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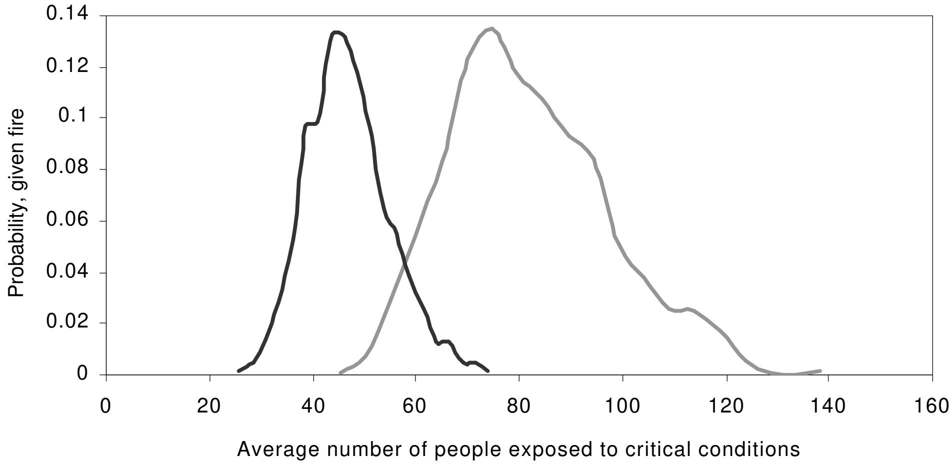
Fire Safety Design of a Large Shopping Mall Using Extended Quantitative Risk Analysis



The Swedish Case Study for the 3rd International Conference on Performance-Based Codes and Fire Safety Design Methods, Lund, June 15th-17th, 2000

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SYCON ENERGIKONSULT AB
Risk & Fire

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1 Introduction

1.1 Background

The biannual "International Conference on Performance-Based Codes and Fire Safety Design Method" held in Lund, Sweden between the 15th and the 17th of June 2000 is the third conference on the subject. During the conference a selection of case studies will be presented. This report constitutes the conference contribution from the department of Risk & Fire at Sycon.

1.2 Objectives and applications

The objective of this report is to undertake a performance-based fire safety design for a shopping mall and to compare the resulting fire safety recommendations with those specified by existing prescriptive requirements. The quantitative comparison between solutions shall include life cycle cost and risk for human life.

An underlying objective with this case study is to try a new method for quantitative analyses where uncertainty analysis is a natural part of the process. This report focuses therefore at the method of quantitative analysis rather than on finding a unique design solution.

1.3 General limitations

The methodology has been focused on the analysis method and not on a specific design solution.

2 Method for Analysis

2.1 The definition of risk

In the CPQRA (1989) risk is defined as a measure of economic loss or human injury in terms of both the likelihood and the magnitude of the loss or injury. The IEC (1995) defines risk as a combination of the frequency, or probability, of occurrence and the consequence of a specified hazardous event. Note that the concept of risk always has two elements: the frequency or probability with which a hazardous event is expected to occur and the consequences of the hazardous event.

Two quantitative risk analysis (QRA) methods can be used to quantify the risk to occupants in for example, a building in which a fire has broken out. The extended QRA considers the inherent uncertainty in the variables explicitly. The standard QRA does not consider uncertainties in the variables and must therefore be accompanied by a sensitivity analysis or an uncertainty analysis (Frantzich, 1998). Both methods provide risk measures such as individual risk and FN curves.

2.2 Risk measures

Risk can be expressed as individual risk or as societal risk. These are the two most frequently used risk measures. Individual risk measures consider the risk to an individual, who may be at any point in the effect zones of incidents, while societal risk measures consider the risk to populations that are in the effect zones of incidents. In this report the effect zone is the analysed shopping mall.

The CPQRA (1989) gives the following illustrative example of the difference between individual and societal risk.

An office building is located near a chemical plant and contains 400 people during office hours and one guard at other times. If the likelihood of an incident causing a fatality at the office building is constant throughout the day, each individual in that building is subject to a certain individual risk. This individual risk is independent of the number of people present – it is the same for each of the 400 people in the building during office hours and for the single guard at other times. However, the societal risk is significantly higher during office hours, when 400 people are affected, than at other times when a single person is affected.

In this report both the individual risk measure and societal risk measure will be used to express the risk. When performing a risk analysis for the case of fire, today's methods do not provide sufficient information to calculate the number of fatalities. Instead, a measure of the number of people who will be exposed to critical, i.e. untenable, conditions will be used. The definition of critical conditions will be discussed in section 4.8.

2.3 Fire safety design processes

In their Draft for Development No. 240 (BSI, 1997), the British Standards Institution outlines a framework for an engineering approach to fire safety in buildings. This framework can be used to show that regulatory or insurance requirements can be satisfied. The basic fire safety design process consists of four main stages.

- A qualitative design review
- A quantitative analysis
- Assessment against criteria
- Reporting and presentation

This basic process is illustrated in Figure 2.1. The BSI (1997) gives guidance in the application of scientific and engineering principles to the protection of people and property against fire. The framework presents an excellent approach on how to handle fire safety design issues. Because of its completeness, this framework is highly recommended as a fire engineering guideline.

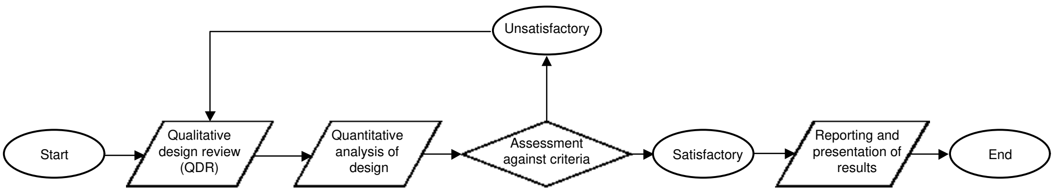

Figure 2.1 The basic fire safety design process

Fire is a transient process, which affects a building and its occupants in different ways at different stages. The process of fire safety design is complicated by the fact that time is one of the key design parameters. As stated by the BSI (1997), it is important when carrying out a quantitative analysis, to recognise the role of time and the interaction of parameters within a consistent time framework. When assessing the number of people exposed to critical conditions a comparison between two time lines is made. One of these time lines represents the course of the fire, in terms of its size, rate of burning and smoke or toxic gas concentration. The other time line represents the response to the fire by the occupants. These time lines and the specific expressions used are presented in Figure 2.2. Note that the expressions differ between different countries.

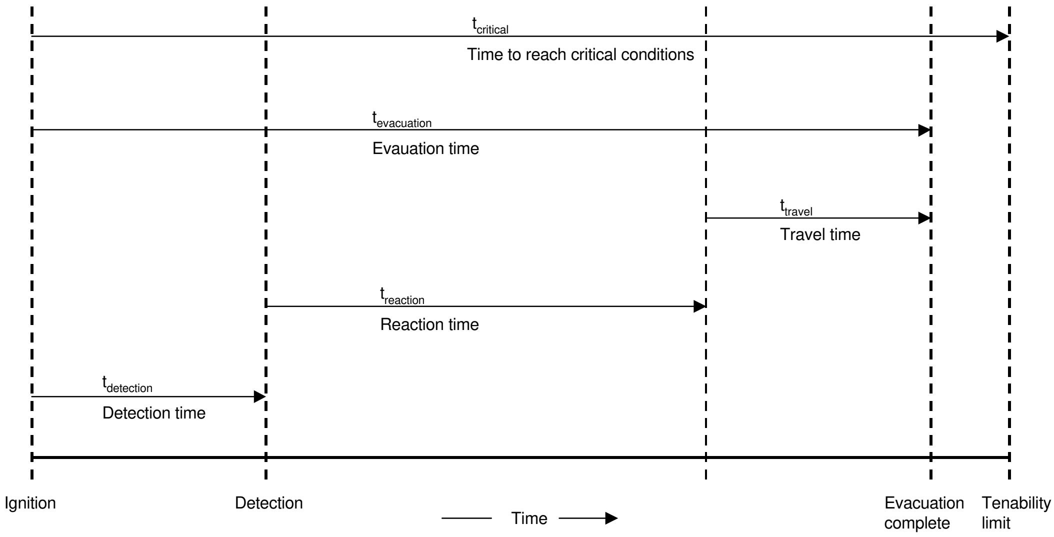

Figure 2.2 Example of a time line comparison of fire development and evacuation

The fire safety design process begins with a qualitative design review (QDR). During the QDR the scope and the objectives of the fire safety design are defined, performance criteria established and one or more potential design solutions proposed. Key information to be used as input in the quantitative analysis is also gathered.

During the quantitative analysis the fundamentals of fire science are applied. The analysis is performed using six sub-systems, which reflect the impact of a fire on people and property at different stages in its development. The sub-systems cover fire growth and development, the spread of combustion products and fire from the source, fire detection and the activation of fire safety systems, fire service intervention and the evacuation of occupants. In performing the quantitative analysis it is necessary to assess the outcome in relation to the established performance criteria. When the report is assembled a minimum amount of information is required. This information consists of, for example, the findings of the QDR, assumptions, references, engineering judgements, methodologies employed, sensitivity analyses and comparison of the results with the performance criteria.

2.4 Extended Quantitative Risk Analysis

The method of analysis chosen for the fire safety engineering process is an extended quantitative risk analysis. Frantzich (1998) explains the methodology of such an analysis in detail. Only a very brief discussion will be included in this report.

When performing a standard QRA the result can be a single FN-curve or some average societal risk measure. But there is no information regarding the certainty of the FN-curve. To be able to make a rationale decision one also need to know about the probable uncertainty of this result. The extended QRA, which combines traditional uncertainty analysis and standard QRA is an available method for this purpose. By defining the parameters describing the standard QRA system with information regarding the uncertainty of the involved parameters the extended QRA can be obtained by running a Monte Carlo simulation of the standard QRA system. The result can be presented as a confidence band in a FN-diagram showing for example the range where the FN-curve with 90 % certainty will be.

2.5 Model description

Following the procedure outlined below performs the analysis.

- Event tree construction
- Collecting relevant model input, i.e. both statistics and information on the probability of the events involved
- Calculating probabilities
- Calculating consequences
- Evaluate risk

In the following sections each step of the procedure will be explained in more detail.

2.5.1 Event tree construction

The computer program PRECISION TREE (Decision tools, 1997) is used to construct the event tree. The event tree describes what can happen when a fire starts in the building and is constructed by putting together different events leading to a specific consequence. Each event is then assigned a specific probability or distribution of probabilities. Examples of events are the effectiveness and reliability of the active systems in the building, the behaviour of the personnel, do they extinguish the fire and do they lead the customers to the evacuation exits etc. The event tree construction is described in Figure 2.3.

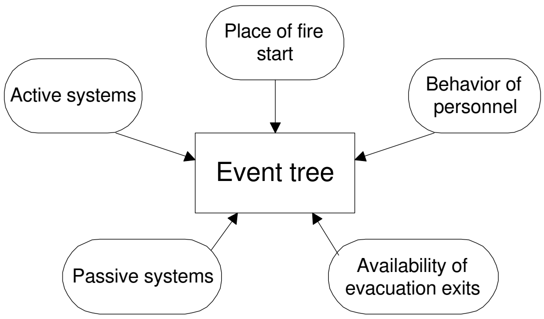

Figure 2.3 A simple description of event tree construction

2.5.2 Collecting relevant model input

When the event tree has been created there is a need to gather information about the events included in the tree. This information either relates to the probability of the event or to the effect that the event has to the scenario.

Literature review and, where no data is available, engineering judgement gather event probabilities. It is also possible to use fault tree technique to estimate the probability of the particular event. An approach that is very common in nuclear power plant PSA-studies (Jacobsson,). When assessing what effect the event has to a scenario literature and experience on human behavior in fire, etc. is used.

2.5.3 Calculating probabilities

For each scenario the probability of occurrence is calculated. For each scenario this is done 1000 times, each time with different input values chosen randomly from the input distributions. The calculations are done using Monte Carlo simulations within the computer program @RISK (Decision tools, 1997).

2.5.4 Calculating consequences

The consequence for each scenario is defined as the number of people not able to evacuate before critical conditions arise. This number is calculated for each scenario by calculating and comparing time to critical conditions, $t_{critical}$, with the total evacuation time. The total time to evacuation consists of time to detection, $t_{detection}$, time to reaction, $t_{reaction}$, and finally the travel time, t_{travel}. The marginal between critical conditions and evacuation time can then be described as:

$$M = t_{critical} - t_{detection} - t_{reaction} - t_{evacuation}$$

How the different times are calculated is described in section 5.2. The number of people not being able to evacuate, N, is then calculated consistent with the following conditions:

If $M > 0$	then $N = 0$
If $M < -t_{evac}$	then $N = N_0$
If $M > -t_{evac}$	then $N = -M \cdot f \cdot N_0 \cdot B$

Where

N_0	= number of people evacuating through the critical exit
F	= flow through opening [people/s]
B	= width of opening [m]

This means that:

- When the marginal is positive the consequence is zero.
- When critical conditions occur before the evacuation has started the consequence is equal to the total number of people in the building at the time of the fire
- When critical conditions occur during the evacuation process the consequence is calculated as a function of the marginal, the number of people evacuating through the critical evacuation exit, and also the width and flow through this exit.

The consequence for each scenario is calculated 1000 times with different input values chosen from the input distributions. This is done using the computer program @RISK (Decision tools, 1997).

2.5.5 Evaluate risk

The individual risk, the average risk and the societal risk is evaluated in the final step of the analysis. There are no difficulties in comparing the individual risk as well as the average risk as they represents point values. But for the societal risk the situation is more complicated.

The outcome of the simulations, described in section 2.5.3 and 2.5.4, is one thousand probability-consequence pairs for each of the scenarios in the event tree. This enormous amount of information must be structured in a logical way. By using MATLAB (MATLAB, 1996) routines written by Frantzich (1998) it is possible to evaluate the thousand risk profiles rationally. The routines calculates the risk profiles of the desired percentile and illustrates them graphically (see Figure 2.4). The evaluation of societal risk is then done comparing the profiles representing the 90th percentile for each alternative.

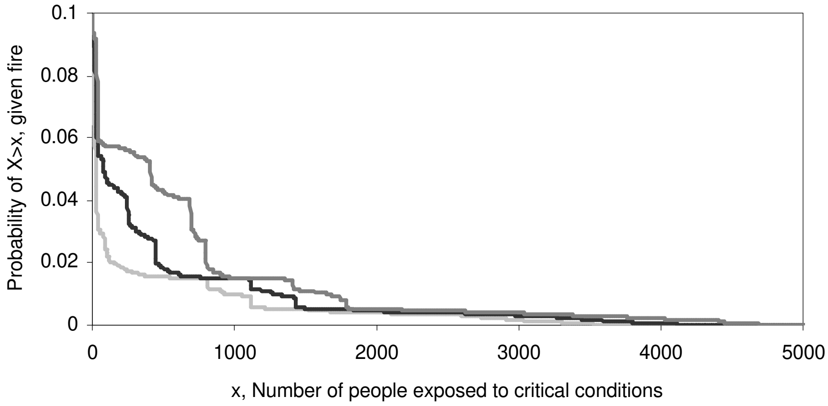

Figure 2.4 *Example of risk profiles produced by the MATLAB routines. Instead of showing all thousand risk profiles, the routines make it possible to draw profiles that represents a certain percentile. The figure shows the risk profiles of the 10th, 50th and 90th percentiles.*

3 Swedish Building Regulations

The Swedish Board of Housing, Building and Planning is responsible for the built environment and the management of natural resources, physical planning, building and housing. The board is responsible for public requirements on buildings. These primarily concern health, safety, accessibility and energy management. Section 5 in the Swedish Building Regulations (BBR, 1999) deals with "Safety in Case of Fire". The regulations consist of mandatory provisions and general recommendations. Text recited from the regulations is written in *italic* and the figures between brackets refer to the relevant section in the regulations.

3.1 General regulations

3.1.1 General (5:1)

Since the regulations of 1994, are performance based, it is always possible for the fire engineer to design the building in other ways than those mentioned in the regulations. Naturally, an extensive analysis is needed to ensure that the safety level is sufficiently high.

Alternative design (5:11)
Fire protection may be designed in a way different from that specified in this section (Section 5) if it is shown by special investigation that the total fire protection of the building will not be inferior to that which would be obtained if all the requirements specified in the section had been complied with.

Documentation (5:12)
Fire protection documentation shall be drawn up. This shall set out the conditions on which fire protection is to be based and the design of the fire protection.

Design by calculations (5:13)
If design of fire protection is based on calculations, calculations shall be based on a carefully selected design fire and shall be performed in accordance with a model, which gives a satisfactory description of the problem at hand. The calculation model selected shall be stated.

Control of design for escape (5:14)
In buildings where there is a high risk of injury to persons, design for escape by calculation may be used only if the correctness of the calculation can be demonstrated by design control.

Sometimes it is necessary to design a building with demands higher than those specified in the regulations. Higher demands on building safety could be required if the fire service is unable to launch an attack within normal time limits. A survey performed at the fire services in the cities of Gävle, Ljusdal and Enköping, Sweden, shows that the emergency force is not able to intervene within the first fifteen to twenty minutes (Sirenen, 1998). When studying fire scenarios at a hospital, this time could be considered too long and may therefore motivate higher demands on safety than those given in the regulations.

3.1.2 Fire resistance classes and other conditions (5:2)

A building shall be constructed to Class Br1, Br2 or Br3. Classification shall take account of factors, which affect the possibility of escape and the risk of injury to persons in the event that the building collapses. The possibility of escape shall be assessed with regard to the height and volume of the building and the activities carried out in the building, and to the number of persons who are expected to be in the building at the same time, and the likelihood that these persons can reach safety on their own.

A building in which a fire would entail a high risk of injury to persons shall be constructed to Class Br1. In such buildings the most stringent requirements are imposed on e.g. finishes and on load bearing and separating structures. A building in which a fire may entail a moderate risk of injury to persons shall be constructed to Class Br2. Other buildings may be constructed to Class Br3.

> ***Buildings, general recommendation (5:21)***
> *Buildings of three or more storeys should be constructed to Class Br1.*

Depending on their function, structural elements are assigned to the following classes:

- R (load bearing capacity),
- E (integrity), and
- I (insulation).

Digits specifying the time requirement, 15, 30, 45, 60, 90, 120, 180, 240 or 360 minutes follow the designations R, RE, E, EI and REI.

The following class designations are also used:

- Non-combustible and combustible material and material of low ignitability (combustible material which complies with certain requirements)
- Ignition retardant cladding
- Surface finish of Class I, II or III (of which Class I complies with the most stringent requirements)

3.1.3 Escape in the event of fire (5:3)

General (5:31)
Buildings shall be designed so that satisfactory escape can be effected in the event of fire. Special attention shall be paid to the risk that persons may be injured by the fall of elements of structure or due to falls and congestion and to the risk that persons may be trapped in recesses or dead ends.

Buildings in which people are present not just temporarily should be designed with at least two independent escape routes. If the building consists of more than one storey, there should be at least one escape route from each floor. The distance of travel inside a fire compartment to the nearest escape route shall not be so great that the compartment cannot be evacuated before critical conditions arise. Along an escape route, the travel distance to the nearest stairway leading to another storey, or to an exit leading into the street or similar space, shall not be so great that escape cannot take place rapidly.

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

Design conditions, general recommendations (5:36)
In evaluating critical conditions, consideration should be given to visibility, thermal radiation, temperature, noxious gases and the combination of temperature and noxious gases. The following limiting values can normally be applied:
Visibility: level of fire gases not lower than 1.6+(0.1xH) m, where H is the height of the room.
Thermal: a short-term radiation intensity of maximum 10 kW/m^2, radiation: a maximum radiant energy of 60 kJ/m^2 in addition to the energy from a radiation of 1 kW/m^2.
Temperature: air temperature not higher than 80°C.

3.1.4 Protection against the spread of fire inside a fire compartment (5:5)

Surface finishes and claddings in escape routes shall be of materials that provide negligible contribution to the spread of fire.

In buildings of *Class Br1* or *Br2*, ceilings and internal walls in escape routes shall have surface finish of Class I. The surface finish shall be applied to non-combustible material or to ignition-retardant cladding. In buildings of *Class Br1* the floor covering in escape routes shall be constructed of a material with a moderate propensity to spread fire and evolve fire gases.

3.1.5 Protection against the spread of fire and fire gases between fire compartments (5:6)

Buildings shall be divided into fire compartments separated by structural elements, which impede the spread of fire and fire gases. Each fire compartment shall comprise a room - or associated groups of rooms - in which the activity has no immediate connection with other activities in the building. A fire compartment shall not - with the exception of dwellings, stairways, lift wells and open garages - comprise spaces on more than two storeys unless an automatic water sprinkler installation or other arrangements protect the spaces.

Each fire compartment shall be separated from other spaces in the building by structural elements (including service penetrations, necessary supports, connections and similar structures) constructed to not less than the fire resistance class commensurate with the requirements in the regulations.

Elements of structure shall be constructed to not less than the fire resistance class set out in Table 5.1 below. The fire resistance class in Column 1 ($f \leq 200$) may be applied to dwellings and offices, schools, hotels, garages for cars, shops for the sale of food, residents' store rooms and comparable fire compartments. This class may also be applied to fire load intensities higher than 200 MJ/m^2 for buildings protected by automatic water sprinkler installation.

Table 3.1 Fire resistance classes for different structural elements.

Element of structure	Fire resistance class for a fire load intensity, f (MJ/m^2)		
	$f \leq 200$	$f \leq 400$	$f > 400$
Elements of structure separating fire compartments in general, and a floor above a basement	EI 60	EI 120	EI 240

Doors, shutters and access panels in elements of structure separating compartments shall normally be constructed to the same fire resistance class as that which applies for the element of structure in question.

3.1.6 Load-bearing capacity in the event of fire (5:8)

Load-bearing structures shall be designed and sized so that in the event of fire there is adequate structural safety with respect to material failure and instability in the form of local, overall and lateral torsional buckling and similar effects. Parts of the load-bearing structure, including supports, joints, connections and similar structures, shall be designed so that collapse does not occur - during a specified period of time in accordance with the fire resistance classes for elements of structure.

Since the collapse of load-bearing structures is most unlikely to occur within the time frame relevant for escape, the issue is not further discussed.

3.2 Merchandise related regulations (5:371 Places of assembly)

Escape routes from places of assembly shall be designed for the number of persons who are permitted to be present in the premises. Escape from places of assembly shall not take place through other places of assembly.

General recommendation (5:371)
If the number of persons is not known, the following assumptions may be made:

–If the premises shall be used by seated persons and the seats are placed in rows, the escape routes should be designed for 1.7 persons/m² net area. The gangways in the premises which are intended for the seated audience should be counted as part of this area, but the stage or dais should not.

-If the premises shall be used for both standing and seated persons, the escape routes should be designed for 2.5 persons/m² net area.

The escape routes in a department store or similar installation for retail trade should be designed for 0.5 persons/m² net area for those spaces to which the public has access.
In places of assembly or in the anterooms of these there should be signs stating the maximum number of persons who are permitted to be in the premises at the same time.

Places of assembly should have not less than three escape routes if they are intended for more than 600 persons, and not less than four if they are intended for more than 1000 persons.

Escape routes from places of assembly may be in communication with one another through intermediate foyers or similar spaces which are separated from the escape routes by construction to not less than Class EI-C30.

3.2.1 Escape alarm (5:3711)

Places of assembly shall be provided with an escape alarm which is activated automatically or from a staffed position when a fire is indicated.

General recommendation
The escape alarm should give those who are present in the place of assembly spoken information regarding appropriate action to be taken for escape.

3.2.2 Emerg1ency lighting etc. (5:3712)

Places of assembly shall be provided with general lighting and emergency lighting. Stairs in places of assembly shall be provided with emergency lighting. Emergency lighting shall be provided immediately before exits to the external air. It shall be possible for the lighting needed in places of assembly in the event of escape to be switched on from one position in the premises. External escape routes from places of assembly shall be lit and provided with emergency lighting along their entire length.

4 Qualitative design review

4.1 Review of architectural design

At the first stage in the QDR, the project is described by reference to schematic drawings, models etc. Special requirements that may be significant in the development of a fire safety strategy are highlighted.

All the relevant information about the building, its contents, is collected. Information on combustible materials, ventilation, and management regimes is provided. The number of people, their distribution and mobility is clarified.

4.2 Characterization of building, environment and occupants

4.2.1 Building

The building is a four-floor building and shall be used as a shopping mall containing parking areas, restaurants and stores. Floor number 2 and 3 are connected by atria and are included in the same fire cell. Toilets and evacuation stairs are made as separated fire cells. Floors number 1 and 4 are connected to the open air.

Table 4.1 Description of the activity in the building.

Floor	Contents
1	Parking area
2&3	Four large size shops, twenty medium size shops and twenty small size shops.
4	Parking area

Each floor is having an area of 21 400 m^2. The opening hours for the shopping mall is 10 a.m. to 7 p.m. every day. The main entrances to the building are the corner entrance at the second floor and the entrances from the parking areas.

The building is assumed to have enough separation distance to the closest neighboring building. According to the fire load in the building the structural elements separating fire compartment shall have a fire resistance class of EI120 if the building is without sprinkler system and EI60 if there is a sprinkler system installed.

The height of the roof is four (4) meters between 1st and 2nd floor and between 2nd and 3rd floor. Between 3rd and 4th floor the height is four (4) meters except in the atria were the height is 8 meters.

There is a fire safety airlock between the 1st and the 2nd floor and also between the atria and the 4th floor. In the atria and at the top of each staircase there is fire ventilation that can be opened automatically.

An automatic fire alarm system and an evacuation alarm system is installed. Fixed fire fighting appliances are placed with a maximum distance of 100 m from each other.

General lightning, lightning of guiding marks and emergency lightning lasting for at least 30 minutes, when without electrical current, is installed in the escape routes. General lightning and emergency lightning are also installed in the stores and walkways.

4.2.2 Occupants

Maximum number of occupants is 10400. This maximum number of occupants has been calculated using following assumptions:

- 0,5 persons per effective area are assumed to be evenly distributed within second and third floor
- In the shopping areas 40% of the total area are supposed to be effective
- In the walkways the effective area is assumed to be 100 % of the total area
- At each floor, 250 persons are supposed to be seated in different restaurant.

The customers of the shopping mall are assumed to be mainly families and couples. The occupants are supposed to have medium mobility and the state of wakefulness are probably good. Most occupants are assumed not to be familiar with the building. The responsiveness is predicted to be high in the case of recognized fire and medium if the fire can not immediately be recognized.

4.2.3 Enclosure and environment

The ambient noise level is supposed to be high during hours of commerce. A ventilation room is placed at the fourth floor. From the ventilation room air is distributed to the second and third floor. The ventilation system is an HVAC-system. Possible fire and smoke spread routes are the atria, the walkways and openings between the shops.

An average value of the fire load in shopping areas can be derived from the CIB W14 workshop report (CIB W14, 1983). According to this the average fire load per square meter floor area is 600 MJ/m^2 (BSI, 1997). In the Swedish regulation the fire resistant classes are connected to fire load per square meter enclosure area. A translation to fire load per square meter enclosure area gives a specific fire load of between 200 and 400 MJ/m^2 which means that fire resistance class EI120 is required if sprinkler system are not installed, see section 3.1.6.

In escape routes inner wall linings and ceiling linings are having fire resistance Class I, attached upon noncombustible material. The floor is noncombustible or in Class G. Outer wall linings is of Class II. Ceilings in other areas have a fire resistance of linings in Class I attached upon noncombustible material or ignition retarded material. Walls have linings at least in Class II. Assembly-halls are having all linings in Class I.

The width and number of escape routes are depending on fire safety alternative, see section 4.9.1 and 4.9.2.

4.2.4 Fire safety management

A plan for fire safety system test, inspection and maintenance requirements and routines shall be established according to BFS 1995:17. The influence on the fire safety objectives from new occupancies shall be evaluated. Education and training shall be performed regularly.

4.3 Fire safety objectives

According to the Case Study building specification the fire safety goals are:

1) *Safeguard occupants (permanent and transient) from injury due to fire until such time as they reach a safe place. (This may include self-relocating to a safe place within the building, self-evacuation to a safe place outside the building, evacuation with assistance from the fire service, or any combination of the above.)*

2) *Safeguard fire fighters while attacking the fire. (This includes protection from falling building parts, the minimisation of distance from safe place to the fire, measures for finding and fighting the fire.)*

3) *Limit flame spread and thermal damage to floor of origin, and limit non-thermal damage to fire floor and the one above.*

4) *Provide sufficient structural stability to meet goals 1, 2 and 3 above.*

4.4 Evacuation strategy

The evacuation strategy is to simultaneously evacuate all people from the building.

4.5 Acceptance criteria

The acceptance criteria for the alternative solution is that the risk should be equal or better compared to the prescriptive solution. This criteria is given in the building regulations (see section 3.1.1) making it possible for the engineer to optimize the design towards societal and client demands.

4.6 Fire hazards

Potential ignition sources in the building are:

- Arson
- Oven, kitchen range
- Electric-light fittings
- Electronic devices (TV, stereos etc)
- Smoking/cigarettes
- Electrical installations

Combustible contents are:

- Textiles
- Wood
- Liquors
- Plastics

Flammable liquids

4.7 Fire scenarios for analysis

When reviewing fire statistics from shopping-related incidents there are a number of possible fire scenarios to consider. The fire scenarios presented here are chosen because they represent some kind of worst credible case. The fire scenarios that are supposed to be the largest contributors to the risk are as follows:

- Fire in a large shop selling electronics caused by an electrical fault. The shop is located close to the atria at the third floor. Fire and smoke can spread into the atria and throughout the whole floor through the walkway and openings to respective shops. The smoke will probably make the escalators in the atria impossible to use quite fast.
- Fire in a provisions-dealer shop at the third floor at the opposite side of the electronic shop. The fire is caused by electric-light fittings and the combustible material ignited is plastic. Fire and smoke can spread out in the walkway and then continue spreading to the nearby shops. The fire can block a lot of escape routs.
- Arson fire using flammable liquids in a shop at the second floor selling beds and bedclothes. The shop is located very close to the main entrance and is supposed to block this exit.

4.8 Critical conditions

The goal is to compare the risk to life why the definition of critical conditions stated in BBR can be used. Analysis shows (Frantzich, Olsson, 1999) that the critical parameter is the height of the smoke layer. According to the BBR the height of the smoke layer is causing critical conditions when it is placed equal or lower than 1,80 meter plus 10 % of the ceiling height.

4.9 Trial fire safety designs

As stated before two trial fire safety designs are being evaluated, one according to prescriptive regulation and the other according to performance-based regulation. Possible fire safety measures above the fire safety measures presented in section 4.9.1 is:

- Dividing the floors into fire cells with fire shutters that close when the fire alarm activates.
- Fire ventilation systems (shutters that open when the fire alarm activates)
- Sprinkler systems
- Escape alarm system with higher reliability than standard systems
- Smoke detectors and fire alarm with higher reliability than standard systems and maybe also higher sensitivity
- Smoke separating windows
- Reversing the direction of the escalators in case of fire
- Organizational measures

The chosen combination of fire safety measures chosen for the performance-based alternative is presented in section 4.9.2.

4.9.1 Prescriptive design alternative

The fire safety design of this alternative is based upon the prescriptive rules stated as advice in BBR (1999). The alternative is therefor generating a minimum safety level according to the building regulations. The following fire safety measures are included in the prescriptive fire safety design:

- An automatic fire alarm
- An automatic escape alarm with a spoken message connected to the fire alarm
- All fire resistance structures separating fire cells have a fire resistance rating of EI120
- A maximum distance to closest emergency exit of 30 meters

Where the last measure results in 29 evacuation exits/stairs according to the building plan presented in Appendix A, and width of each evacuation exit presented in Table 4.2.

Table 4.2 Width of evacuation exits/stairs.

Staircase number	Width
T1, T3, T13-T15, T24-T29	1,2
T5	2,0
T6-T12, T16-T23	2,5
T2	2,85
T4	3,25

4.9.2 Performance based design alternative

The performance-based solution contains the installation of a sprinkler system. The following fire safety measures are included in the alternative:

- An automatic fire alarm
- An automatic escape alarm with a spoken message connected to the fire alarm
- All fire resistance structures separating fire cells have a fire resistance rating of EI60
- A sprinkler system at the 2nd and 3rd floor of the building according to RUS 120:4 (RUS, 1993)
- An automatic reversing of the direction of the escalators going up connected to the fire alarm

The main deviation compared to the prescriptive alternative is that the numbers of evacuation exits are less (20 emergency stairs instead of 29), resulting in a longer distance to the closest exit. Placing of evacuation exits is presented in Appendix A. Width of each evacuation staircase is presented in

Table 4.3.

Table 4.3 Width of evacuation exits/stairs.

Staircase number	Width
T1, T3, T14-T15, T24-T29	1,2
T5	2,0
T6, T8, T10, T12, T16, T19, T21	2,5
T2	2,85
T4	3,25

If the automatic connection to reverse the up going escalators do not work trained personnel can manually stop the escalators. The reason for not installing a sprinkler system at the 1st floor is because of the large openings to the open air resulting in a questionable suppressing effect and a safe escape is expected even without a sprinkler system at this floor.

4.10 Method of analysis

When considering the complexity of the building and the many uncertainties of both technical systems and human behaviour there is only one method appropriate to use when performing the fire safety design. The method is called extended quantitative risk analysis. For further information on the method see section 2.4.

The quantitative analysis is only done on the fire safety objective stating "safeguard occupants (permanent and transient) from injury due to fire until such time as they reach a safe place" (see section 4.3).

5 Quantitative risk analysis of prescriptive alternative

5.1 Description of event tree

The risk analysis is done using event trees. Following events are considered in the risk analysis:

- Place of fire start
- Automatic detection
- Fire is extinguished
- Automatic escape alarm
- Correct behavior of personnel
- All escape routes available

In the following chapters assumptions regarding probabilities, times and consequences will be described for each of these events. The event tree for the prescriptive alternative is presented in Appendix B.

5.1.1 Place of fire start

According to the QDR three different places of fire start shall be considered in the analysis. These are; fire in an electronic shop at the third floor near the escalators, fire in a provisions-dealer shop at the third floor at the opposite side of the electronic shop and fire in a bed-clothes shop at the second floor near the main entrance.

This event influences the fire growth rate and thereby the time to critical conditions, $t_{critical}$, see section 5.2.4. The event also influence on the maximum number of people that have to be evacuated. If the fire is on the 2^{nd} floor the number of people evacuating through a certain exit will be dependent on how many people evacuating from the 3^{rd} floor. The number of people is used as input to the calculations of evacuation time, see section 5.2.3.

The probabilities can be decided comparing the floor area of each store. The electronic shop has a floor area of 1400 m^2. The provisions-dealer shop has a floor area of 600 m^2 and the bedclothes shop has an area of 150 m^2. This gives a relative probability as follows:

- P(fire in electronic shop) = 0,651
- P(fire in provisions-dealer shop) = 0,279
- P(fire in bedclothes shop) = 0,070

5.1.2 Automatic detection

Automatic detection occurs when the detectors are functioning correctly. Without automatic detection the fire is detected manually. The automatic detection is connected to the escape alarm and if there is no automatic detection there will be no escape alarm either. The probability of automatic detection is defined as a uniform distribution between 0,9 and 0,95.

The respective detection times given with automatic detection are decided using an analytical expression given by a regression analysis of DETACT-T2 (Evans et.al., 1985) according to Olsson and Frantzich (1999).

If there is no automatic detection the fire will be detected manually. This is assumed to happen when the smoke has reached the ceiling level and started to spread out in the room. The time from automatic detection to manual detection is than dependent on the fire growth rate and the manual detection times are therefore assumed to be 10% longer than the respective automatic detection times.

5.1.3 Fire is extinguished

The fire can be selfextinguished or be extinguished by personnel or visitors using fire hoses or hand extinguishers. Fire extinguishing by personnel or visitors is only a possibility after automatic detection. If the fire is extinguished no critical conditions can occur and therefore no time to critical conditions can be decided resulting in zero consequence.

With an automatic detection the probability of the event can be described as a normal distribution with an expected value of 0,486 and a standard deviation of 0,0367 (Johansson, 1999). With no automatic detection the only way the fire can be extinguished is by it self. The probability of this can be described with a normal distribution with an expected value of 0,308 and a standard deviation of 0,0339 (Johansson, 1999).

5.1.4 Automatic escape alarm

The escape alarm is started automatically after fire detection. If there is no automatic fire detection than there is no escape alarm either. The mean value of the probability of automatic escape alarm is 0,85 (Boverket, 1997). A triangular distribution between 0,8 and 0,9 with a mean value of 0,85 is used as input to the calculations.

When the automatic escape alarm is working as planned the time to reaction, $t_{reaction}$, will be faster than if no escape alarm sounds. According to an Australian fire code reform (FCR, 1998) the reaction times are also dependent on the actual threat that the fire generates. The fire code reform (FCR, 1998) states that the main evacuation will not start until there is some kind of threat from the fire.

With escape alarm the reaction times for the shop of fire origin are assumed as follows. When the place of fire start is in the electronic shop or in the provisions-dealer shop the reaction times are assumed to vary between 15 and 60 and a triangular distribution with a median value of 30 seconds is used as input to the calculations. When the place of fire origin is in the small bedclothes shop the reaction times are assumed to vary between 10 and 30 and a triangular distribution with a median value of 20 seconds is used as input to the calculations.

With escape alarm the reaction time in the walkway is assumed to vary between 60 and 120 seconds. A triangular distribution with a median value of 90 seconds is used as input to the calculations.

Without escape alarm the reaction times for all areas are decided as 1/3 of the time to critical conditions in respective area.

In the event tree, the escape alarm do not influence the choice of evacuation exit directly. Instead the number of people choosing the main entrances are described as distributions.

5.1.5 Correct behavior of personnel

When the personnel behaves as planned they guide the customers in the shop of fire origin to the closest exits. An incorrect behavior will therefore increase the evacuation time. The probability of correct behavior is assumed to vary between 0,5 and 0,7. A uniform distribution of the probability between these values is used as input to the calculations.

A correct behavior of the personnel in the room of fire origin results in an optimal evacuation strategy from the room. This means that equally many people evacuate through each exit of the room. When the personnel do not act correctly the visitors choose the exits themselves and the main exit will probably be a frequently chosen exit. When there are more than two (2) evacuation exits from the shop an incorrect behavior of the personnel are assumed to generate that 50% of the customers choose the main entrance otherwise for evacuating. When there are less than two (2) evacuation exits 75% of the customers are assumed to choose the main entrance. When the personnel behaves incorrect in the same scenario as an evacuation exit is blocked the number of people evacuating through the main entrance will increase further more, see section 5.2.3.

5.1.6 All escape routes available

Escape routes can be blocked by the fire, by inventory or because the door is locked. In this analyses only the event of fire blocking the door will be considered. When an escape route is blocked the number of people escaping through the narrowest exit will increase and therefor also the evacuation time will increase.

The probability of fire blocking an escape route can be decided by dividing the probable area of the fire with the total floor area of the shop divided with the number of escape routes from the shop i.e.

$$P_{blocked} = \frac{A_{fire}}{A_{floor} / N_{exit}}$$

If the fire is assumed to occupy an area of a circle with a uniform distribution of a radius between 2,5 to 4,5 meters this gives the following medium values:

- Electronic shop: 0,16
- Provisions-dealer shop: 0,13
- Bedclothes shop: 0,26

When all evacuation exits are available the number of people evacuating through each exit is calculated as the total number of people in the store divided by the number of evacuation exits.

When one of the evacuation exits are blocked the number of people evacuating through the other exits increase. The new number of people evacuating through an exit is calculated as the total number of people in the store divided by the number of exits minus one. That is the number of people normally evacuating through the blocked exit is distributed uniformly between the reminding exits.

If an evacuation exit is blocked *and* the personnel behaves incorrect the number of people choosing the main entrance is calculated as 50% of the people plus the reminding 50% of the people divided by the number of evacuation exits i.e.

$$N = \left(0,5 \cdot N_{people} + \left(\frac{(1-0,5)N_{people}}{N_{exit}}\right)\right)$$

This means that the number of people is increased with 100% of those originally assumed to evacuate through the blocked exit.

5.2 Calculation of consequence

5.2.1 Detection time

With automatic detection the detection time is decided using the following analytical expression:

$$t_{\det ection} = 21,8 \cdot \alpha^{-0,31} \cdot H^{0,34}$$

This analytical expression is based on a regression analysis done according to section 5.1.2. Time to manual detection is 10% longer than the respective automatic detection time, see section 5.1.2.

5.2.2 Reaction time

The reaction times are dependent on the activation of the escape alarm and are decided according to section 5.1.4.

5.2.3 Travel time

The travel time is calculated both for the evacuation from the fire room and for the evacuation from the affected walkway. The travel time is depending on the number of people evacuating through a certain exit. The travel time is calculated with the following analytical expression.

$$t_{travel} = \frac{N}{F_s \cdot W}$$

Where N is the number of people, F_s is the flow through the opening and W is the width of the exit. This expression calculates the time for a group of people to pass a door opening. Usually the parameter F_s has a value of between 1,0 and 1,5 people/second. Using available literature and calculations with the computer program SIMULEX, this parameter is decided to 1,3 people/second.

The exit width is decided by the exit that is assumed to be the last exit to be evacuated through, i.e. the critical exit. From the store of fire origin the critical exit is assumed to be equal to the narrowest exit from the store. From the walkway the critical exit is assumed to be equal to the escalators in the atria. The narrowest exit from the shops is assumed to be 1,2 meters and the escalators in the atria are assumed to be 1,2 meters respectively resulting in a total width of 2.4 meters.

The number of people used to calculate the evacuation time from the fire room is dependent on where the fire starts, if the personnel behave correctly and if all exits are available, see section 5.1.5 and 5.1.6. In Table 5.1 all possible combinations of these events are presented together with the number of people assumed to evacuate through the critical exit.

Table 5.1 Number of peoples evacuating from the fire room through the critical exit.

Place of fire start	Correct behavior		All exits available		Number of people
	Yes	No	Yes	No	
Electronic shop	x		x		120
Electronic shop	x			x	150
Electronic shop		x	x		300
Electronic shop		x		x	360
Provisions-dealer shop	x		x		100
Provisions-dealer shop	x			x	200
Provisions-dealer shop		x	x		150
Provisions-dealer shop		x		x	200
Bedclothes shop	x	x	x	x	40*

*Independent of scenario.

The number of people used to calculate the evacuation time from the walkway is described as a triangular distribution. The minimum value in the distribution is presented by an optimal evacuation, i.e. all evacuation exits are used evenly. The mean value represent the case when 50% of the customers in the walkway plus 100% of the customers in the small shop area. The maximum value represents the case when 100% of the people in the walkways plus 100% of the customers in the small shop area escapes via the escalators. When the fire starts on the 2nd floor this means that the values will be doubled because all the people coming down from the 3rd floor. In Table 5.2 the number of people assumed to escape through the atria escalators is presented.

Table 5.2 Input to a triangular distribution representing the number of people evacuating through the atria escalators.

Place of fire start	Number of people		
	Min	Mean	Max
Electronic shop, 3rd floor	650	1200	2000
Provisions-dealer shop, 3rd floor	650	1200	2000
Bedclothes shop, 2nd floor	1300	2400	4000

5.2.4 Time to critical conditions

Time to critical conditions is decided both for the room of fire origin and for the walkway outside this room. A regression analysis of each room configuration is done with FAST (Peacock et.al., 1998), the room configurations and other assumptions used in this analysis are described in Appendix C. This results in three different analytical expressions for the fire room and another three for the walkway. These are as follows:

1. Electronic shop: $t_{crit,room} = 148 \cdot \alpha^{-0,28}$; $t_{crit,corridor} = 543 \cdot \alpha^{0,17}$
2. Provisions-dealer shop: $t_{crit,room} = 97 \cdot \alpha^{-0,26}$; $t_{crit,corridor} = 342 \cdot \alpha^{0,17}$
3. Bedclothes shop: $t_{crit,room} = 48 \cdot \alpha^{-0,21}$; $t_{crit,corridor} = 343 \cdot \alpha^{0,18}$

Time to critical conditions is depending on the rate of fire growth. This is different for each place of fire start. A log normal distribution is used to describe the variance in fire growth rate. The input to respective distribution is presented in Table 5.3 below.

Table 5.3 Input to log normal distribution of rate of fire growth.

Place of fire start	Mean value [kW/m^{2}s]	Variance [%]	Standard deviation [kW/m^{2}s]
Electronic shop	0,047	20	0,0094
Provisions-dealer shop	0,012	30	0,0036
Bedclothes shop	0,19	10	0,019

5.3 Results

Risk profiles for the 10th, 50th and 90th percentile could be derived by the following the procedure outlined by Frantzich (1998). These risk profiles are based upon a statistical analysis of the 1000 iterations of probabilities and consequences in one simulation. The risk profiles are shown in Figure 5.1.

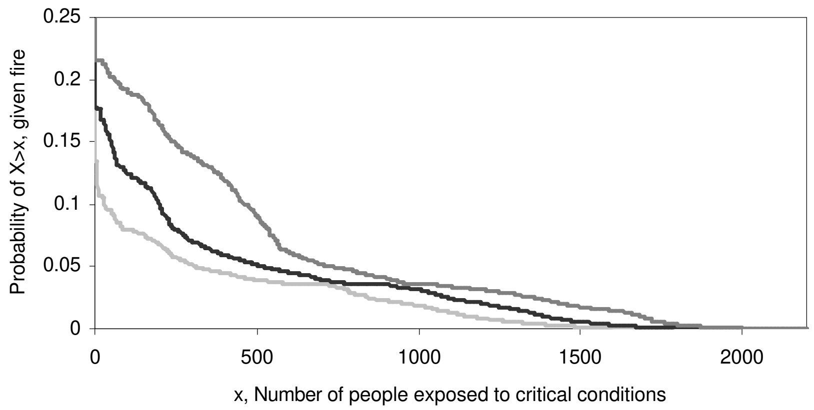

Figure 5.1 Risk profiles representing the 10th, 50th and 90th percentile.

From Figure 5.1 it is possible to withdraw information on the level of individual risk in the building. The individual risk (50th percentile) that one or more individuals are exposed to critical conditions is 0.18 given fire. The values for the 10th and the 90th percentiles are 0.13 and 0.22 respectively. Furthermore it is possible to express the risk by using the average risk measures. The average risk is represented by a distribution, illustrated in Figure 5.2.

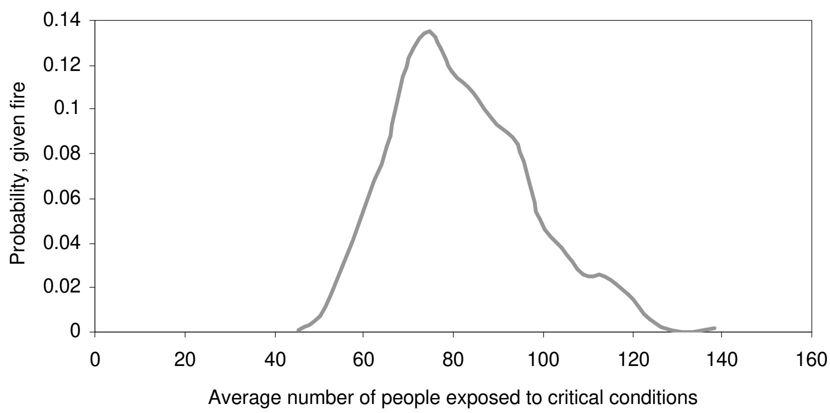

Figure 5.2 The distribution of the average risk measure

6 Quantitative risk analysis of the performance based design alternative

The analysis is done in the same way for this alternative as for the prescriptive alternative. Only the differences between the alternatives will be presented in this chapter.

6.1 Description of event tree

Following events are considered in risk analysis of the performance-based alternative and not in the prescriptive alternative:

- Reversed direction of escalators
- Sprinkler system

In the following chapters assumptions regarding probabilities, times and consequences will be described for each of these events. Events also considered in the prescriptive alternative are described in section 5.1.

6.1.1 Reversed direction of escalators

In this design alternative the automatic detection is connected with a signal to the up going escalators reversing their direction and the personnel are trained to stop the up going escalators if their direction are not reversed. This will increase the width of the exit used in the evacuation time calculations. The probability for this event is assumed to be 1,0 if the detection system works and 0,0 if it does not work. This event is therefore not presented in the event tree.

6.1.2 Sprinkler system

The sprinkler system activates automatically at the time of automatic detection. Without automatic detection the sprinkler system do not activate. After sprinkler activation the rate of heat release is assumed to be constant. The maximum rate of heat release is therefore equal to the rate of heat release at the time of automatic detection.

The probability of sprinkler activation is assumed to have a mean value of 0,95 and to vary between 0,92 and 0,96. A triangular distribution with these input values is used in the calculations.

6.2 Calculation of consequences

6.2.1 Detection time

See section 5.2.1.

6.2.2 Reaction time

See section 5.2.2

6.2.3 Travel time

Because this alternative design contains less number of evacuation exits the number of people evacuating through the remaining exits will rise and the travel time will increase. It is though assumed that this does not affect the evacuation exits inside the shops but only the exits from the walkway. The number of people evacuating from the fire room is therefore the same as in the prescriptive alternative while the number of people evacuating through the atria escalators will rise.

As in the prescriptive alternative the number of people evacuating through the escalators is described as a triangular distribution. The minimum value in the distribution is calculated in the same way as before i.e. the total number of people divided by the total number of exits. Compared to the prescriptive alternative the mean value is increased with a factor representing the number of people that with the original assumptions should have evacuated through the reduced number of exits. The maximum value is increased with 100 people per reduced number of evacuation exits compared to the maximum value in the prescriptive alternative. These assumptions give the number of people evacuating through the escalators presented in Table 6.1.

Table 6.1 Input to a triangular distribution representing the number of people evacuating through the atria escalators

Place of fire start	Number of people		
	Min	Mean	Max
Electronic shop, 3rd floor	800	1360	2300
Provisions-dealer shop, 3rd floor	1040	1720	2600
Bedclothes shop, 2nd floor	1486	2080	2900

The width of the evacuation exit from the walkway is changed in those scenarios where the direction of the escalator is reversed/stopped. Each escalator having a width of 1,2 meters gives a total exit width of 4,8 meters.

6.2.4 Time to critical conditions

As for the prescriptive alternative the time to critical conditions when the sprinklers activate is decided with analytical expression created from a regression analysis with FAST (Peacock et.al., 1998), see Appendix C. The difference between the regression analysis compared to the one described earlier is that the heat release rate is maximized by the sprinkler system activation. When the sprinkler system activates the rate of heat release stops growing and is then assumed to be constant throughout the fire. The regression analysis showed that no critical conditions were obtained in the walkway when the sprinkler activated as planned.

The analytical expressions for the sprinkled fire are as follows.

1. Electronic shop: $t_{crit,room} = 689 \cdot \alpha^{-0,11}$
2. Provisions-dealer shop: $t_{crit,room} = 252 \cdot \alpha^{-0,14}$
3. Bedclothes-shop: $t_{crit,room} = 64 \cdot \alpha^{-0,18}$

In those scenarios were the sprinkler system do not activate the expressions is the same as presented in section 5.2.4.

6.3 Results

Risk profiles for the 10th, 50th and 90th percentile are derived from the simulation output and shown in Figure 6.1.

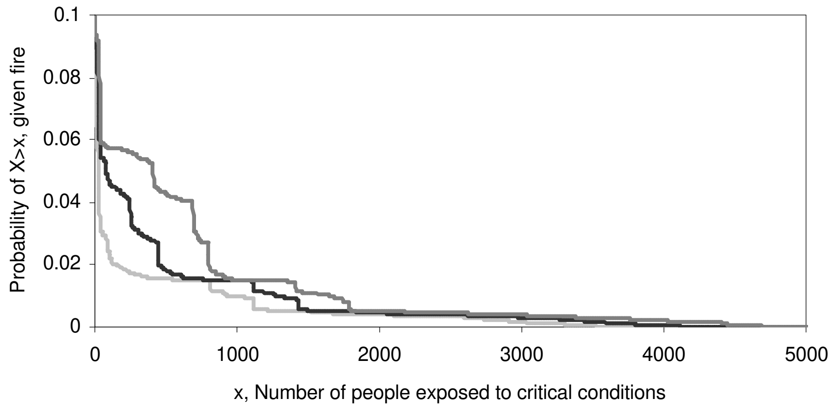

Figure 6.1 Risk profiles for the 10th, 50th and 90th percentile.

The individual risk is assessed to 0.09 (50th percentile). Corresponding values for the 10th and 90th percentiles are 0.07 and 0,10. The distribution of the average risk is shown in Figure 6.2.

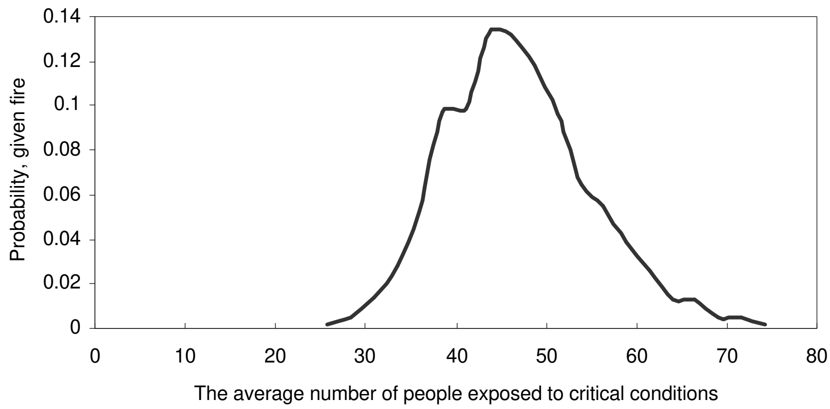

Figure 6.2 Distribution of the average risk measure

7 Life cycle cost analysis

7.1 Calculation of life cycle cost

The life cycle cost for each design alternative is calculated with the following formula:

$$LCC = \sum_{i=0}^{n} \frac{DU_i}{(1+r)^i} + A + \frac{A_v}{(1+r)^n}$$

Where:

A = Acquisition cost

LCC = Life cycle cost

DU_i = Cost of management and support year i

n = Buildings lenght of life

r = Real calculation interest

A_v = Cost of liquidation

Input for this formula is acquired from literature, suppliers, contractors etc. The chosen input values are described in the following sections.

7.1.1 General assumptions

When calculating the respective life cycle cost only the differences are considered. These differences may only be a few percent of the total building cost but this is not considered in this analysis. The expected real interest [r] is deliberately set low, at 3%. The building's length of life is set to 30 years, which also is a conservative estimate. It is possible that the building, sprinkler system and stairs can be in use for a considerably longer period of time. No change of costs during time is expected. No liquidation costs are expected from these installations.

7.1.2 Prescriptive design alternative

Compared to the performance-based alternative the prescriptive alternative includes a larger number of evacuation exits and therefore also a larger number of staircases. The life cycle cost per emergency exit/staircase is therefor calculated. Another difference between the two alternatives is the fire resistance of the fire separating structures. The life cycle cost resulting from having a fire resistance of EI120 instead of EI60 is though not calculated, even if this could be important.

The stairs is made from concrete and all require different dimensions according to the number of people expected to use them in case of evacuation. These calculations only consider two sizes, that are considered representative. The cost for space not available for renting is included. The rent loss per year is 1200 SEK/m^2 (Lundin, Olsson, 2000). The cost for concrete structures is 1000 SEK/m^2 (SBF, 1998).

Cost for size 1 (T1, T3, T13-15 and T24-29)
Required width is 1,2 m. The area is 24 m^2. Doors 16 800 SEK, walls 168 000 SEK, and stairs 64 646 SEK. A maintenance cost is expected in the end of every 5-year period, 5000 SEK/5years and an extra 10000 SEK/10years. This results in a total cost of 780 000 SEK/stair.

Cost for size 2 (T2, T4-12, and T16-23)
Required width is 2,85 m. The area is 48 m^2. The costs dominating installation of emergency stairs are acquisition and rent loss. Doors 33 600 SEK, walls 240 000 SEK and staircases 153 535 SEK. A maintenance cost of 8000 SEK/5years and an extra 12 000/10 years. Which results in a total cost of approximately 1 470 000 SEK/staircase.

7.2 Performance based design alternative

The performance-based alternative requires installation of sprinkler systems in the 1st and 2nd floor. The life cycle cost of this system is calculated here. The life cycle cost for the automatic reversing of escalators is assumed to be negligent compared to the cost for the sprinkler system. The life cycle cost for this installation is therefore assumed to be zero.

The total cost for sprinklers for an area of 42 400 m^2 (2 floors) is calculated to approximately 7 300 000 SEK. This includes an installation cost of 150 SEK/m^2, pump station 250 000 SEK and water container cost lays between 250 000 SEK and 500 000 SEK depending on water flow to the container.(Sprays AB, 2000). The estimated cost used here is 375 000 SEK. A yearly cost of 20 000 SEK for testing and maintenance is also included. A condition for the low installation cost per square meter is that there are no constructions that require special solutions. A conclusion that can be drawn from the calculations is that when installing a sprinkler system the figure of the real interest is not very significant since the dominating cost is in acquisition.

7.3 Result

Compared to the performance-based alternative the prescriptive alternative includes nine (9) emergency staircases more. Eight (8) of these staircases are of size 2 according to section 7.1.2 and one (1) of size 1. These extra staircases are equivalent to a life cycle cost of 12 540 000 SEK.

The life cycle cost for the sprinkler system is calculated 7 300 000 SEK. The differences in life cycle cost between the two alternatives is then 5 240 000 SEK.

8 Evaluation of design alternatives

8.1 Risk to life

The risk to life is evaluated by the use of three different risk measures. These risk measures are

- Individual risk
- Average risk
- Societal risk

Using the information that represents the 90th percentile of the result, where applicable performs the comparison. Using this information tells us that it will only get worse in 1 of 10 cases. Since fire is a rather rare occasion, this approach could be accepted.

8.1.1 Comparison of individual risk

The individual risk expresses the probability that one or more people are exposed to critical conditions. Results from section 5.3 and 6.3 are repeated in Table 8.1 below.

Table 8.1 Individual risk for the both design alternatives

Alternative	Individual risk (90th percentile)
Prescriptive design alternative	0.22
Performance-based design alternative	0.10

The individual risk is reduced by 55 % when comparing the performance-based alternative towards the prescriptive. This result fulfils the acceptance criteria in section 4.5.

8.1.2 Comparison of average risk

The distributions for average risk are given in Figure 8.1 below.

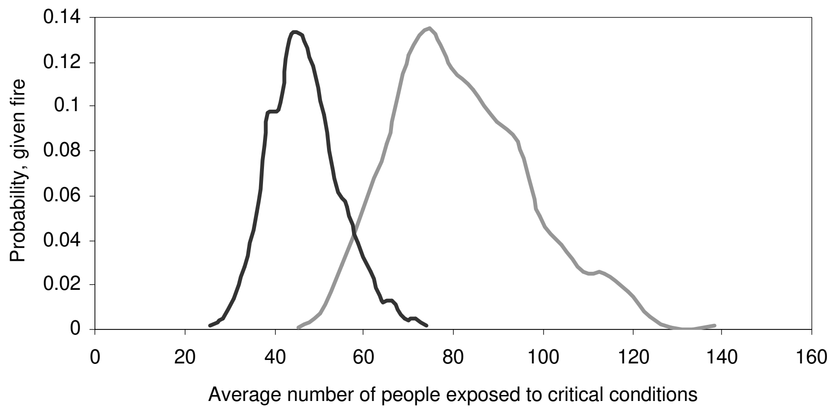

Figure 8.1 Comparison of average risk. The black line represents the performance-based alternative and the gray line the prescriptive.

One could clearly tell that the performance-based alternative provides a much safer building in case of fire, compared to the prescriptive alternative. The mean value of the average risk is 45 and 75 people exposed to critical conditions for the performance-based and the prescriptive alternative, respectively. The average risk for the performance-based alternative does also have a much less deviation, which gives us a more reliable result. The probability that the average risk of the performance based alternative is lower than the prescriptive is 0.92.

8.1.3 Comparison of societal risk

The societal risk i.e the risk profiles of the design alternatives is compared in Figure 8.2 below.

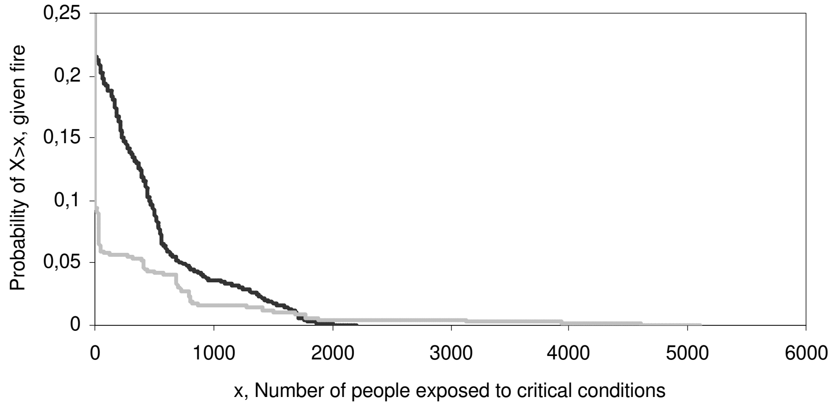

Figure 8.2 Comparison of societal risk. The black line represents the prescriptive alternative and the gray the performance-based.

The societal risk for the performance-based alternative is lower than the prescriptive alternative, until the consequence reaches app. 1800 people. The maximum consequence is larger for the performance-based alternative, which is illustrated by the tail reaching to app. 5100 people exposed to critical conditions.

By strict means this is enough to reject the performance-based solution. But, it is necessary to discuss the information given in Figure 8.2 from another point of view. When risk is evaluated the most common way is to compare the probability for a given consequence. The performance-based alternative is the best choice for a consequence of 1, 10, 100 and 1000 people exposed to critical conditions. Does it really matter there is a larger probability of a consequence between 2000 and 4000 people. Considering the risk evaluation principle of avoiding catastrophes which says that catastrophes should by all means be avoided, signals that there already is a large ongoing consequence. It is therefor recommended that fire risk is evaluated by fixed values saying 1, 10, 100 and 1000 people exposed to critical conditions. This statement is of course necessary to discuss in a broader forum.

8.1.4 Conclusions

With the comparison of individual risk, average risk and societal risk it is concluded that the performance-based alternative meets the acceptance criteria established in section 4.5. It is stated that the risk is reduced by choosing the performance-based alternative, despite the exceeding tails of the risk profile given in Figure 8.2.

The four fire safety objectives stated in section 4.3 are all met with the performance-based alternative. The first objective to safeguard occupants has been analyzed with quantitative methods in the study. The three other objectives are meet be following the recommendations given in the building regulations. The performance-based alternative does not mean any change in structural safety or surface linings.

8.2 Comparison of life cycle cost

According to section 7.3 the difference in life cycle cost between the two alternatives is 5 240 000 SEK in favor for the performance-based alternative. A large contribute to this difference is the rent of the area used by the staircases in the prescriptive alternative but not in the performance-based alternative. The rent is therefore an important uncertainty factor. When comparing the life cycle costs one should also note that these are only extracts from the total life cycle cost for the building. If the difference is very small compared to the total building cost the difference may be of very little importance when making a decision.

9 Discussion

Traditional risk analyses use point estimates to present the risk. There are mainly two problems associated with this approach. First, it is highly desirable for decision-makers to be aware of the full range of possible risks in order to make balanced decisions. Second, point risk estimates frequently are very conservative as a result of the accumulation of the effects of various conservative assumptions made at intermediate steps in the analysis. The consideration and treatment of uncertainties in risk analysis adds considerably to the credibility of the results. This is the main advantage of using extended QRA in fire safety design.

When performing the QDR it is easy to notice that the building in hand is very complex from a fire safety point of view. The number of occupant exceeds 10000 people and there are very large open areas. Despite these facts the Swedish building regulations do not require any other fire safety measure in their general recommendations, i.e. deemed to satisfy solutions, than those required for assembly building with a maximum number of one thousand people. There are no requirements on automatic fire extinguish systems like sprinkler and there are no requirement concerning a more extensive fire compartment division. Reviewing results from previous Swedish building fire risk analyses provides the same information. The recommendations are not suitable for all kind of building. The more complex building the more inappropriate are the regulations.

One way to deal with the problem of inappropriate building regulations is to define probabilistic acceptance criteria. These criteria would state the society's acceptance on individual as well as on societal risk. The authorities should also demand that the fire safety design in buildings where the consequence is assumed to be large should be based upon a fire risk analysis. In order for a solution to be accepted the risk must fulfil the acceptance criteria, no matter what the general recommendations of the building code says. It is of great importance that future research focuses on which situations where the fire safety design can be performed by the use of general recommendations. The limitations of the deemed to satisfy solutions must be made fully understood.

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To
3rd International Conference on Performance-based Codes and Fire Safety Design Methods, Lund, Sweden, June 15th-17th, 2000

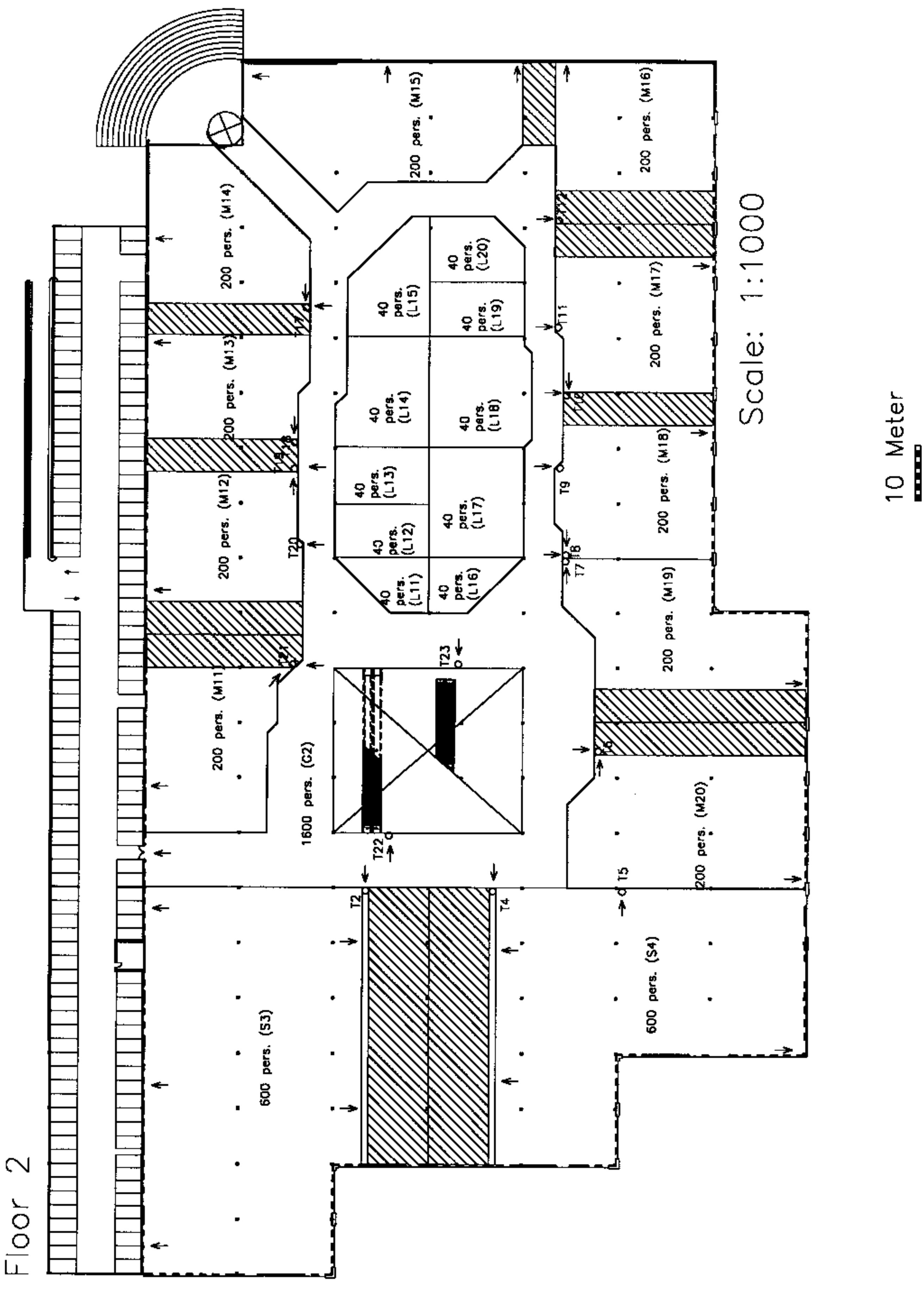
För info

Appendix A – Drawings

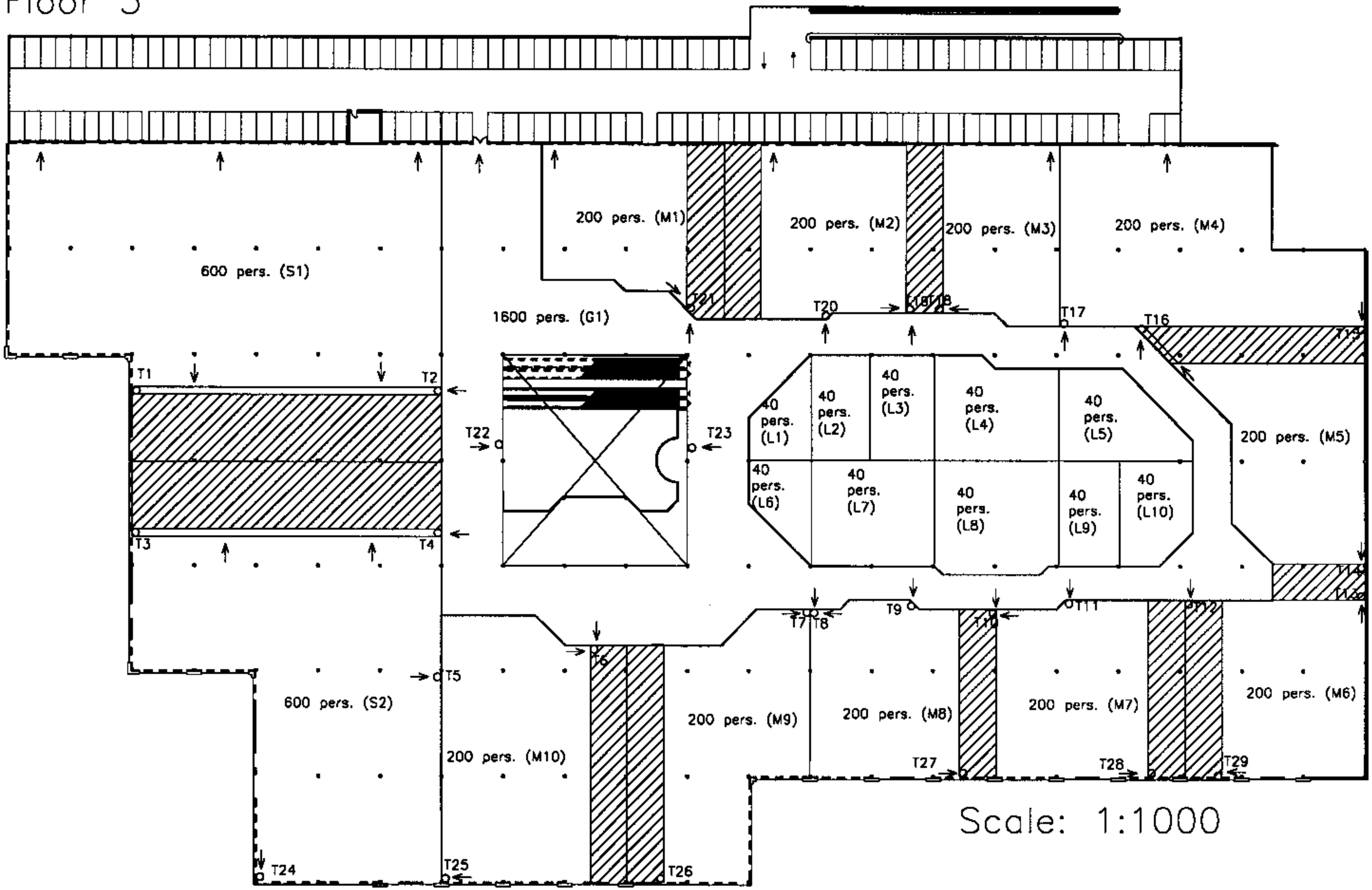
In the following pages one will find sketches and drawings which explain the geometry, construction and some fire safety measures of the building in design.

BUILDING PLAN
PRESCRIPTIVE DESIGN ALTERNATIVE

Appendix A 1



Floor 3



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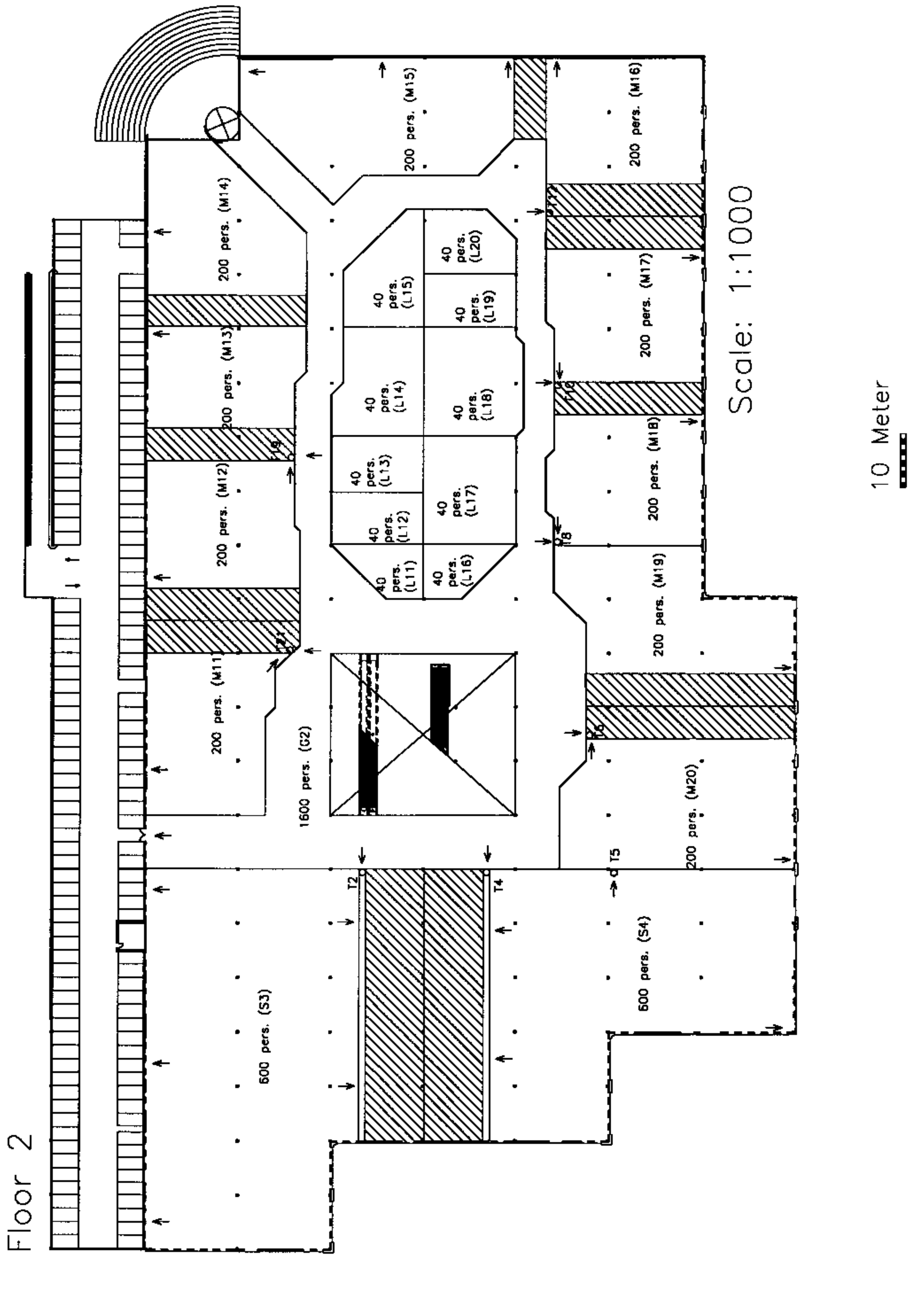
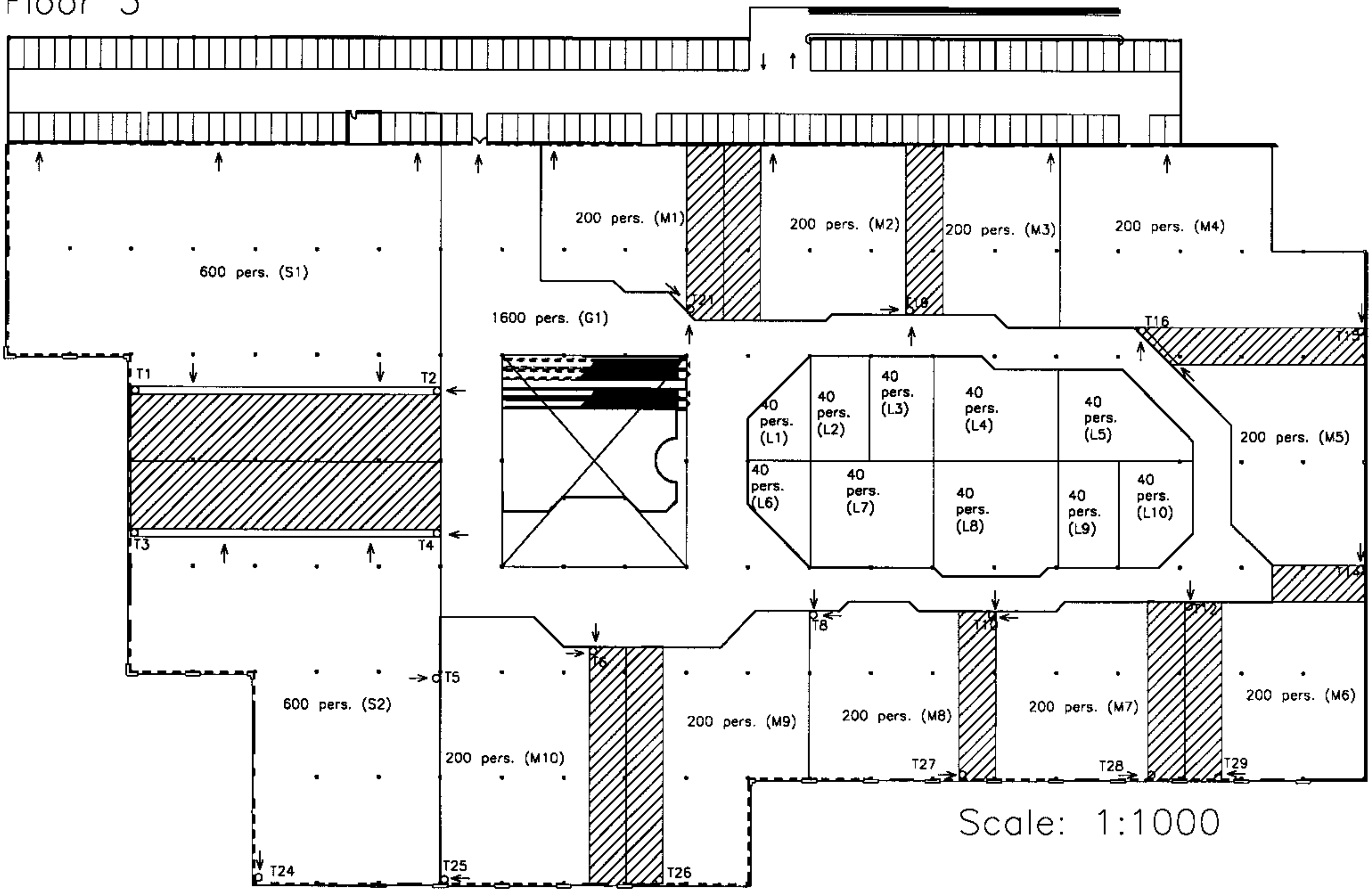
10 Meter

Appendix A

PERFORMANCE-BASED DESIGN ALTERNATIVE



Floor 3



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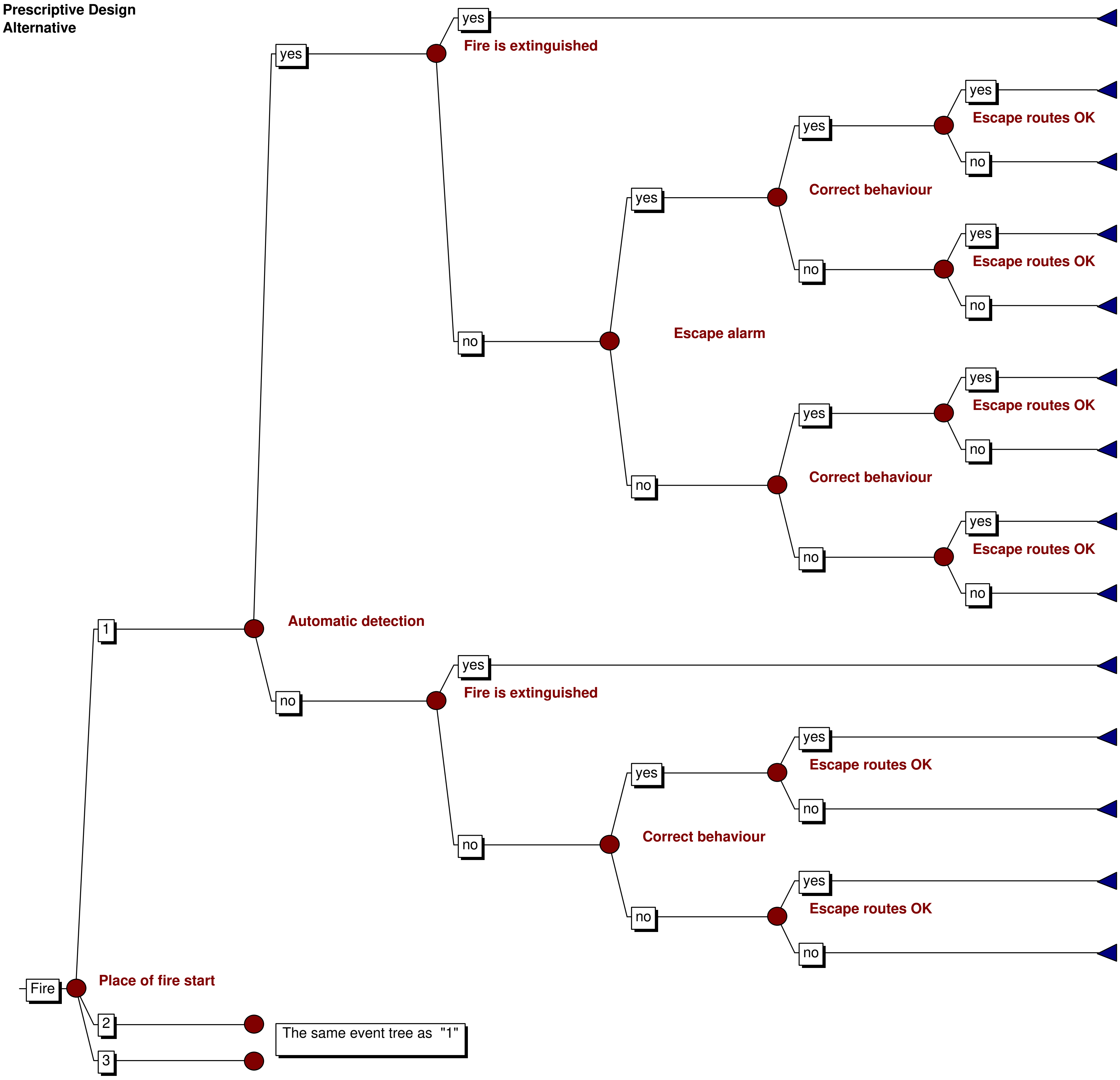
För info

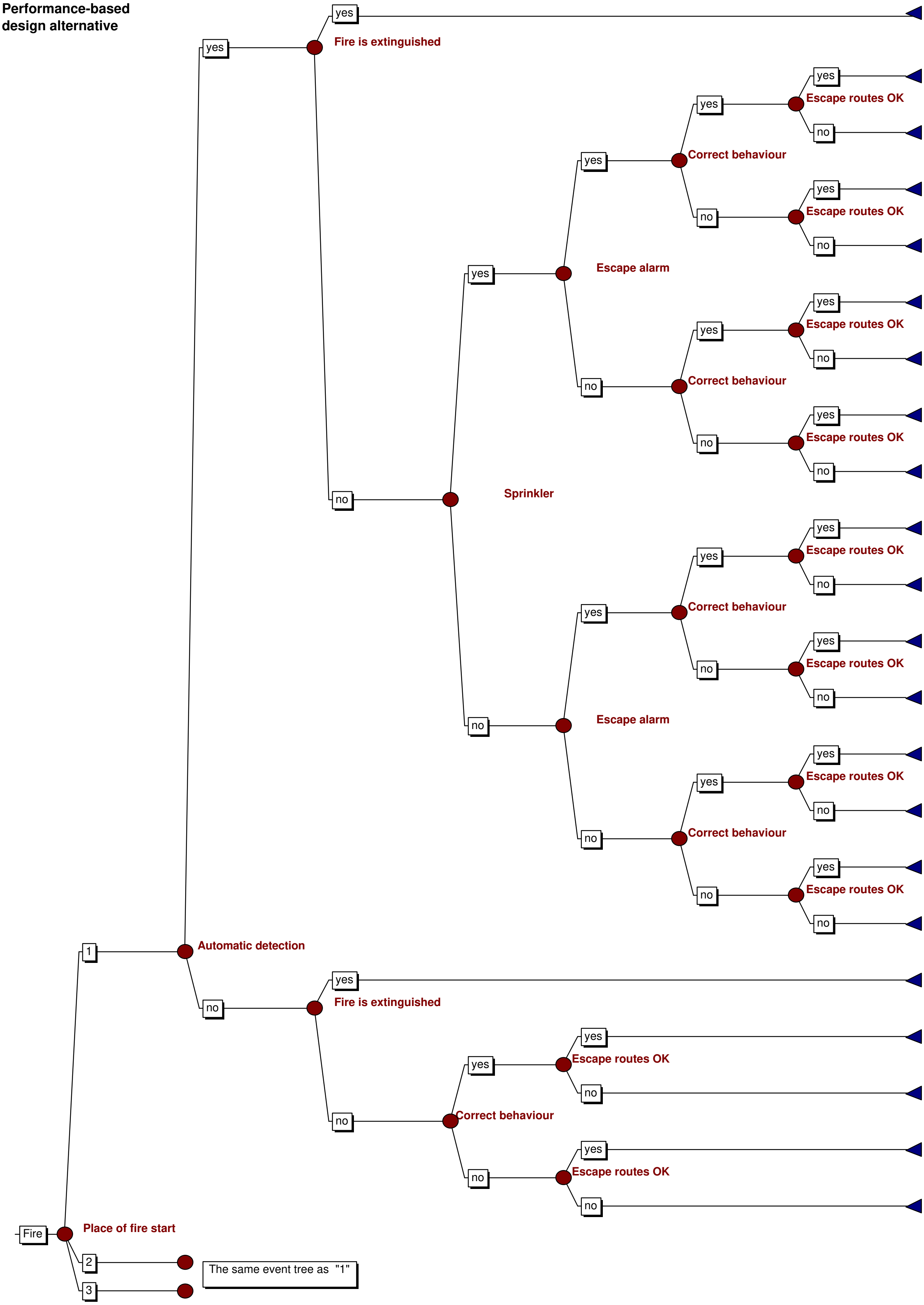
Appendix B – Event trees

This appendix contains event trees for the prescriptive and the performance-based design alternative. It is only the structure of the event trees that are shown. Please refer to the main report to fins details on probabilities, etc.

Prescriptive Design Alternative



Performance-based design alternative



Appendix C – Regression Analysis of FAST

An analytical expression for calculating available time for evacuation or time to critical conditions is decided making a regression analysis of with FAST calculated times. Time to critical conditions can then be described with the following generic expression:

$$t_{crit} = C_1 \alpha^{C2} Area^{C3} Height^{C4}$$

In this case an analytical expression is decided for each room configuration why the only parameter changed in the analysis is the α-value.

$$t_{crit} = C_5 \alpha^{C6}$$

Were C5 and C6 will be the results from the regression analysis.

The definition of critical conditions used in the regression analysis is a smoke layer height of 1,6 meters + 0,1· room height.

The α-values 0,1, 0,2, 0,3, 0,4, 0,5, 0,6, 0,7 were used in the analysis. The maximum heat release with the prescriptive design solution is decided by the ventilation control. The maximum heat release with the performance-based alternative is decided as the heat release at the time of automatic detection. After detection the heat release is supposed to be constant throughout the fire scenario.

Assumed room configurations for each place of fire start will be described below.

Electronic-shop

The walkway outside the electronic shop is defined as a room with a depth of 10 meters and a width of 45 meters. The atria outside the shop is defined as a room connected to the walkway with a 20*4 meter large opening. The area of the atria room is 40*20 meters. The height of the atria is 8 meters.

Provisions-dealer shop
The walkway is defined as a room with a depth of 40 meters and a width of 3,3 meters. The room of fire origin is connected to the walkway with an opening with a width of 1,2 meters and height of 2,0 meters. An opening with a width of 2 meters and height of 4 meters is connecting the walkway to the rest of the shopping centre.

Bedclothes shop
The walkway outside the shop is defined as a room with a depth of 40 meters and a width of 3,3 meters. The room of fire origin is connected to the walkway with an opening with a width of 1,2 meters and height of 2,0 meters. An opening with a width of 2 meters and height of 4 meters is connecting the walkway to the rest of the shopping centre.