slice file of the visibility in the sprinkler extinguished case at 600s; visibility 10m is marked up in black.

### 10.3.4 Establishing the Consequences of the End Scenarios

When the exposures have been determined through the simulation of the two fire scenarios, one being the sprinkler controlled, the other being the sprinkler extinguished. The exposure will be matched to the, in section 10.3.2, established TDLs, as described in section 6.2 and the result will be the amount of ruined stock.

There are however uncertainties involved in the consequence analysis, one part being the inherent uncertainty of the model itself, this is discussed in Section 9.3, the other being the uncertainty in the establishment of the TDLs. With regards to the latter, the uncertainties of the temperature TDL becomes less important (due to the small contribution to the ruined stock). The uncertainties with regards to the smoke exposure TDL can however be considered fairly large, considering the fact that no preferences as to how to determine smoke damage has been provided by IKEA, or has been found through any other channel.

To take these uncertainties into account the following distributions will be used in the event tree model, these distributions are based on the observations of the buoyant smoke layer made from the simulations, the distributions are arbitrarily chosen:

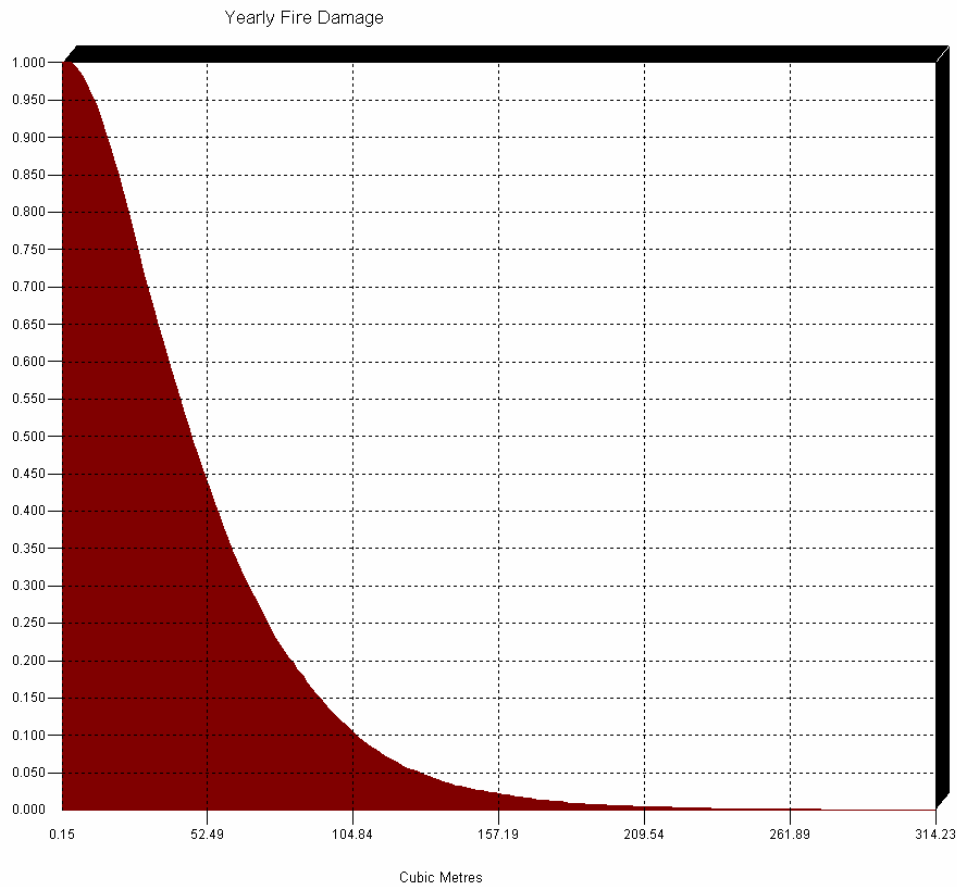
- 
- For the sprinkler controlled case, where the observed exposure levels pointed towards the destruction of about 2/5 of the stock, a triangular distribution with the following parameters: 0.2; 0.4; 0.6 is suggested for input into the event tree model.
  - For the sprinkler extinguished case, where the observed exposure levels pointed towards the destruction of about 1/6 – 1/7 of the stock, a triangular distribution with the following parameters: 0.10; 0.15; 0.20 is suggested for input into the event tree model.

### **10.4 Calculate Risks**

In accordance with the methodology determined in Section 9.5 the results of the risk analysis shall be illustrated by risk profiles and annotations of the uncertainties connected to the results. Using the event tree described in Section 10.2.1, the frequencies determined in Sections 10.2.2 and 10.2.3 was combined with the consequence estimations presented in Section 10.3.4. A Monte Carlo technique was used to simulate the outcome of the event tree, i.e. the averaged yearly damage due to fire. If desired the output of this study can be combined with the averaged goods value of the palletized stock to produce monetary estimates of the expected loss.

### **10.5 Case study results**

The result of the case study was plotted using a cumulative descending risk profile, showing the probability of particular yearly fire damage. This risk profile is shown in Figure 10-13. The characteristics of the distribution are also tabled in Table 10-3.



**Figure 10-13. Probability distribution of the yearly fire damage (m<sup>3</sup>/year).**

<b>Probability distribution of yearly fire damage (m<sup>3</sup>)</b>	
5 <sup>th</sup> percentile	9
Mean value	53
95 <sup>th</sup> Percentile	125
Maximum value	314
Std deviation	38
Variance	1443

**Table 10-3. Probability distribution of yearly fire damage.**

The analysis results goes to show that, with the assumptions made during the analysis, the likely average yearly fire damage will not exceed 125 m<sup>3</sup>, which is the 95% percentile of the results. A regression analysis was also performed, which showed that the distribution used to approximate the fire frequency is responsible for 97.6% of the variability in the result. The results from this analysis are also shown in Appendix A6.

With this information as a basis the decision makers can go on to decide whether or not this is an acceptable level of risk or if measures needs to be taken to reduce or eliminate certain risks.

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## **10.6 Performance of the fire risk analysis methodology**

The methodology proposed in Section 9.5 has been used on a case study and the performance of the individual parts of the methodology will be discussed in this section. The bullet points shown below are outtakes from Section 9.5.

### **10.6.1 Hazard identification**

- Perform a checklist analysis to expose apparent and significant ignition sources.
- If any significant ignition sources are discovered these should be attended to before commencing on the later stages of risk analysis. This is to ensure that the assumptions of this work are valid for the case in question.

In section 9.5 it was proposed that the hazard identification should be performed using a comparative method, namely a checklist. The hazard identification was not intended to find the ignition sources that needed further investigation, but rather to confirm that no significant ignition sources are present and thus the warehouse in question can be regarded to fall within the limitations of this work, i.e. absence of significant ignition sources. It was found that the use of a checklist is viable but that the checklist proposed could be further enhanced. It was also found that it does require that the end-user needs to have some knowledge in fire dynamics and an intimate knowledge of the compound.

### **10.6.2 Frequency analysis**

- The frequency of a fire is determined using the aforementioned correlation between fire occurrence and the type of occupancy and building size
- All available plant specific data is collected and the generic data derived from the previous step is updated using Bayesian updating

The use of an estimate of fire frequency based on compartment size was used and proved successful. It is however the authors' opinion that the generic estimation of fire frequency overestimates the fire frequency in automated high bay warehouses and that better results could be produced using a larger statistical basis. In this particular case it is believed that a lot more site specific data could be produced and that the results could be refined to better represent the reality. This data was however not readily available to the authors and thus, this has not been further investigated.

The generic ignition frequency was represented by a continuous probability distribution, initially chosen for its simplicity when being updated. The distribution chosen, a gamma distribution is however continuous which proved to complicate the sensitivity analysis.

### **10.6.3 Consequence analysis**

- Determine what phenomena that threatens stock in case of a fire, i.e. radiative heat, convective heat and combustion species (smoke)
- Determine what levels of exposure to these phenomena the stock may end up being subjected to in the event of a fire with a certain degree of involvement from fire protective measures
- Establish the threshold damage limits for these exposures
- Calculate the consequences of the end scenarios by combining the threshold damage limits with the predicted exposure levels

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In accordance with the proposed methodology, the consequence of a fire was analysed using field modeling coupled with threshold damage limits. This approach, although potentially having great accuracy, was negatively affected by the lack of applicable data regarding threshold damage limits for palletized stock.

#### **10.6.4 Risk calculations**

- Construct an event tree the first event being “fire started”, the branches of the event tree should represent different degrees of function of fire protection, i.e. sprinklers activates and controls the fire. The probability distribution of an occurred fire can now be determined
- The expected yearly loss due to fire can now be calculated by multiplying the expected value of an occurred fire with the frequency of a fire. This should be expressed as a probability distribution

The risk analysis results were done using Monte Carlo modeling and illustrated using risk profiles and tabled data for the uncertainties affiliated with the modeling. The use of these methods was successful and it is the author’s opinion that these measures are adequate for their purpose.





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## 11 Results

A framework for fire risk analysis in automated high bay warehouses has been presented. The theory behind the framework is based on the International Electrotechnical Commission's framework for risk analysis: *Risk Analysis in Technological Systems*. It was intended to determine fire risk in high bay warehouses, where fires are highly infrequent but associated with large economical consequences.

As presumption made before the project was that a viable framework could be produced if a suitable methodology could be found for the following sections of the IEC framework:

- *Hazard identification*
- *Frequency analysis*
- *Consequence analysis*
- *Risk calculations*

Another presumption was that the methodologies should be chosen for their respective ability to suit a number of criteria set up at the beginning of the project. The criteria were that the methodologies chosen should be:

- Simple. The tools used shall, to a reasonable extent, be simplistic and demand little training from the end user.
- Expandable. The tools shall be able to provide means of incorporating new information and constant updates.
- Quantitative. As the analysis is intended to be used in an investment process it is decided that the results of the analysis should be quantitative. Tools will be chosen to comply with this requirement

A range of risk analysis methodologies and tools were studied in order to gain understanding of their applicability in respect to the criteria listed above.

In order to understand the activities and fire risk characteristics connected to automated high bay warehouses a site visit was carried out at the IKEA distribution centre in Älmhult. A number of characteristics was found and it was decided that these would need to be given due respect when constructing the fire risk analysis framework. Thus, the characteristics was forged into the framework, and set the basis to which different risk analysis methodologies and tools were compared to. The high bay warehouse characteristics found was:

- Well defined system- In terms of technical complicity, the automated high bay warehouse is regarded as rather simple. The pallet loader and stacker cranes are, at least mechanically, easy to understand and describe. Fuel load and configuration is known.
- Low fire frequency- There is little doubt that fires in automated high bay warehouses are rare. This stems from the fact that the automatization itself eliminates many of the common fire starters, such as human negligence.
- Unknown Fire Behaviour- The fire dynamics in high bay areas are hard to determine.
- Unknown Damage Criteria- The resistance of pallet goods towards smoke, heat and water is unknown.

With these characteristics and the presumed criteria in mind the framework was set up. Although the methodology proposed does link back to the IEC model, it was thought to be more intuitive to not

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blindly follow the IEC's set up of a risk analysis program. Hence the following methodology was proposed:

1. Perform a checklist analysis to expose apparent and significant ignition sources.
2. If any significant ignition sources are discovered these should be attended to before commencing on the later stages of risk analysis. This is to ensure that the assumptions of this work are valid for the case in question.
3. The frequency of a fire is determined using the aforementioned correlation between fire occurrence and the type of occupancy and building size
4. All available plant specific data is collected and the generic data derived from the previous step is updated using Bayesian updating
5. Construct an event tree the first event being "fire started", the branches of the event tree should represent different degrees of function of fire protection, i.e. sprinklers activates and controls the fire.
6. Determine what phenomena that threatens stock in case of a fire, i.e. radiative heat, convective heat and combustion species (smoke)
7. Determine what levels of exposure to these phenomena the stock may end up being subjected to in the event of a fire with a certain degree of involvement from fire protective measures
8. Establish the threshold damage limits for these exposures
9. Calculate the consequences of the end scenarios by combining the threshold damage limits with the predicted exposure levels
10. The probability distribution of an occurred fire can now be determined
11. The expected yearly loss due to fire can now be calculated by multiplying the expected value of an occurred fire with the frequency of a fire. This should be expressed as a probability distribution

To confirm that this methodology is connected to the IEC model a setup showing the used methodologies is shown below.

- Hazard identification method: Checklists of ignition sources
- Frequency analysis method: Ignition frequency based on building size
- Consequence analysis: damage criteria and Computational modelling
- Risk calculations: Event tree analysis and Monte Carlo analysis.

A case study was performed at Ikea's high bay warehouse in Älmhult, Sweden. The framework proved capable to estimate the fire risk present in the facility but a number of possible improvements were found. The conclusions regarding the frameworks abilities included:

- In all, the proposed framework was a success as it proved to be reasonably easy to work with and did provide a quantitative estimate of the fire risk in the studied automated high bay warehouse.
- The use of a checklist to identify ignition sources is viable. It was however found that it does require that the end-user needs to have some knowledge in fire dynamics and an intimate knowledge of the compound.
- The use of an estimate of fire frequency based on compartment size proved successful. It is however the authors' opinion that the generic estimation of fire frequency overestimates the fire frequency in automated high bay warehouses and that more accurate results could be produced using a larger statistical basis.

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- The use of a continuous probability distribution, initially chosen for its simplicity when being updated, proved to complicate the sensitivity analysis to such an extent that it lost its purpose.
  - Regarding the consequence analysis; the accuracy provided by the CFD modelling was somewhat diminished by the lack of good, reliable Threshold Damage Limits for palletised goods.
  - The use of event trees, Monte Carlo analysis and illustrating risk with risk profiles was successful and deemed sufficient for the purposes of the study.



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## 12 Discussion

The framework presented in this report was based on the International Electrotechnical Commissions generic risk analysis model: Risk Analysis of Technological Systems. This was one of the presumptions to this report and the authors do not envisage that the results would have been greatly dissimilar, should another generic risk analysis framework been utilised as a basis for the project.

The plan of this project- to construct a new framework by choosing methods based on a number of prerequisites- was shown to be successful.

In the process of constructing this framework it became apparent that the intricacies of the system under examination meant that the IEC model no longer could be used as straightforward as first intended. The reason for this is mainly the lack of risk sources. For instance, it is worth nothing that general risk management processes suggest that the hazard identification should be used to determine the significant risk sources, when in this case it is assumed that there are no significant risk sources. This beckons a use of the hazard identification that is somewhat unorthodox as it is only used to ensure that there are, in fact, no significant risk sources and the future risk analysis can, or rather must, be based on strategies other than the commonplace tactics of reducing identified risk sources. Unfortunately, this separation of the hazard identification from the later parts of the risk analysis process brings with it other more unwanted effects, such as an inability to reward ignition source reducing investments. The hazard identification tool does not allow for quantitative estimates of any found ignition sources' respective ability to induce a fire. This method was chosen mainly because it was not envisaged that any highly significant ignition sources would be found in an environment so freed from recorded fires. The fire occurrence could then be assumed to be of a more random nature and this was also reflected in the choice of fire frequency analysis tool.

The fire frequency analysis tool chosen, a model based on fire frequencies being based on floor area, was considered to be a successful choice in the risk analysis, as it does engulf all types of fire ignition sources. As the frequency analysis tool is set up around the presumption that a fire already has started, it is however burdened with a serious downside as it can not handle risk reducing measures aimed to affect fire occurrence. This is however alleviated in this case of fire risk analysis in automated high bay warehouses, as it is not likely that ignition sources would be the first priority when attempting to lower fire risk in such a facility. This model is still applicable for assessing risk reducing measures aimed to reduce the consequences of a fire scenario given that a fire occurs.

The statistical model used to estimate the fire frequency also proved difficult to work with as it is a continuous distribution, and hence complicates the sensitivity analysis with its massive differences in estimates of the fire frequency. It should be attempted to alleviate this by truncating the distribution but this was not possible in the simulations performed during this work.

The consequence analysis model proposed (simulations using the field model FDS), proved to deliver satisfying results, facilitating an accurate assessment of the exposure levels that the palletized goods, in the case of a fire, would be subjected to. The problems encountered were instead with finding threshold values to couple with the estimated exposure levels. A rough estimate of the threshold damage limit for temperature could be formed through studies of tabulated values of temperature exposure effects for various materials. But for smoke exposure no data or research seems to be available, not from within IKEA or elsewhere. Due to this fact considerable uncertainties can be assumed to accompany the calculated consequences. These uncertainties, however, are not dependent on the methods proposed in the framework presented in this thesis, but

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rather a product of the fact that no data regarding damage limits of materials subjected to smoke are available. In conclusion it is the authors' opinion that the proposed consequence analysis methodology is a good choice, with regard to facilitating an accurate assessment of exposure levels. Its superior accuracy (compared to that of zone models and hand calculations) can however, to a certain extent, be argued to be wasted due to the lack of accuracy in the threshold damage limits of smoke exposure.

After first producing a proposal for a framework for fire risk analysis in high bay warehouses, and later using the proposed framework in a case study to evaluate the fire risk exposure at the IKEA distribution centre in Älmhult, Sweden, two distinct proposals for areas where continued work would be of particular benefit has crystallized; First, the amount of plant specific data, that for this thesis was based on three years of operation of IKEA Daces, could be made something in the order of ten times larger just by an investigation of old reports of fire occurrence (or more so, the lack of such). Second, there is no useful data available regarding Threshold Damage Limits for exposure to airborne combustion products, in this thesis the TDL for such exposure had to be rather crudely approximated through the use of visibility as an indication for the smoke layer.

Apart from the two aforementioned factors there are of course a number of further factors contributing to the uncertainties in the analysis, one of which is the gamma distribution of the fire occurrence. The fire occurrence in this simulation varies from  $2 \cdot 10^{-9}$  to  $4 \cdot 10^{-6}$ , making the biggest calculated value 2000 times bigger than the smallest. A truncation of this variable would lower its influence over the result, but as little was known of the fire frequency no truncation was employed.

The general procedures of this thesis are, although firstly intended for automated high bay areas, such that it is believed that is not unlikely that they could be applied on other areas of fire risk analysis too. This would likely necessitate modifying some of the methods. For instance in smaller premises it would be more fitting to utilise zone models rather than field models to establish exposure levels, and in a similar manner it is assumed that for other premises or activities the fire frequency is not best determined by correlating it to floor area. In final, the authors believe and hope that the results presented herein could serve as inspiration for further work within the area of fire risk analysis, and more specific the economic consequences of such.

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## 13 Reference list

### Books and Reports

Barry, T.F. (2002), *Risk-Informed Performance-Based Fire Protection*, ISBN 1-882194-09-8, Tennessee Valley Publishing, Knoxville, USA

*Enterprise Risk Management-Integrated Framework*. (2004) Committee of Sponsoring Organizations of the Treadway Commission.

*Competitive steel buildings through natural fire safety concept – Part 4: Statistics*. (1999) Profil Arbed – Centre de Recherches

Davidsson, G., Lindgren, M., Mett, L. (1997), *Värdering av risk*, Department for Risk- and Environmental Studies, Swedish Rescue Services Agency, ISBN 91-88890-82-1, Karlstad, Sweden.

Davis, W., Notarianni, K., McGrattan, K.B. (1996), *Comparison of fire model predictions with experiments conducted in a hangar with a 15 meter ceiling*, Building and Fire Research Laboratory, NIST, Gaithersburg, MD 20899

DiNenno, P.M., et al., Editors, (1995), *SFPE Handbook of Fire Protection Engineering, 2<sup>nd</sup> Edition*, National Fire Protection Association, Quincy, MA

Drysdale, D. (2002), *An introduction to Fire Dynamics, 2<sup>nd</sup> ed.*, ISBN 0-8493-1300-7 Wiley-Interscience, New York, USA.

Frantzich, H. (1998), *Uncertainty and Risk Analysis in Fire Safety Engineering*, ISSN 1102-8246, Department of Fire Safety Engineering, Lund Institute of Technology, Lund, Sweden.

Friday, P. A.; Mowrer, F. W. (2001), *Comparison of FDS Model Predictions With FM/SNL Fire Test Data*, NIST GCR 01-810, National Department of Fire Protection Engineering University of Maryland

Ingason, H. (1996), *Experimental and Theoretical Study of Rack Storage Fires*, ISSN: 1102-8246, Department of Fire Safety Engineering, Lund Institute of Technology, Lund, Sweden.

Johansson, H. (2003), *Decision Analysis in Fire Safety Engineering-Analysing Investments in Fire Safety*, ISSN 1402-3504, Department of Fire Safety Engineering, Lund Institute of Technology, Lund, Sweden.

Karlsson, B., Quintiere, J. (2000), *Enclosure Fire Dynamics*, ISBN: 0-8493-1300-7, CRC Press LLC, Boca Raton, USA.

Mattson, B., (2000) *Riskhantering vid skydd mot olyckor – Problemlösning och beslutsfattande*, Swedish Rescue Services Agency, Karlstad, Sweden.

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*Methods for determining and processing probabilities, 2<sup>nd</sup> ed.* (1997), Report CPR-12E, ISBN 90 12 08543 8, Committee for the Prevention of Disasters, The Hague, The Netherlands.

McGrattan, K., Floyd, J. (2001), *Large Eddy Simulations of Fire Tests in a Large Hall*, Building and Fire Research Laboratory, NIST, Gaithersburg, MD 20899

McGrattan, K., (2005), *Fire Dynamics Simulator (Version 4) Technical Reference Guide*, NIST Special Publication 1018, Building and Fire Research Laboratory

Moussa, N.A., Toong, T.Y., Garris, C.A. (1976), *Mechanism of Smoldering Combustion of Cellulosic Materials*, 16th Symp. (Int.) on Combustion, 1976, pp. 1447-1457

Nystedt, F., (2000), *Risikanalysmetoder*, Department of Fire Safety Engineering, Lund Institute of Technology, Lund, Sweden.

*Risk analysis of technological systems* (1995), International Standard IEC 300-3-9, International Electrotechnical Commission, Geneva, Switzerland.

Sandberg, M. (2004), *Statistical Determination of Ignition Frequency*, ISSN: 1404-6342, Centre for Mathematical Sciences-Mathematical Statistics, Lund institute of Technology, Lund, Sweden.

Särdqvist, S., (1993), *Initial Fires: RHR, Smoke Production and CO Generation from Single Items and Room Fire Tests*, ISRN LUTVDG/TVBB—3070—SE, Department of Fire Safety Engineering, Lund University, Lund, Sweden.

### **Journal Articles and Conference Papers**

Kaplan, S., Garrick, B.J. (1981) *On The Quantitative Definition of Risk*, Risk Analysis, Vol. 1, No. 1, pp11-27.

Parks, L., Kushler, B., Serapiglia, M., McKenna, L., Budnick, E., Watts, J. (1998) *Fire Risk Assessment for Telecommunications Central Offices*, Fire Technology, Vol. 34, No.2

Ingason, H., De Ris, J. (1996) *Flame Heat Transfer in Storage Geometries* Submitted to Fire Safety Journal

Rahikainen J., Keski-Rahkonen O., Determination of Ignition Frequency of Fire in Different Premises in Finland, EUROFIRE 98, Brussels

Spetzler, C. S. (1977), *Establishing a corporate risk policy*, Readings in Decision Analysis, (eds.) Howard, R. A., Matheson, J. E., Stanford Research Institute, Stanford, USA.



## Appendices



## A1. FDS Input Files

### A1.1. FDS Data file for the sprinkler controlled case

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&GRID IBAR=50, JBAR=50, KBAR=230 /Fire

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&OBST XB=3.5, 99, 12.6, 14, 6, 7, RGB=0.3, 0.3, 0.3 / rack 5

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&OBST XB=3.5, 99, 18.6, 20, 4.5, 5.5, RGB=0.3, 0.3, 0.3 / rack 7  
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&OBST XB=3.5, 99, 18.6, 20, 7.5, 8.5, RGB=0.3, 0.3, 0.3 / rack 7  
&OBST XB=3.5, 99, 18.6, 20, 9, 10, RGB=0.3, 0.3, 0.3 / rack 7  
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&OBST XB=3.5, 99, 18.6, 20, 12, 13, RGB=0.3, 0.3, 0.3 / rack 7  
&OBST XB=3.5, 99, 18.6, 20, 13.5, 14.5, RGB=0.3, 0.3, 0.3 / rack 7  
&OBST XB=3.5, 99, 18.6, 20, 15, 16, RGB=0.3, 0.3, 0.3 / rack 7  
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&OBST XB=3.5, 99, 22.4, 23.8, 3, 4, RGB=0.3, 0.3, 0.3 / rack 8  
&OBST XB=3.5, 99, 22.4, 23.8, 4.5, 5.5, RGB=0.3, 0.3, 0.3 / rack 8  
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&OBST XB=3.5, 99, 22.4, 23.8, 12, 13, RGB=0.3, 0.3, 0.3 / rack 8  
&OBST XB=3.5, 99, 22.4, 23.8, 13.5, 14.5, RGB=0.3, 0.3, 0.3 / rack 8  
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&OBST XB=3.5, 99, 22.4, 23.8, 18, 19, RGB=0.3, 0.3, 0.3 / rack 8  
&OBST XB=3.5, 99, 22.4, 23.8, 19.5, 20.5, RGB=0.3, 0.3, 0.3 / rack 8

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&OBST XB=3.5, 99, 24.6, 26, 0, 1, RGB=0.3, 0.3, 0.3 / rack 9  
 &OBST XB=3.5, 99, 24.6, 26, 1.5, 2.5, RGB=0.3, 0.3, 0.3 / rack 9  
 &OBST XB=3.5, 99, 24.6, 26, 3, 4, RGB=0.3, 0.3, 0.3 / rack 9  
 &OBST XB=3.5, 99, 24.6, 26, 4.5, 5.5, RGB=0.3, 0.3, 0.3 / rack 9  
 &OBST XB=3.5, 99, 24.6, 26, 6, 7, RGB=0.3, 0.3, 0.3 / rack 9  
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 &OBST XB=3.5, 99, 24.6, 26, 9, 10, RGB=0.3, 0.3, 0.3 / rack 9  
 &OBST XB=3.5, 99, 24.6, 26, 10.5, 11.5, RGB=0.3, 0.3, 0.3 / rack 9  
 &OBST XB=3.5, 99, 24.6, 26, 12, 13, RGB=0.3, 0.3, 0.3 / rack 9  
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 &OBST XB=3.5, 99, 24.6, 26, 15, 16, RGB=0.3, 0.3, 0.3 / rack 9  
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 &OBST XB=3.5, 99, 24.6, 26, 19.5, 20.5, RGB=0.3, 0.3, 0.3 / rack 9

/Mellanrum mellan pallar (4 och 4)

&HOLE XB=8.2, 9.4, 0, 27, 0, 21 /  
 &HOLE XB=12.6, 13.8, 0, 27, 0, 21 /  
 &HOLE XB=17, 18.2, 0, 27, 0, 21 /  
 &HOLE XB=21.4, 22.6, 0, 27, 0, 21 /  
 &HOLE XB=25.8, 27, 0, 27, 0, 21 /  
 &HOLE XB=30.2, 31.4, 0, 27, 0, 21 /  
 &HOLE XB=34.6, 35.8, 0, 27, 0, 21 /  
 &HOLE XB=39, 40.2, 0, 27, 0, 21 /  
 &HOLE XB=43.4, 44.6, 0, 27, 0, 21 /  
 &HOLE XB=47.8, 49, 0, 27, 0, 21 /  
 &HOLE XB=52.2, 53.4, 0, 27, 0, 21 /  
 &HOLE XB=56.6, 57.8, 0, 27, 0, 21 /  
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 &HOLE XB=65.4, 66.6, 0, 27, 0, 21 /  
 &HOLE XB=69.8, 71, 0, 27, 0, 21 /  
 &HOLE XB=74.2, 75.4, 0, 27, 0, 21 /  
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 &HOLE XB=83.0000000000001, 84.2000000000001, 0, 27, 0, 21 /  
 &HOLE XB=87.4000000000001, 88.6000000000001, 0, 27, 0, 21 /  
 &HOLE XB=91.8000000000001, 93.0000000000001, 0, 27, 0, 21 /  
 &HOLE XB=96.2000000000001, 97.4000000000001, 0, 27, 0, 21 /

/Takluckor

/&HOLE XB= 17, 20, 11, 13, 23, 23.5 / vent 1  
 /&HOLE XB= 36, 39, 11, 13, 23, 23.5 / vent 2  
 /&HOLE XB= 54, 57, 11, 13, 23, 23.5 / vent 3  
 /&HOLE XB= 74, 77, 11, 13, 23, 23.5 / vent 4  
 /&HOLE XB= 90, 93, 11, 13, 23, 23.5 / vent 5

/Inlets

&HOLE XB= 90, 92, 27.5, 28, 1, 3 / leakages  
 &VENT XB= 90, 92, 28, 28, 1,3 ,SURF\_ID='OPEN' /leakages

/Boundary conditions

&VENT CB='XBAR0',SURF\_ID='MIRROR' /

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&VENT CB='YBAR',SURF_ID='MIRROR' /

&PL3D DTSAM=30 QUANTITIES='TEMPERATURE','U-VELOCITY','V-VELOCITY','W-
VELOCITY','visibility'/

&ISOF DTSAM=10 QUANTITY='visibility',VALUE(1)=10.,VALUE(2)=20./
&ISOF DTSAM=10 QUANTITY='TEMPERATURE',VALUE(1)=100./

&SLCF PBX=98.5, QUANTITY='TEMPERATURE' /
&SLCF PBX=98.5, QUANTITY='visibility' /
&SLCF PBX=98.5, QUANTITY='MIXTURE_FRACTION' /
&SLCF PBX=98.5, QUANTITY='ABSORPTION_COEFFICIENT' /
&SLCF PBX=60, QUANTITY='TEMPERATURE' /
&SLCF PBX=60, QUANTITY='visibility' /
&SLCF PBX=60, QUANTITY='MIXTURE_FRACTION' /
&SLCF PBX=60, QUANTITY='ABSORPTION_COEFFICIENT' /
&SLCF PBX=85, QUANTITY='TEMPERATURE' /
&SLCF PBX=85, QUANTITY='visibility' /
&SLCF PBX=85, QUANTITY='MIXTURE_FRACTION' /
&SLCF PBX=85, QUANTITY='ABSORPTION_COEFFICIENT' /
&SLCF PBY=12, QUANTITY='TEMPERATURE' /
&SLCF PBY=12, QUANTITY='visibility' /
&SLCF PBY=12, QUANTITY='MIXTURE_FRACTION' /
&SLCF PBY=12, QUANTITY='ABSORPTION_COEFFICIENT' /
&SLCF PBY=0.5, QUANTITY='TEMPERATURE' /
&SLCF PBY=0.5, QUANTITY='visibility' /
&SLCF PBY=0.5, QUANTITY='MIXTURE_FRACTION' /
&SLCF PBY=0.5, QUANTITY='ABSORPTION_COEFFICIENT' /

&THCP XB=96, 99, 0, 3, 0, 3, QUANTITY='HRR', LABEL='HRR ' / HRR

&THCP XB=17, 20, 11, 13, 23.5, 23.5, QUANTITY='MASS FLOW', LABEL='vent 1' / vent 1
&THCP XB=36, 39, 11, 13, 23.5, 23.5, QUANTITY='MASS FLOW', LABEL='vent 2' / vent 2
&THCP XB=54, 57, 11, 13, 23.5, 23.5, QUANTITY='MASS FLOW', LABEL='vent 3' / vent 3
&THCP XB=74, 77, 11, 13, 23.5, 23.5, QUANTITY='MASS FLOW', LABEL='vent 4' / vent 4
&THCP XB=90, 93, 11, 13, 23.5, 23.5, QUANTITY='MASS FLOW', LABEL='vent 5' / vent 5
&THCP XB=90, 92, 28, 28, 1, 3, QUANTITY='MASS FLOW', LABEL='inlet' / inlet

&THCP XB=17, 20, 11, 13, 23.5, 23.5, QUANTITY='DENSITY', LABEL='vent 1' / vent 1
&THCP XB=36, 39, 11, 13, 23.5, 23.5, QUANTITY='DENSITY', LABEL='vent 2' / vent 2
&THCP XB=54, 57, 11, 13, 23.5, 23.5, QUANTITY='DENSITY', LABEL='vent 3' / vent 3
&THCP XB=74, 77, 11, 13, 23.5, 23.5, QUANTITY='DENSITY', LABEL='vent 4' / vent 4
&THCP XB=90, 93, 11, 13, 23.5, 23.5, QUANTITY='DENSITY', LABEL='vent 5' / vent 5
&THCP XB=90, 92, 28, 28, 1, 3, QUANTITY='DENSITY', LABEL='inlet' / inlet

&THCP XYZ=98, 0.5, 0.2, QUANTITY='TEMPERATURE', LABEL='fire1' / fire1
&THCP XYZ=98, 0.5, 0.5, QUANTITY='TEMPERATURE', LABEL='fire2' / fire2
&THCP XYZ=98, 0.5, 1, QUANTITY='TEMPERATURE', LABEL='fire3' / fire3
&THCP XYZ=98, 0.5, 1.5, QUANTITY='TEMPERATURE', LABEL='fire4' / fire4
&THCP XYZ=98, 0.5, 2, QUANTITY='TEMPERATURE', LABEL='fire5' / fire5
&THCP XYZ=98, 1.5, 0.2, QUANTITY='TEMPERATURE', LABEL='fire6' / fire6
&THCP XYZ=98, 1.5, 0.5, QUANTITY='TEMPERATURE', LABEL='fire7' / fire7
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&THCP XYZ=98, 1.5, 1, QUANTITY='TEMPERATURE', LABEL='fire8' / fire8  
 &THCP XYZ=98, 1.5, 1.5, QUANTITY='TEMPERATURE', LABEL='fire9' / fire9  
 &THCP XYZ=98, 1.5, 2, QUANTITY='TEMPERATURE', LABEL='fire10' / fire10

### **A1.2. FDS Data file for the sprinkler extinguished case**

&HEAD CHID='ikea-sprkext-NV-grid',TITLE='IKEA DC Fire 4MW sprinkler extinguished no roof vents-  
grid verification' /

&PDIM XBAR0=94, XBAR=99, YBAR0=0, YBAR=5, ZBAR0=0, ZBAR=23 /Fire  
 &GRID IBAR=50, JBAR=50, KBAR=230 /Fire

&PDIM XBAR0=1, XBAR=94, YBAR0=0, YBAR=28, ZBAR0=0, ZBAR=23 /enclosure 1  
 &GRID IBAR=225, JBAR=72, KBAR=56 /enclosure 1  
 &PDIM XBAR0=94, XBAR=99, YBAR0=5, YBAR=28, ZBAR0=0, ZBAR=23 /enclosure 2  
 &GRID IBAR=12, JBAR=60, KBAR=56 /enclosure 2

&TIME TWFIN=900/

&MISC SURF\_DEFAULT='INERT',NFRAMES=300,  
 DATABASE='database4.data'  
 REACTION='POLYURETHANE' /

&SURF ID='FIRE1',HRRPUA=875, RAMP\_Q='SPRKEXT' /

&RAMP ID='SPRKEXT' , T=0.0 , F=0.0 /  
 &RAMP ID='SPRKEXT' , T=300. , F=0.19 /  
 &RAMP ID='SPRKEXT' , T=330. , F=1.0 /  
 &RAMP ID='SPRKEXT' , T=600. , F=0.0 /

&VENT XB= 97.8, 99, 0, 1.2, 0, 0, SURF\_ID='FIRE1' /

/Omslutning

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 &OBST XB=0, 0.5, 0, 27.5, 0, 23.5, RGB=0.5, 0.5, 0.5 / kortsida  
 &OBST XB=0, 99, 0, 28, 23, 23.5, RGB=0.5, 0.5, 0.5 / tak  
 &OBST XB=0, 99, 0, 28, 0, 0, RGB=0.5, 0.5, 0.5 / golv

/Ställagen

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 &OBST XB=3.5, 99, 0.6, 2, 10.5, 11.5, RGB=0.3, 0.3, 0.3 / rack 1  
 &OBST XB=3.5, 99, 0.6, 2, 12, 13, RGB=0.3, 0.3, 0.3 / rack 1  
 &OBST XB=3.5, 99, 0.6, 2, 13.5, 14.5, RGB=0.3, 0.3, 0.3 / rack 1  
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 &OBST XB=3.5, 99, 0.6, 2, 16.5, 17.5, RGB=0.3, 0.3, 0.3 / rack 1  
 &OBST XB=3.5, 99, 0.6, 2, 18, 19, RGB=0.3, 0.3, 0.3 / rack 1



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&OBST XB=3.5, 99, 0.6, 2, 19.5, 20.5, RGB=0.3, 0.3, 0.3 / rack 1

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&OBST XB=3.5, 99, 4.4, 5.8, 18, 19, RGB=0.3, 0.3, 0.3 / rack 2  
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&OBST XB=3.5, 99, 6.6, 8, 7.5, 8.5, RGB=0.3, 0.3, 0.3 / rack 3  
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&OBST XB=3.5, 99, 10.4, 11.8, 9, 10, RGB=0.3, 0.3, 0.3 / rack 4  
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&OBST XB=3.5, 99, 10.4, 11.8, 13.5, 14.5, RGB=0.3, 0.3, 0.3 / rack 4  
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&OBST XB=3.5, 99, 12.6, 14, 7.5, 8.5, RGB=0.3, 0.3, 0.3 / rack 5

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&OBST XB=3.5, 99, 12.6, 14, 9, 10, RGB=0.3, 0.3, 0.3 / rack 5  
&OBST XB=3.5, 99, 12.6, 14, 10.5, 11.5, RGB=0.3, 0.3, 0.3 / rack 5  
&OBST XB=3.5, 99, 12.6, 14, 12, 13, RGB=0.3, 0.3, 0.3 / rack 5  
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&OBST XB=3.5, 99, 12.6, 14, 15, 16, RGB=0.3, 0.3, 0.3 / rack 5  
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&OBST XB=3.5, 99, 12.6, 14, 19.5, 20.5, RGB=0.3, 0.3, 0.3 / rack 5

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&OBST XB=3.5, 99, 16.4, 17.8, 6, 7, RGB=0.3, 0.3, 0.3 / rack 6  
&OBST XB=3.5, 99, 16.4, 17.8, 7.5, 8.5, RGB=0.3, 0.3, 0.3 / rack 6  
&OBST XB=3.5, 99, 16.4, 17.8, 9, 10, RGB=0.3, 0.3, 0.3 / rack 6  
&OBST XB=3.5, 99, 16.4, 17.8, 10.5, 11.5, RGB=0.3, 0.3, 0.3 / rack 6  
&OBST XB=3.5, 99, 16.4, 17.8, 12, 13, RGB=0.3, 0.3, 0.3 / rack 6  
&OBST XB=3.5, 99, 16.4, 17.8, 13.5, 14.5, RGB=0.3, 0.3, 0.3 / rack 6  
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&OBST XB=3.5, 99, 16.4, 17.8, 18, 19, RGB=0.3, 0.3, 0.3 / rack 6  
&OBST XB=3.5, 99, 16.4, 17.8, 19.5, 20.5, RGB=0.3, 0.3, 0.3 / rack 6

&OBST XB=3.5, 99, 18.6, 20, 0, 1, RGB=0.3, 0.3, 0.3 / rack 7  
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&OBST XB=3.5, 99, 18.6, 20, 3, 4, RGB=0.3, 0.3, 0.3 / rack 7  
&OBST XB=3.5, 99, 18.6, 20, 4.5, 5.5, RGB=0.3, 0.3, 0.3 / rack 7  
&OBST XB=3.5, 99, 18.6, 20, 6, 7, RGB=0.3, 0.3, 0.3 / rack 7  
&OBST XB=3.5, 99, 18.6, 20, 7.5, 8.5, RGB=0.3, 0.3, 0.3 / rack 7  
&OBST XB=3.5, 99, 18.6, 20, 9, 10, RGB=0.3, 0.3, 0.3 / rack 7  
&OBST XB=3.5, 99, 18.6, 20, 10.5, 11.5, RGB=0.3, 0.3, 0.3 / rack 7  
&OBST XB=3.5, 99, 18.6, 20, 12, 13, RGB=0.3, 0.3, 0.3 / rack 7  
&OBST XB=3.5, 99, 18.6, 20, 13.5, 14.5, RGB=0.3, 0.3, 0.3 / rack 7  
&OBST XB=3.5, 99, 18.6, 20, 15, 16, RGB=0.3, 0.3, 0.3 / rack 7  
&OBST XB=3.5, 99, 18.6, 20, 16.5, 17.5, RGB=0.3, 0.3, 0.3 / rack 7  
&OBST XB=3.5, 99, 18.6, 20, 18, 19, RGB=0.3, 0.3, 0.3 / rack 7  
&OBST XB=3.5, 99, 18.6, 20, 19.5, 20.5, RGB=0.3, 0.3, 0.3 / rack 7

&OBST XB=3.5, 99, 22.4, 23.8, 0, 1, RGB=0.3, 0.3, 0.3 / rack 8  
&OBST XB=3.5, 99, 22.4, 23.8, 1.5, 2.5, RGB=0.3, 0.3, 0.3 / rack 8  
&OBST XB=3.5, 99, 22.4, 23.8, 3, 4, RGB=0.3, 0.3, 0.3 / rack 8  
&OBST XB=3.5, 99, 22.4, 23.8, 4.5, 5.5, RGB=0.3, 0.3, 0.3 / rack 8  
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&OBST XB=3.5, 99, 22.4, 23.8, 9, 10, RGB=0.3, 0.3, 0.3 / rack 8  
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&OBST XB=3.5, 99, 22.4, 23.8, 16.5, 17.5, RGB=0.3, 0.3, 0.3 / rack 8  
&OBST XB=3.5, 99, 22.4, 23.8, 18, 19, RGB=0.3, 0.3, 0.3 / rack 8  
&OBST XB=3.5, 99, 22.4, 23.8, 19.5, 20.5, RGB=0.3, 0.3, 0.3 / rack 8

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&OBST XB=3.5, 99, 24.6, 26, 0, 1, RGB=0.3, 0.3, 0.3 / rack 9  
&OBST XB=3.5, 99, 24.6, 26, 1.5, 2.5, RGB=0.3, 0.3, 0.3 / rack 9  
&OBST XB=3.5, 99, 24.6, 26, 3, 4, RGB=0.3, 0.3, 0.3 / rack 9  
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&OBST XB=3.5, 99, 24.6, 26, 6, 7, RGB=0.3, 0.3, 0.3 / rack 9  
&OBST XB=3.5, 99, 24.6, 26, 7.5, 8.5, RGB=0.3, 0.3, 0.3 / rack 9  
&OBST XB=3.5, 99, 24.6, 26, 9, 10, RGB=0.3, 0.3, 0.3 / rack 9  
&OBST XB=3.5, 99, 24.6, 26, 10.5, 11.5, RGB=0.3, 0.3, 0.3 / rack 9  
&OBST XB=3.5, 99, 24.6, 26, 12, 13, RGB=0.3, 0.3, 0.3 / rack 9  
&OBST XB=3.5, 99, 24.6, 26, 13.5, 14.5, RGB=0.3, 0.3, 0.3 / rack 9  
&OBST XB=3.5, 99, 24.6, 26, 15, 16, RGB=0.3, 0.3, 0.3 / rack 9  
&OBST XB=3.5, 99, 24.6, 26, 16.5, 17.5, RGB=0.3, 0.3, 0.3 / rack 9  
&OBST XB=3.5, 99, 24.6, 26, 18, 19, RGB=0.3, 0.3, 0.3 / rack 9  
&OBST XB=3.5, 99, 24.6, 26, 19.5, 20.5, RGB=0.3, 0.3, 0.3 / rack 9

/Mellanrum mellan pallar (4 och 4)

&HOLE XB=8.2, 9.4, 0, 27, 0, 21 /  
&HOLE XB=12.6, 13.8, 0, 27, 0, 21 /  
&HOLE XB=17, 18.2, 0, 27, 0, 21 /  
&HOLE XB=21.4, 22.6, 0, 27, 0, 21 /  
&HOLE XB=25.8, 27, 0, 27, 0, 21 /  
&HOLE XB=30.2, 31.4, 0, 27, 0, 21 /  
&HOLE XB=34.6, 35.8, 0, 27, 0, 21 /  
&HOLE XB=39, 40.2, 0, 27, 0, 21 /  
&HOLE XB=43.4, 44.6, 0, 27, 0, 21 /  
&HOLE XB=47.8, 49, 0, 27, 0, 21 /  
&HOLE XB=52.2, 53.4, 0, 27, 0, 21 /  
&HOLE XB=56.6, 57.8, 0, 27, 0, 21 /  
&HOLE XB=61, 62.2, 0, 27, 0, 21 /  
&HOLE XB=65.4, 66.6, 0, 27, 0, 21 /  
&HOLE XB=69.8, 71, 0, 27, 0, 21 /  
&HOLE XB=74.2, 75.4, 0, 27, 0, 21 /  
&HOLE XB=78.6000000000001, 79.8000000000001, 0, 27, 0, 21 /  
&HOLE XB=83.0000000000001, 84.2000000000001, 0, 27, 0, 21 /  
&HOLE XB=87.4000000000001, 88.6000000000001, 0, 27, 0, 21 /  
&HOLE XB=91.8000000000001, 93.0000000000001, 0, 27, 0, 21 /  
&HOLE XB=96.2000000000001, 97.4000000000001, 0, 27, 0, 21 /

/Takluckor

/&HOLE XB= 17, 20, 11, 13, 23, 23.5 / vent 1  
/&HOLE XB= 36, 39, 11, 13, 23, 23.5 / vent 2  
/&HOLE XB= 54, 57, 11, 13, 23, 23.5 / vent 3  
/&HOLE XB= 74, 77, 11, 13, 23, 23.5 / vent 4  
/&HOLE XB= 90, 93, 11, 13, 23, 23.5 / vent 5

/Inlets

&HOLE XB= 90, 92, 27.5, 28, 1, 3 / leakages  
&VENT XB= 90, 92, 28, 28, 1,3 ,SURF\_ID='OPEN' /leakages

/Boundary conditions

---

&VENT CB='XBAR0',SURF\_ID='MIRROR' /

&VENT CB='YBAR',SURF\_ID='MIRROR' /

&PL3D DTSAM=30 QUANTITIES='TEMPERATURE','U-VELOCITY','V-VELOCITY','W-VELOCITY','visibility' /

&ISOF DTSAM=10 QUANTITY='visibility',VALUE(1)=10.,VALUE(2)=20./

&ISOF DTSAM=10 QUANTITY='TEMPERATURE',VALUE(1)=100./

&SLCF PBX=98.5, QUANTITY='TEMPERATURE' /

&SLCF PBX=98.5, QUANTITY='visibility' /

&SLCF PBX=98.5, QUANTITY='MIXTURE\_FRACTION' /

&SLCF PBX=98.5, QUANTITY='ABSORPTION\_COEFFICIENT' /

&SLCF PBX=60, QUANTITY='TEMPERATURE' /

&SLCF PBX=60, QUANTITY='visibility' /

&SLCF PBX=60, QUANTITY='MIXTURE\_FRACTION' /

&SLCF PBX=60, QUANTITY='ABSORPTION\_COEFFICIENT' /

&SLCF PBX=85, QUANTITY='TEMPERATURE' /

&SLCF PBX=85, QUANTITY='visibility' /

&SLCF PBX=85, QUANTITY='MIXTURE\_FRACTION' /

&SLCF PBX=85, QUANTITY='ABSORPTION\_COEFFICIENT' /

&SLCF PBY=12, QUANTITY='TEMPERATURE' /

&SLCF PBY=12, QUANTITY='visibility' /

&SLCF PBY=12, QUANTITY='MIXTURE\_FRACTION' /

&SLCF PBY=12, QUANTITY='ABSORPTION\_COEFFICIENT' /

&SLCF PBY=0.5, QUANTITY='TEMPERATURE' /

&SLCF PBY=0.5, QUANTITY='visibility' /

&SLCF PBY=0.5, QUANTITY='MIXTURE\_FRACTION' /

&SLCF PBY=0.5, QUANTITY='ABSORPTION\_COEFFICIENT' /

&THCP XB=96, 99, 0, 3, 0, 3, QUANTITY='HRR', LABEL='HRR ' / HRR

&THCP XB=17, 20, 11, 13, 23.5, 23.5, QUANTITY='MASS FLOW', LABEL='vent 1' / vent 1

&THCP XB=36, 39, 11, 13, 23.5, 23.5, QUANTITY='MASS FLOW', LABEL='vent 2' / vent 2

&THCP XB=54, 57, 11, 13, 23.5, 23.5, QUANTITY='MASS FLOW', LABEL='vent 3' / vent 3

&THCP XB=74, 77, 11, 13, 23.5, 23.5, QUANTITY='MASS FLOW', LABEL='vent 4' / vent 4

&THCP XB=90, 93, 11, 13, 23.5, 23.5, QUANTITY='MASS FLOW', LABEL='vent 5' / vent 5

&THCP XB=90, 92, 28, 28, 1, 3, QUANTITY='MASS FLOW', LABEL='inlet' / inlet

&THCP XB=17, 20, 11, 13, 23.5, 23.5, QUANTITY='DENSITY', LABEL='vent 1' / vent 1

&THCP XB=36, 39, 11, 13, 23.5, 23.5, QUANTITY='DENSITY', LABEL='vent 2' / vent 2

&THCP XB=54, 57, 11, 13, 23.5, 23.5, QUANTITY='DENSITY', LABEL='vent 3' / vent 3

&THCP XB=74, 77, 11, 13, 23.5, 23.5, QUANTITY='DENSITY', LABEL='vent 4' / vent 4

&THCP XB=90, 93, 11, 13, 23.5, 23.5, QUANTITY='DENSITY', LABEL='vent 5' / vent 5

&THCP XB=90, 92, 28, 28, 1, 3, QUANTITY='DENSITY', LABEL='inlet' / inlet

&THCP XYZ=98, 0.5, 0.2, QUANTITY='TEMPERATURE', LABEL='fire1' / fire1

&THCP XYZ=98, 0.5, 0.5, QUANTITY='TEMPERATURE', LABEL='fire2' / fire2

&THCP XYZ=98, 0.5, 1, QUANTITY='TEMPERATURE', LABEL='fire3' / fire3

&THCP XYZ=98, 0.5, 1.5, QUANTITY='TEMPERATURE', LABEL='fire4' / fire4

&THCP XYZ=98, 0.5, 2, QUANTITY='TEMPERATURE', LABEL='fire5' / fire5

&THCP XYZ=98, 1.5, 0.2, QUANTITY='TEMPERATURE', LABEL='fire6' / fire6  
&THCP XYZ=98, 1.5, 0.5, QUANTITY='TEMPERATURE', LABEL='fire7' / fire7  
&THCP XYZ=98, 1.5, 1, QUANTITY='TEMPERATURE', LABEL='fire8' / fire8  
&THCP XYZ=98, 1.5, 1.5, QUANTITY='TEMPERATURE', LABEL='fire9' / fire9  
&THCP XYZ=98, 1.5, 2, QUANTITY='TEMPERATURE', LABEL='fire10' / fire10



## A2. Initial Fires

### A2.1. Outtake of Initial Fires, pallet systems Y3.3/59-60

#### Pallet systems

PET bottles in crates (Swedish standard bottle) on wood pallet  
 Bottles: Polyethene, volume 1.5 l, empty  
 Crates: Plastic, each containing 6 bottles  
 Crate size: 0.27 x 0.30 x 0.40 m<sup>3</sup>  
 Pallet load: 36 crates in a 3 x 4 x 3 array  
 Pallet size: 0.81 x 1.21 x 1.34 m<sup>3</sup>  
 Total mass: 83.2 kg

59:  
Single pallet

60:  
Double row steel rack  
Fuel array: 8 pallets in a 2 x 2 x 2 array  
Water sprinkler started at 330 s

#### Test procedure:

Method: Freeburning in industry calorimeter  
 Ignition source: Fibre insulating board, 75 mm in diameter and 75 mm long, soaked in with 120 ml of heptane and wrapped in a polyethylene bag, placed in the center of the flue space at the bottom of the pallet loads of the lowest tier.

#### Also available:

Required Delivered Density for the sprinkler system

#### Note:

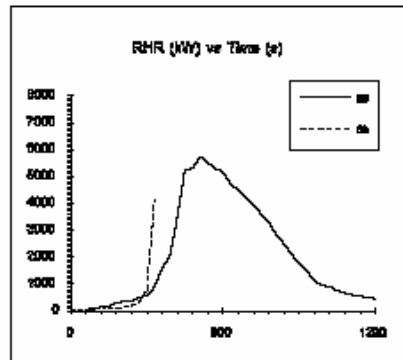
In sample 60, water sprinkler were used. The rate of heat release is given until the sprinkler was activated.

A test was performed with bottles filled with sparkling water that showed to be almost self-extinguishing. No data available.

#### Reference:

Arvidson, M. & Persson, H  
 Sprinkling av PETflaskor  
 Brand & Rådning, 3/93, pp 26-27, ISSN 0283-1155  
 Kattneholm, Sweden 1993

Y3.3/59-60

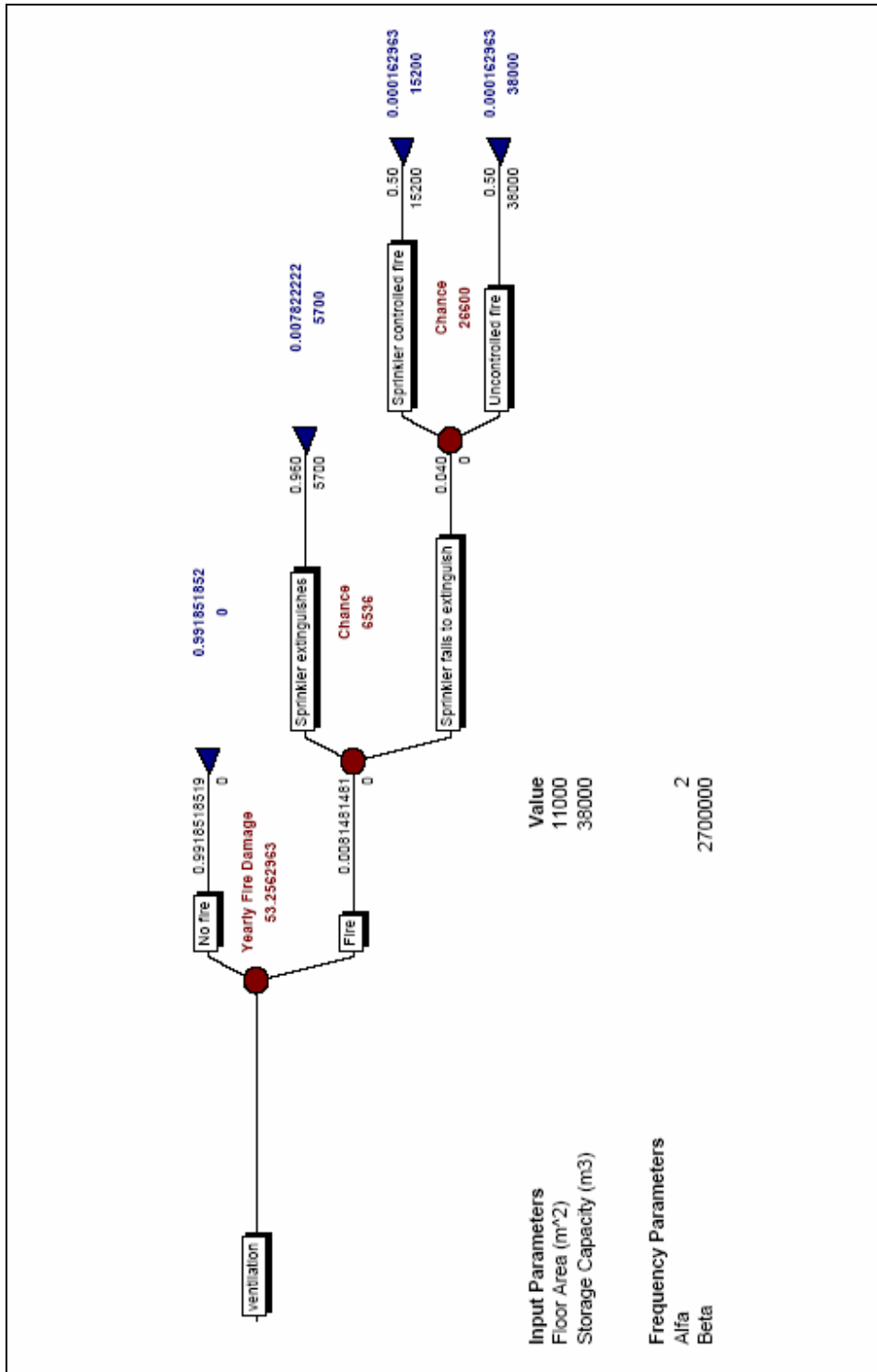






## A3. Event Tree Analysis

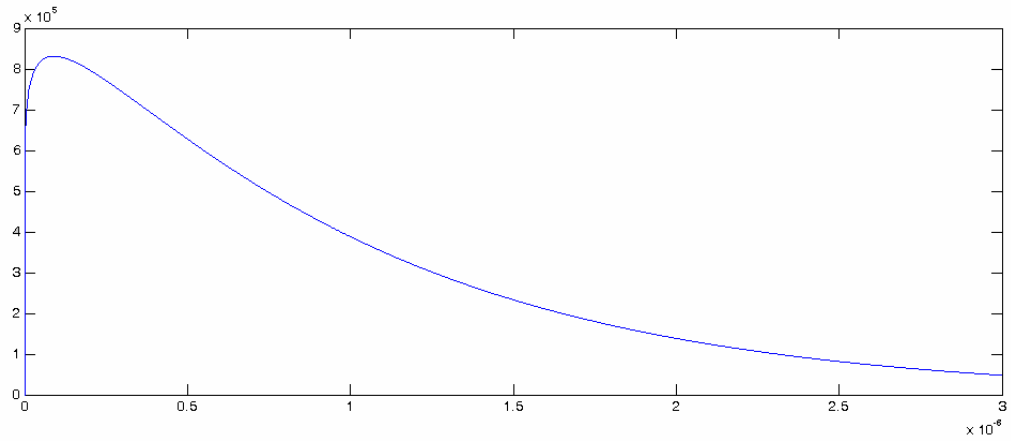
### A3.1. Event Tree Description



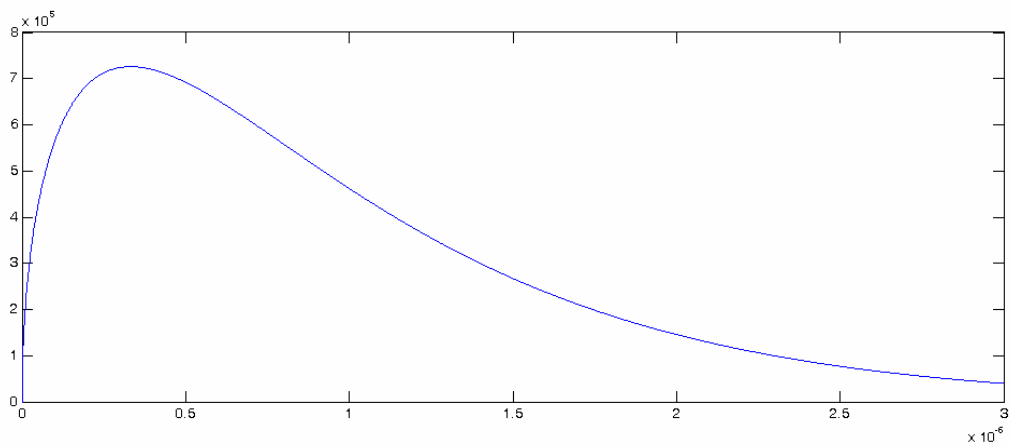


## A4. Gamma Probability Distribution Profiles

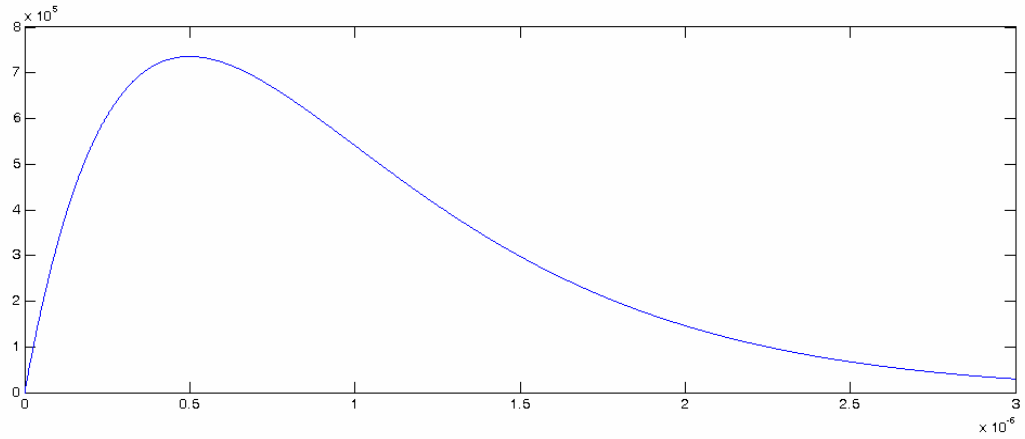
### A4.1. *Alfa=1.1; Beta=1 100 000*



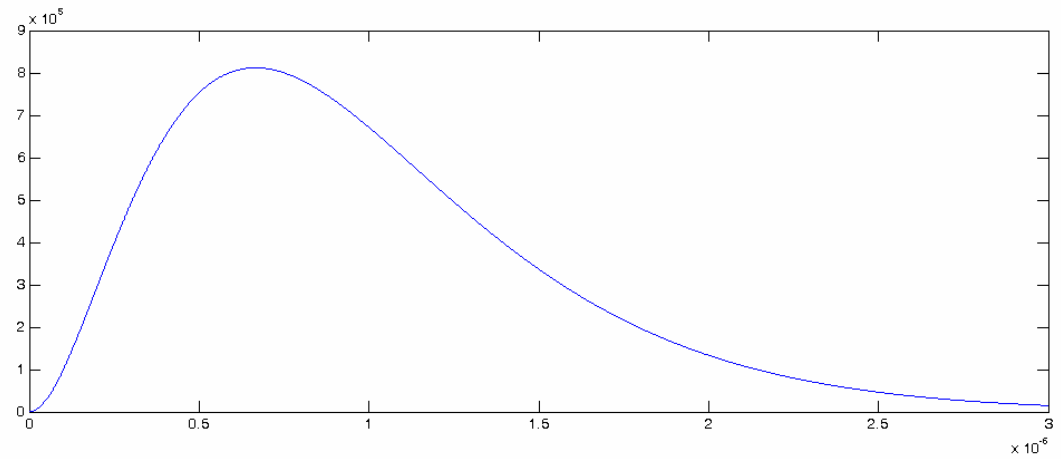
### A4.2. *Alfa=1.5; Beta=1 500 000*

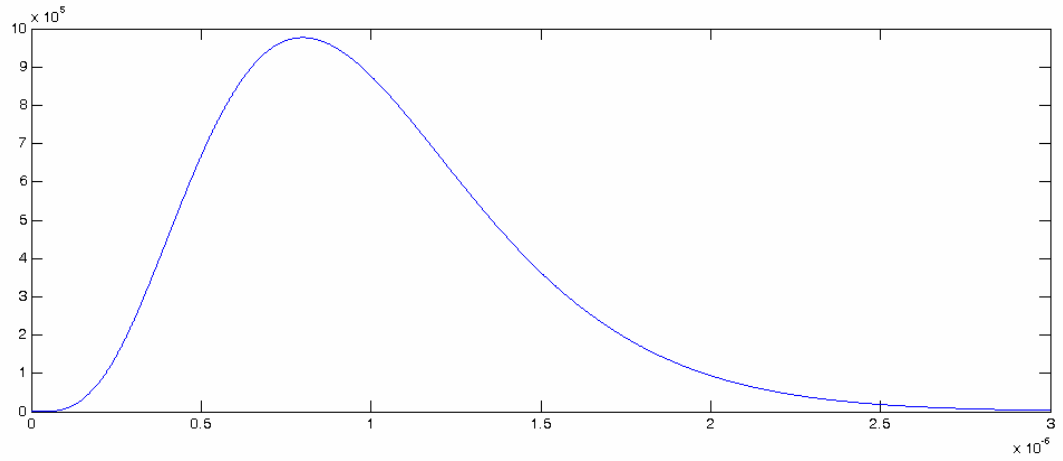


**A4.3. Alfa=2; Beta=2 000 000**



**A4.4. Alfa=3; Beta=3 000 000**



**A4.5. Alfa=5; Beta=5 000 000**



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## A5. Ikea Automated High Bay List

Received from IKEA4.ULIM

05-12-01 10.09

Hello Marcus, hello Frey,

We didn't have a single fire incident in the time period Sep 1, 03 - Oct 30, 05. In this period we had the following high bays in IKEA DCs. I have added information about the size in m3. This information is more useful since it takes the different heights into account. I do not have the exact m2. However, you will have the m2 and m3 from Älmhult and possibly could convert the below mentioned high bays into m2, by using the same relation.

Werne: 17.000 m3  
17.000 m3  
Salzgitter: 50.000 m3  
Erfurth: 42.000 m3  
50.000 m3  
Älmhult 57.500 m3 (for 2 silos)  
Torsvik: 53.400 m3  
44.000 m3  
Peterborough: 57.000 m3  
Doncaster: 56.000 m3  
Winterslag: 46.000 m3  
65.000 m3  
Ousterhoud: 55.000 m3  
Metz: 60.000 m3  
42.000 m3  
Valls: 47.000 m3  
Jarosty: 60.000 m3  
Itingen: 17.000 m3  
Wels: 40.000 m3  
23.000 m3  
Montreal: 37.000 m3  
New Jersey: 49.000 m3  
Perryville: 55.000 m3  
Tejon: 50.000 m3  
50.000 m3  
Shah Alam: 62.000 m3

I hope this gives you a good basis for you calculation even if I didn't list the building years. The incident data is absolutely reliable, I have checked it twice. There is some older date available, too, with the same result: not a single fire case.

However, I would prefer concentrating on the time period mentioned above. Then we can relate directly to the listed high bays.

I will start a trainee as store manager and my last day at Risk Management is December 16. I have updated NN on your project. He will support you for the future.

Thanks for the good co-operation and good luck for the project.

Best regards,





## A6. Risk Calculations

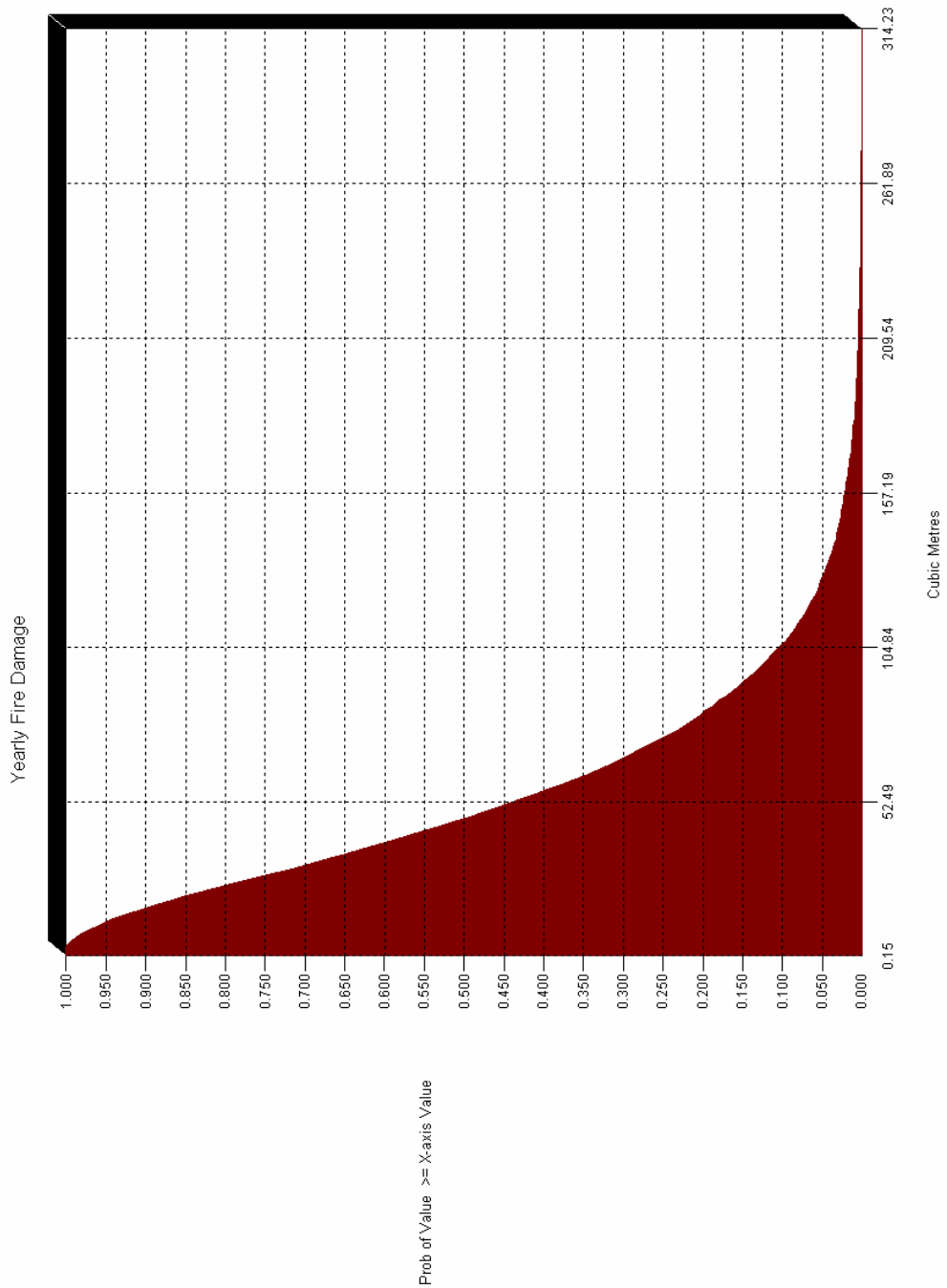
### A6.1. Monte Carlo Simulation Results

Name	Output	Triang(0.94,0.96,0.98)	Triang(0.1,0.15,0.2)
Description	B4	C5	C6
Cell			
Minimum =	<b>0.1461035</b>	0.9402704	0.1002859
Maximum =	<b>314.2336</b>	0.9799674	0.1999012
Mean =	<b>53.12989</b>	0.9600022	0.1500559
Std Deviation =	<b>37.9886</b>	8.14E-03	2.04E-02
Variance =	<b>1443.134</b>	6.63E-05	4.17E-04
Skewness =	<b>1.432672</b>	1.09E-02	1.18E-04
Kurtosis =	<b>6.045478</b>	2.41247	2.402638
Errors Calculated =	<b>0</b>	0	0
Mode =	<b>24.84027</b>	0.9439096	0.1239014
5% Perc =	<b>9.175817</b>	0.94645	0.115657
10% Perc =	<b>13.99344</b>	0.9490705	0.1225102
15% Perc =	<b>18.13401</b>	0.9510902	0.1273353
20% Perc =	<b>21.76568</b>	0.9526739	0.1318502
25% Perc =	<b>25.03629</b>	0.9541574	0.1355021
30% Perc =	<b>28.53547</b>	0.9554712	0.1387218
35% Perc =	<b>32.21149</b>	0.9566454	0.1417565
40% Perc =	<b>36.19737</b>	0.9578871	0.14464
45% Perc =	<b>40.25071</b>	0.9589982	0.147453
50% Perc =	<b>44.38585</b>	0.9599885	0.149961
55% Perc =	<b>49.02617</b>	0.9610287	0.1526214
60% Perc =	<b>53.8939</b>	0.9621342	0.1553961
65% Perc =	<b>58.90081</b>	0.9632547	0.1583377
70% Perc =	<b>65.10937</b>	0.9645104	0.1614093
75% Perc =	<b>71.99998</b>	0.9657746	0.1648856
80% Perc =	<b>80.18103</b>	0.9673178	0.1684081
85% Perc =	<b>90.31199</b>	0.9689702	0.1726063
90% Perc =	<b>103.5078</b>	0.9710009	0.1777742
95% Perc =	<b>125.9146</b>	0.9737174	0.1842908
Filter Minimum =			
Filter Maximum =			
Type (1 or 2) =			
# Values Filtered =	<b>0</b>	0	0

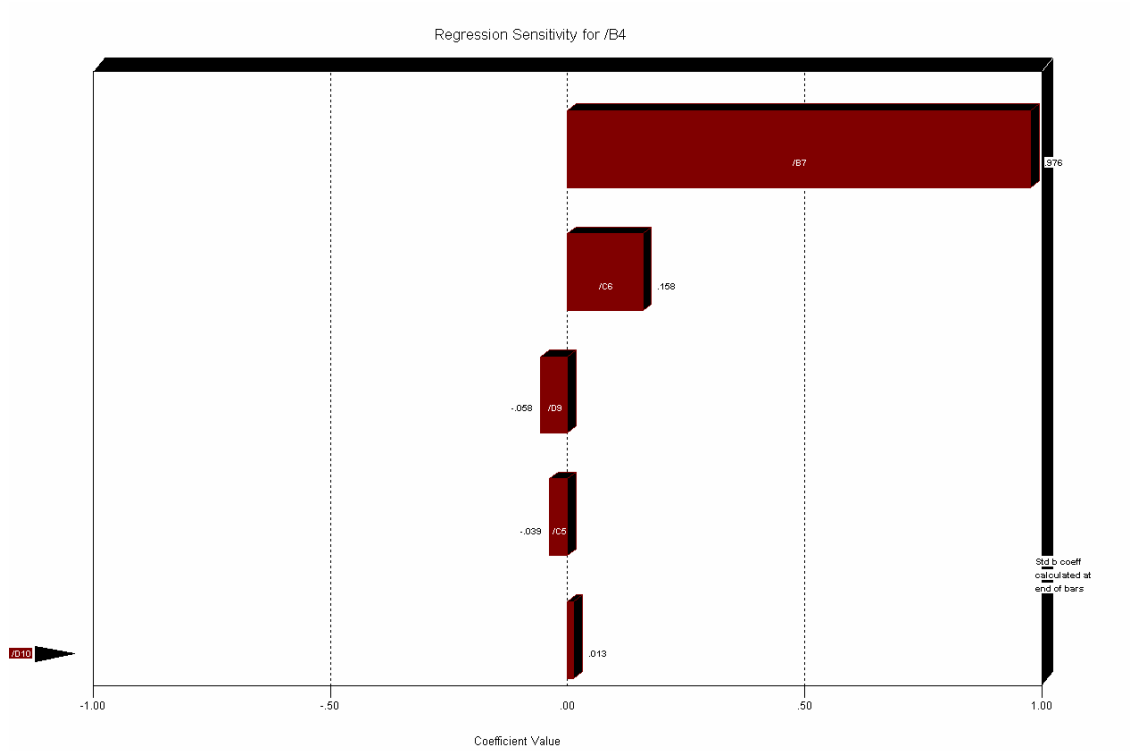
**A6.2. Monte Carlo Simulation Results (Continued)**

Name	Erlang(B21,1/B22)	Uniform(0,1)	Triang(0.2,0.4,0.6)
Description	B7	D9	D10
Cell			
Minimum =	2.17E-09	2.67E-05	0.2005123
Maximum =	4.06E-06	0.9998838	0.5966597
Mean =	7.38E-07	0.4968745	0.4000341
Std Deviation =	5.15E-07	0.2871012	8.17E-02
Variance =	2.65E-13	0.0824271	6.68E-03
Skewness =	1.326103	4.10E-03	-0.0163554
Kurtosis =	5.463251	1.805176	2.412246
Errors Calculated =	0	0	0
Mode =	3.90E-07	0.7495838	0.3390676
5% Perc =	1.30E-07	5.06E-02	0.2621838
10% Perc =	1.98E-07	0.1003215	0.2882333
15% Perc =	2.55E-07	0.1512191	0.3092351
20% Perc =	3.05E-07	0.2002141	0.3272483
25% Perc =	3.55E-07	0.2473968	0.3416987
30% Perc =	4.06E-07	0.2960614	0.3552097
35% Perc =	4.57E-07	0.346662	0.3676161
40% Perc =	5.10E-07	0.3969378	0.3795993
45% Perc =	5.67E-07	0.4469661	0.3904087
50% Perc =	6.26E-07	0.4979086	0.4005832
55% Perc =	6.87E-07	0.5490943	0.4107538
60% Perc =	7.52E-07	0.5969079	0.4215544
65% Perc =	8.22E-07	0.6457867	0.4333833
70% Perc =	9.02E-07	0.6924171	0.4451637
75% Perc =	9.97E-07	0.7443022	0.4573143
80% Perc =	1.11E-06	0.795387	0.4730276
85% Perc =	1.24E-06	0.842463	0.4902135
90% Perc =	1.43E-06	0.8932899	0.5102392
95% Perc =	1.75E-06	0.9459016	0.53663
Filter Minimum =			
Filter Maximum =			
Type (1 or 2) =			
# Values Filtered =	0	0	0

**A6.3. Estimated Yearly fire damage**



### A6.4. Regression analysis



In order from above: B7,C6, D9, C5 and D10

