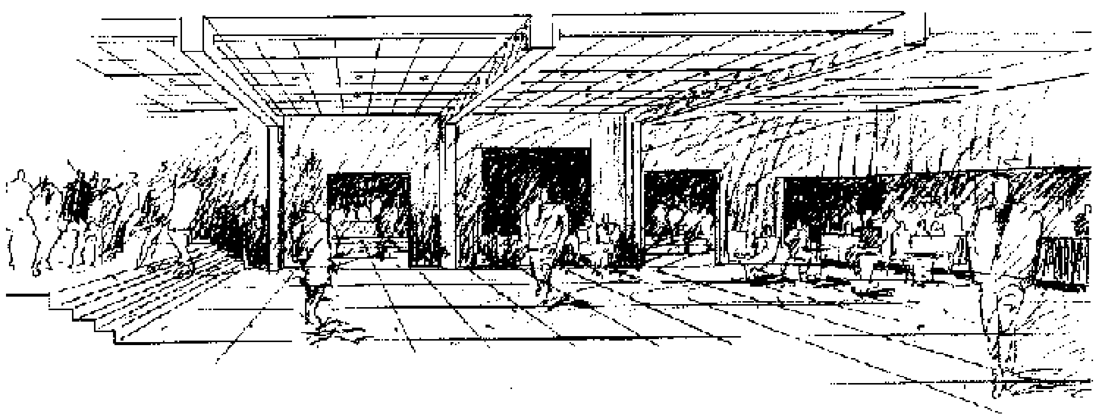
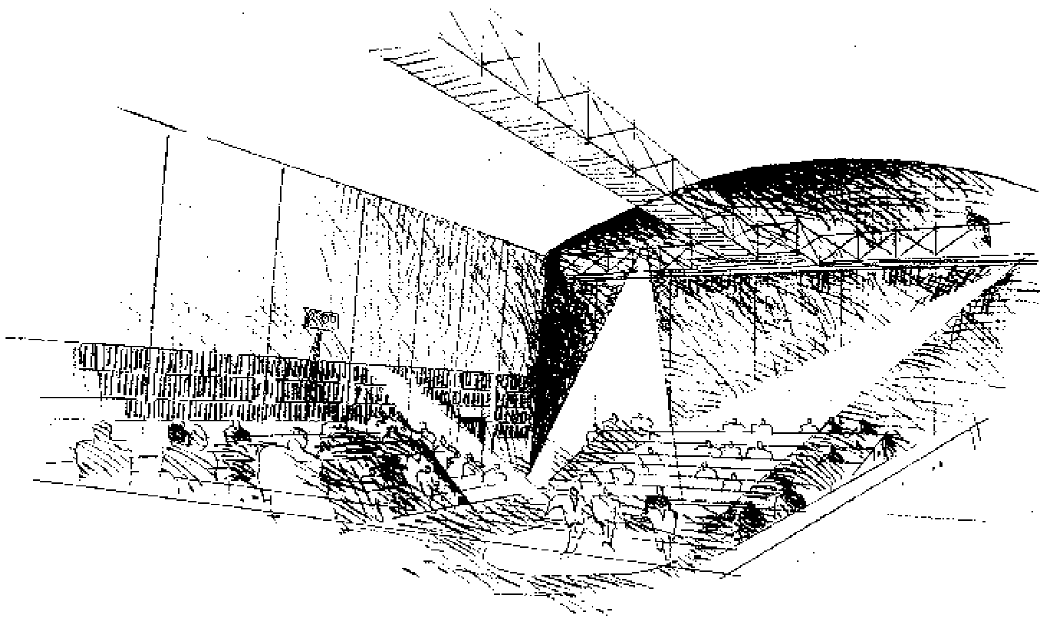
Quantitative Risk Assessment
of

Amager Bio





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Limitations: This report was made during the instruction of the above mentioned course. The main purpose was to practise problem solving and the methodology in problem solving. This reports conclusions and calculations have not been object for a investigation of quality in the range that quality safety requires. Therefore the report must be used by a great carefulness. Whom that uses the results from this report, in any context, bear the responsibility on his or her own.

Keywords: Deterministic risk assessment, assembly hall, QRA, event tree, risk profile, mechanical smoke ventilation, natural smoke ventilation, extra exits.

Synopsis

In this report a fire scenario at the assembly hall Amager Bio has been evaluated using a quantitative risk assessment method (QRA).

Earlier Amager Bio was subject of a fire safety evaluation which is used as basis of this report. The fire safety analysis showed that the present fire protection system not was sufficient enough to secure a safe evacuation i.e. a fire will exposed people inside the building for untenable conditions.

The fire scenario - fire in electrical installations - is analysed in this report. The QRA shows that a fire in the electrical installations will start $3.88 \cdot 10^{-2}$ per year resulting in $1.94 \cdot 10^{-3}$ times per year where it will develop critical conditions in Amager Bio.

The calculated risk profiles shows that if one of the mechanical components fire protection system fails the consequence will be that many people will be exposed to critical conditions. This fact holds even if there is implemented natural smoke ventilation in Amager Bio.

The suggested solution according to the risk profiles mentioned above is to make the available time for evacuation independent of the mechanical components. This could be done by implementing extra exits located in the opposite direction of the present exits. If this solution is realised the evacuation will be less one sided and the evacuation time will be reduced. Further the consequence of failure in the fire protection system will be less than today, since fewer people will be exposed to critical conditions.

Preface

This report was made during the course ”Risk Management 2” at the School of Fire Safety Engineering, Lund University in the period from September 1st 1998 to October the 5th 1998.

This report refers to an report made earlier by the authors during the course ”Fire Safety Evaluation”. The report which is referred to was made in the course ”Fire Safety Evaluation” and it is named ”Fire Safety Evaluation of Amager Bio” [1].

During the report som references are made by [number], where the number in side the brackets are the reference’s number in list over references. In chapter 6 ”References” the used literature is listed.

Lund 5th of October 1998

Jakob Andersen Henrik Bygbjerg

The limitations of this report are translated into Swedish as well as into Danish down below:

In Swedish:

”Följande rapport är framtagen i undervisningen. Det huvudsakliga syfte har varit träning i problemlösning och metodik. Rapportens slutsatser och beräkningsresultat har inte kvalitetsgranskats i den omfatning som krävs för kvalitetssäkring. Rapporten måste därför användas med stor försiktighet. Den som åberopar resultaten från rapporten i något sammanhang bär själv ansvaret.”

In Danish

”Følgende rapport er udarbejdet gennem undervigningen. Det overordnede formål har været at opnå træning i problemløsning og metode. Rapportens konsklusioner og beregningsresultater har ikke været underkastet en kvalitetsgranskning i det omfang, der kræves for kvalitetssikring. Rapporten bør derfor anvendes med stor forsigtighed. Den som anvender resultater fra denne rapport bærer selv ansvaret.”

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1. Introduction

The Fire Safety Analysis of Amager Bio was carried out on the basis that every component in the fire protection system will operate as designed with a probability equal to 100%. In reality some unavailability of the components must be expected. Instead one may carry out an analysis according to the Quantitative Risk Assessment method (QRA). In this report each component in the fire protection system in Amager Bio is associated with a probability of not operating at all. The influences of the components on the fire safety in Amager Bio have been analysed and the results are represented in risk profiles. The risk profiles shows the probability of more than x number of people being exposed to critical conditions during a fire.

Only one fire scenario has been made subject to an analysis according to the QRA. In the QRA only deterministic values are used.

1.1 Description of the object

The object (Amager Bio), which is located on the Danish island Amager south of Copenhagen, was earlier an cinema which now have been rebuilt into a assembly hall. It contains a big assembly hall, in which a balcony is located, a foyer, a dressing room section, a basement for storage and some offices (the offices were not analysed in the Fire Safety Evaluation of Amager Bio).

The activities in Amager Bio were divided into two different kinds:

- Theatre (with seated people). Expected number of people 300
- Discotheque (with standing people) Expected number of people 1500

The prior Fire Safety Evaluation of Amager Bio shows that the safety level at discotheques generally is minor to the safety level at theatre activities. Therefore the discotheque activities is subject for further analysis.

For a more detailed description of Amager Bio please refer to [1].

1.2 Safety margin

In an ordinary fire safety analysis a measure to determine whether a building is safe or not the safety margin can be used. The safety margin describes the difference between available time for evacuation and the actual evacuation time. The following safety margin, M, is used in the remaining of this report

$$M = t_{critical} - t_{evacuation} \qquad (0.1)$$

Where

$t_{critical}$ is the available time for evacuation.
$t_{evacuation}$ is the actual evacuation time.

The evacuation time can further be divided into

$$t_{evacuation} = t_{alert} + t_{reaction} + t_{walk} \tag{0.2}$$

Where

t_{alert} is the time it will take to alert the people inside the building.
$t_{reaction}$ is the time it will take for the people to react on the alert.
t_{walk} is the time it will take the people to walk to a safe location.

If the safety margin is positive the people inside the building are able to evacuate the building without being exposed to conditions that are life threatening. Otherwise are a negative safety margin obtained the people will not be able to evacuate the building before they are exposed to critical conditions. This leads to that the safety margin should at least be obtained *M* equals zero, which means that the people will just have reached a safe location when critical conditions inside the building are obtained.

1.3 Evaluated fire scenario

The fire scenario analysed throughout this QRA is the fire in electrical installations. All facts about this fire scenario are given in [1]. Here it should be mentioned that the rate of heat release, *RHR*, reaches its maximum after 1200 seconds where *RHR* = 4000 kW. The analysed fire scenario describes that a fire starts in some of the electrical installations that are located in a room in the dressing room section. The room for the electrical installations is connected to the assembly hall and the dressing room by doors. All doors are equipped with automatic door closer.

1.3.1 Critical conditions

The design criteria used in this report are defined that if persons are exposed to critical conditions they are not able to evacuate the building. This criterion does not contain any information on the physical injury of the persons which the exposure might lead to. This definition will not imply that the persons inside the building will become fatal victims during the fire.

The critical condition used in [1] as well as in this report and they are listed in Table 0.1:

The mean temperature in the upper layer	> 500 °C
The mean temperature in the lower layer	> 80 °C
The height of the lower layer	< 2.5 m
The radiation at the floor	> 1.0 kW/m^2
The visibility inside the building	< 10 m

Table 0.1: Critical conditions. [6]

The analysis in [1] shows that criteria for smoke layer height is first exceed.

1.3.2 Critical time

The critical time, $t_{critical}$, i.e. the time at which the conditions inside the building becomes critical to humans and therefore gives the available time for evacuation, was determined by usage of a two zone model (Hazard I [2]). The method for the determination of $t_{critical}$ will not be reproduced here, the reader should consult [1]. The critical time for fire in electrical installations - if both mechanical ventilators was activated and functioning as designed - was determined to approximately 640 seconds [1].

1.4 Evacuation scenario

For the above mentioned fire scenario two different evacuation scenarios were analysed. One scenario where all people evacuates through the nearest exit and one scenario where 60% of the people evacuates through the main entrance. The last mentioned evacuation scenario is most likely to occur according to fact that people will evacuate the same way as they entered the building. For more details please refer to [1].

The time to which people inside Amager Bio - attending a discotheque - have reached a safe location by evacuating through the nearest exit was determined $t_{evacuation}$ = 488 seconds. The evacuation time was determined to 630 seconds if 60% of the people evacuates through the main entrance. According to [1] there will be sufficient time for the people to evacuate - if all components in the fire protection system are working as designed.

2. Event tree

A way of describing the fire scenario and the components in the fire protection system is to set up an event tree. The event tree contains information about the probability of the component working as designed. Therefore a number of sub scenarios are obtained. The sub scenarios lead to consequences and a probability of the current sub scenario.

A fire in the electrical installations breaks out and it will be detected by smoke detectors after approximately 2 minutes (120 seconds). The detection of the fire will start the alert device, which plays a taped message. Activating of the smoke detectors also starts the mechanical smoke ventilation. There exist a possibility for manual activation of the alert device and the mechanical ventilation. The manual activation (fire button) is placed in the bar-area in the foyer. If the smoke detectors fail the only way to active the alert device and the mechanical ventilation is by pressing the fire button in the bar.

In order to expose people inside the concert hall the door between the room for electrical installations and the concert hall must be open. Besides the door maintained open any attempt to extinguish the fire should fail. The event tree for a fire in electrical installation developing to expose people inside the concert hall is shown in Figure 0.1.

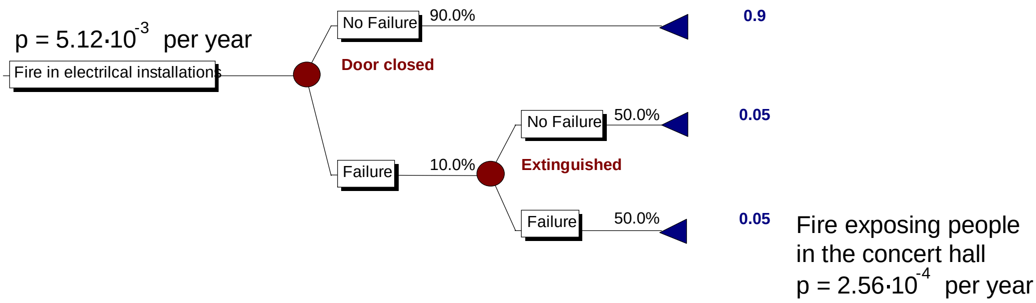


Figure 0.1: Probability for a fire in the electrical installations exposing people in the concert hall.

The probability, p_{fire}, for a fire starting in the assembly hall can be calculated to [5]

$$P_{fire} = 9.7 \cdot 10^{-5} \cdot \text{floorarea} = 9.7 \cdot 10^{-5} \cdot 400\,\text{m}^2 = 3.88 \cdot 10^{-2} \text{ starts per year} \quad (0.1)$$

According NFIRS [x] fire in the electrical distribution occurs in 13,2% of all fires in assembly halls. Therefore the probability of a fire starting in the electrical installations can be calculated by multiplying p_{fire} by 0,132. By the assumption that the probability for the door will be maintained open is 10% and the attempt to extinguish the fire will only succeed in 50% of all cases, a fire in the electrical installation will expose the people inside the concert hall in 5% for each fire start. The probability, $p_{initial}$, for the fire developing and exposing people inside the concert hall can be calculated to

$$P_{initial} = 3.88 \cdot 10^{-2} \cdot 0.132 \cdot 0.05 = 2.56 \cdot 10^{-4} \text{ times per year} \quad (0.2)$$

This means that one fire over the period of 3905 years will development and expose people inside the concert hall. In the remaining of this report it is assumed that $p_{initial}$ = 1.0 in order to be able to illustrate the consequences of a fire in the electrical installations - exposing people inside the concert hall.

2.1 Reliability used in the event trees

In the event trees different probabilities of failure as well as probabilities for no failure are used and they are linked with references in Table 0.1.

Component	No failure	Comments	Reference
Door closing system	0,90		[5]
Extinguished	0.50	Assumed	-
Smoke detector system	0.95		[4]
Manual detection	0.50	Assumed	-
Alert Device	0.90		[4]
Mechanical ventilation	0.90		[5]
Natural ventilation	0.90		[5]

Table 0.1: Probabilities used in the event tree.

2.2 Event tree for present fire protection system

The probability for a fire starting in the room for electrical installations is assumed to be 0,00194 times, see above standing calculation. Another approach can be to observe the probability for a fire starting in a assembly hall without no regard to the floor area. The probability for a fire starting in a assembly hall can be assumed to be 0,12 times per year [5]. The probability for a fire starting in a assembly hall covers all possibly fires that can occur in the assembly hall. A fire in the electrical installation is only little part of the possible fires that can occur in an assembly hall. Therefore the first mentioned probability is used in this analysis.

If a fire develops according to Figure 0.1, then some devices have to be activated in order to secured a safe evacuation from the concert hall. Each of these devices can fail according to the probabilities listed in Table 0.1. An event tree for a fire developing in the electrical installation is drawn in Figure 0.2.

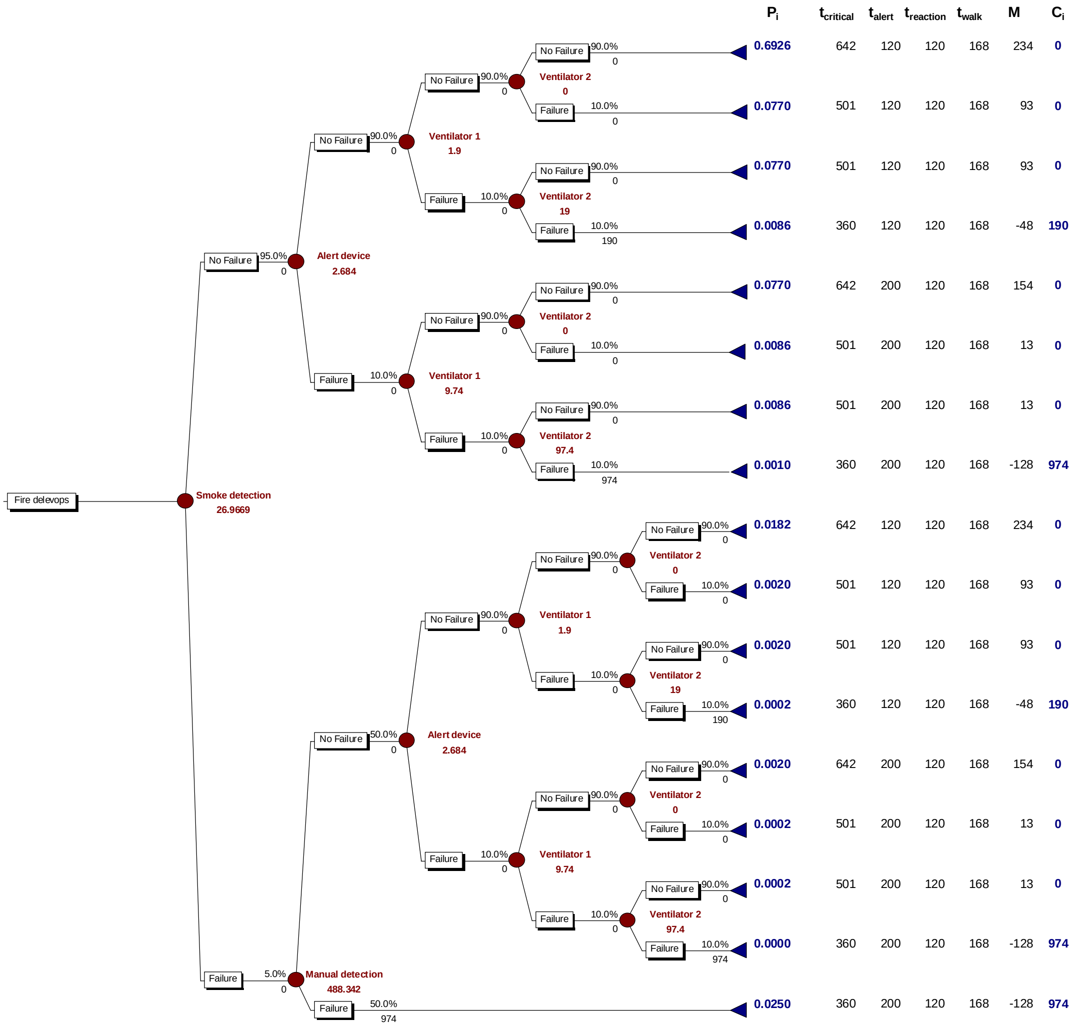
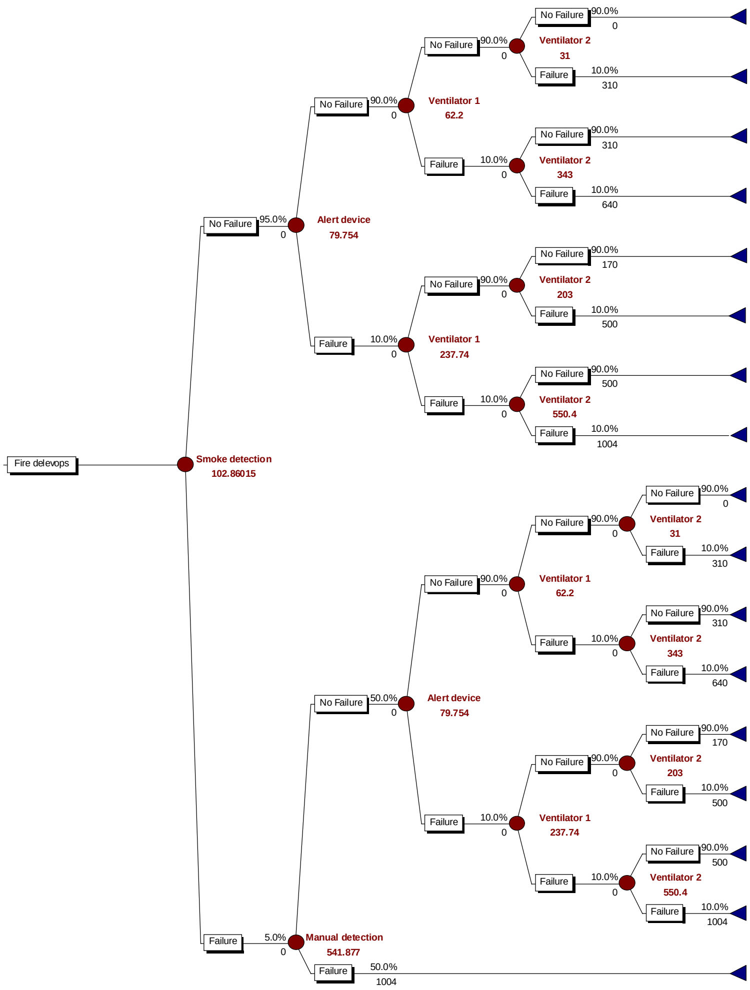


Figure 0.2: Event tree for present fire protection system. Evacuation through nearest exit.

A risk profile has been drawn in order to illustrate the different outcome of the event tree - drawn in Figure 0.2 - and the linked consequences. The risk is drawn in Figure 0.4.

For the other evacuation scenario - 60% evacuating through the main entrance - an event tree is also drawn, where the walking time differs from that used in Figure 0.2. The event tree for the evacuation scenario 60/40 is drawn in Figure 0.3.



P_i	$t_{critical}$	t_{alert}	$t_{reaction}$	t_{walk}	M	C_i
0.69255	642	120	120	390	12	0
0.0770	501	120	120	390	-129	310
0.0770	501	120	120	390	-129	310
0.0086	360	120	120	390	-270	640
0.0770	642	200	120	390	-68	170
0.0086	501	200	120	390	-209	500
0.0086	501	200	120	390	-209	500
0.0010	360	200	120	390	-350	1004
0.0182	642	120	120	390	12	0
0.0020	501	120	120	390	-129	310
0.0020	501	120	120	390	-129	310
0.0002	360	120	120	390	-270	640
0.0020	642	200	120	390	-68	170
0.0002	501	200	120	390	-209	500
0.0002	501	200	120	390	-209	500
0.0000	360	200	120	390	-350	1004
0.0250	360	200	120	390	-350	1004

Figure 0.3: Event tree for present fire protection system. Evacuation 60% to main entrance.

As for evacuation through the nearest exit a risk profile for 60 evacuating through the main entrance is drawn, see Figure 0.4.

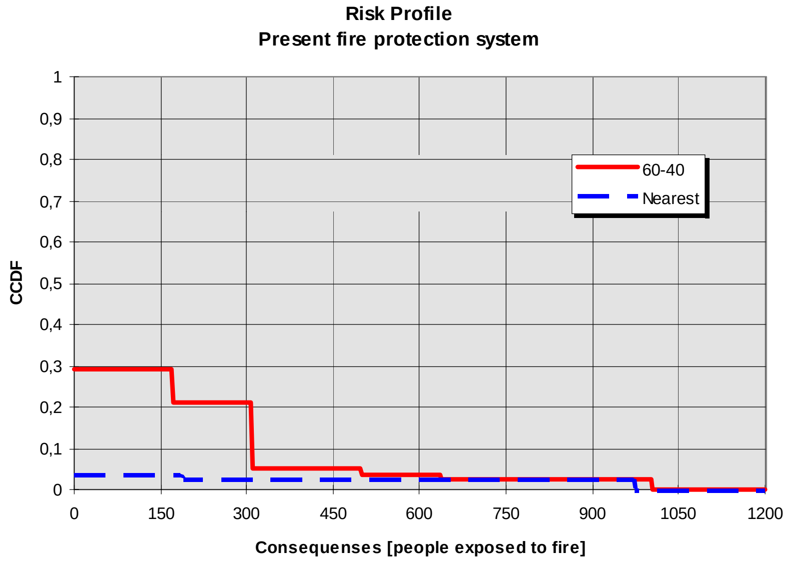


Figure 0.4: Risk for present fire protection system.

Observing the risk profiles in Figure 0.4, when people evacuate through the nearest exit, it is seen that there will be approximately 5% probability of less than 150 persons will be subjected to critical conditions inside Amager Bio. The probability of more than 150 persons will be subjected to critical conditions is approximately 4%. But from the risk profile it is not possible to determine how many persons that will not be able to evacuate Amager Bio before critical conditions occur - except that it is more than 150 persons.

It is also seen - from Figure 0.4 - that there will be approximately 30% probability of more than 160 persons will be affected by critical conditions - when 60% evacuates through the main entrance, i.e. they will not be able to evacuate before critical conditions occur inside Amager Bio. The probability of more than 160 persons will be subjected to critical conditions.

Since it is most likely that people will evacuate through the exit the entered the building - if they are unfamiliar with the building - a probability of 21% for more than 150 persons will not be able to evacuate from Amager Bio before critical conditions occur is not acceptable.

From the risk profiles, see Figure 0.4, it is seen that the consequences are high, i.e. many people will be exposed to critical conditions. Therefore improvements have to be done in order to lower the consequences of fire in the electrical installations.

3. Improvements

According to the report ”Fire safety evaluation in Amager Bio” three main improvements were given [1]:

- Improvements of the mechanical smoke ventilation.
- Provide Amager Bio with natural smoke ventilation.
- Decrease the number of people visiting Amager Bio.

The main purpose is to decrease the dependence of functioning mechanical smoke ventilation. This is obtained by implementing natural smoke ventilation in the walls of Amager Bio. An area of 12 m^2 of natural smoke ventilation will have the same effect as the present mechanical smoke ventilation.

An analysis was made of this improvement in order to see the effect. An event tree for the improvement - implementation of natural ventilation - was set up, se Figure 0.1.

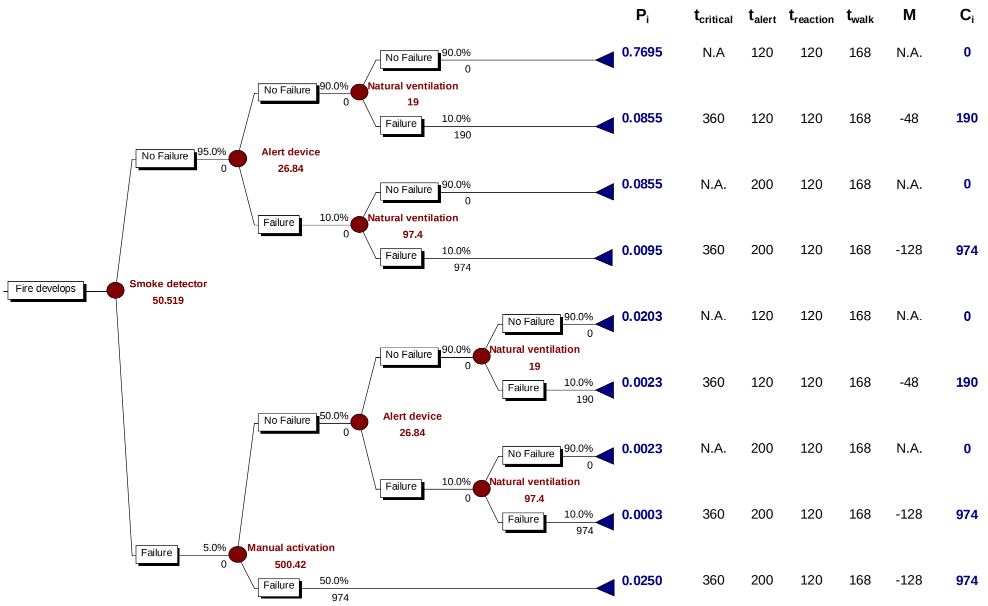


Figure 0.1: Event tree for suggested improved fire protection system. Evacuation to nearest exit.

The event tree for suggested improved fire protection system. Evacuation 60% through main entrance is showed in Figure 0.2.

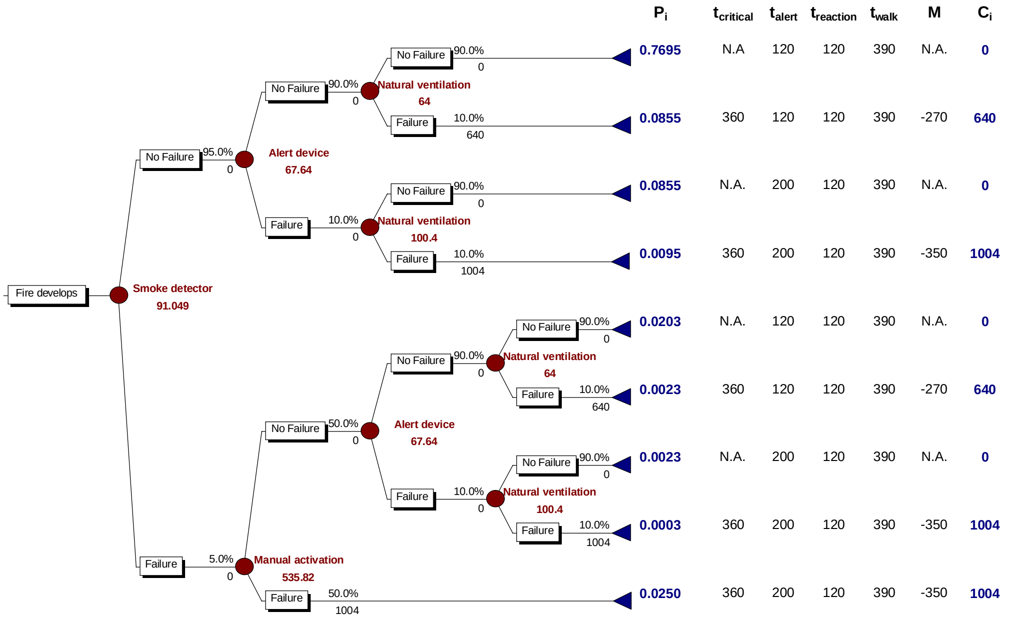


Figure 0.2: Event tree for suggested improved fire protection system. Evacuation 60% through main entrance.

The calculated risk profile for the event tree in Figure 0.1 and in Figure 0.2 is drawn in Figure 0.3.

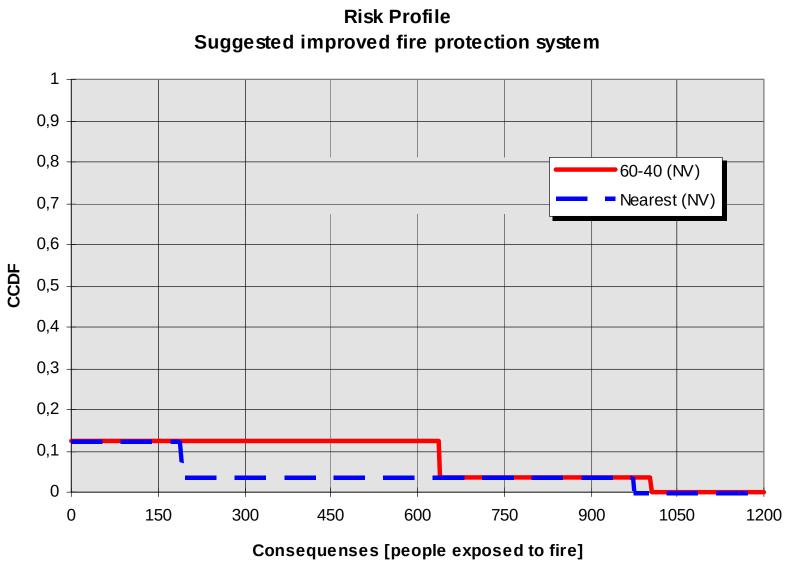


Figure 0.3: Risk profile for suggested improved fire protection system (natural smoke control system).

4. Comparison of present and future solution

One way of comparing the present fire protection system and the suggested solution is to determine their risk profile. This comparison is done for the suggested solution and the two evacuation scenarios, i.e. evacuating through the nearest exit and when 60% of the people are evacuating through the main entrance.

For people evacuating through the nearest exits the calculated risk profile for the present fire protection system and the suggested solution are shown in Figure 0.1.

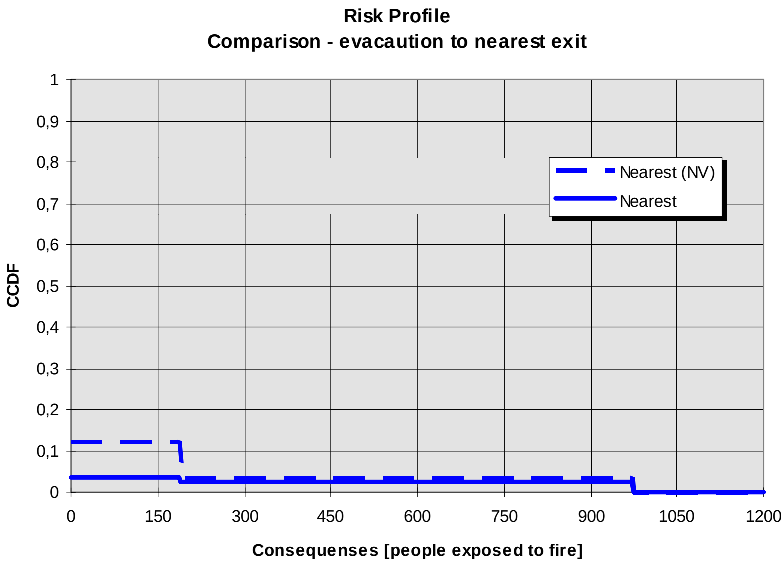


Figure 0.1: Comparison of risk profile for the evacuation scenario when people are evacuating through the nearest exit.

From the risk profiles in Figure 0.1 it is observed that large consequences can occur if there is a failure in one of the technical installations used for the fire protecting system. This means that in order to be able to prevent the large consequences the safety must be made independent of the technical fire protection solution.

The risk profile when 60% of the people are evacuating through the main entrance is shown in Figure 0.2 for both the present solution and the suggested solution.

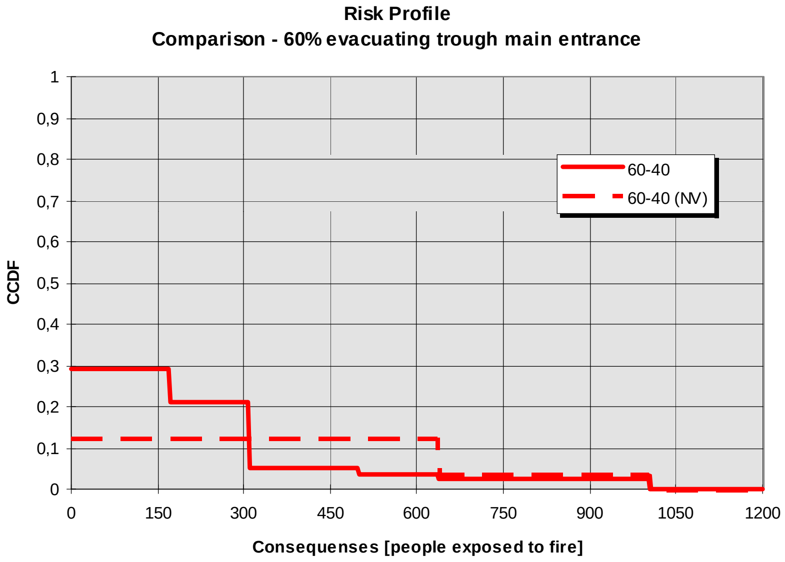


Figure 0.2: Comparison of risk profile for the evacuation scenario when 60% of the people are evacuating through the main entrance.

From Figure 0.2 it is obtained that the risk profile for the future solution lies below the present risk profile. This means that the future solution is an increment of the safety. Again it should be mentioned that if the mechanical smoke ventilation fails functioning properly there would be great consequences in form of people been exposed to critical conditions.

A risk profile can be used to compared different solution as done above and/or be used for securing a satisfactory fire safety level according to the standards set by society. In Denmark no accepted risk profiles are adapted, therefore the Dutch risk profile is adapted in order to compared the scenarios to accepted risk profile and hereby decide whether the fire safety level is satisfactory or not. Though shall it be kept in mind that exposed to fire is not equal to lethal exposure. Therefore the comparison in Figure 0.3 will not give a an accurate comparison. One could assume that 1 or 2 or 3 minutes exposure to critical conditions will be fatal. Further investigations should be carried out in order to estimate the fatal consequences of a fire.

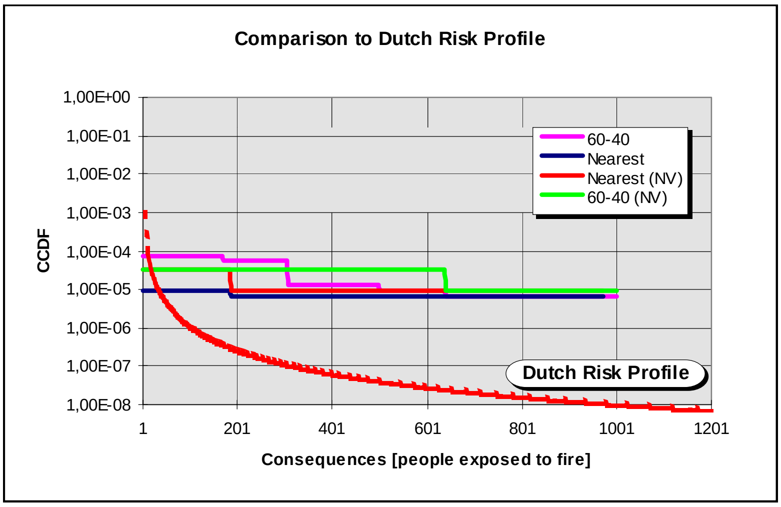


Figure 0.3: Comparison to Dutch Risk Profile.

The mean risk can be calculated by summing up the multiply of the consequences and the consequences. The number (mean) of people being exposed in case of a fire, that will develop in such a way that smoke spread will happen.

	Nearest	**60-40**	**Nearest (NV)**	**60-40 (NV)**
Mean risk	27	103	51	91

Table 0.1: Mean number of people exposed to critical conditions in case of a fire developing.

4.1 Conclusion

As mentioned in the comparison of the risk profiles for the suggested solution and the present fire protection system an acceptable risk is not reached unless the mechanical fire protection system does not functioning properly. Therefore the time available for evacuation Amager Bio must be independent of the mechanical fire protection system.

The risk profiles shows if one component fails the consequences of many people been exposed to critical conditions is just as likely as the consequence of less people been exposed to critical conditions. The event trees show, however, that the probability of failure of the individual component is small for failure in the components. Here it should be mentioned that if the smoke detector fails a large number of people will be exposed to critical conditions. The same consequences is obtained if the alert device or the mechanical smoke ventilation fails.

It could be said that the alert device is responsible to the large probability in the lower left corner of the risk profiles.

A failure in the smoke ventilation system will have fatal consequences in all evacuation scenarios analysed in this report. This is why the available time for evacuation or the evacuation time it self must be made independent of the smoke ventilation system. Implementing more exits in Amager Bio could do this. They should be installed in the opposite direction of the present exits - in the side away from the alley. If this is done the one way evacuation will be prevented and the evacuation will be more sufficient. The risk profile for this solution could lie underneath the risk profiles calculated in this report, but the investigation must be thoroughly carried out for either justify or reject this solution.

Overall the conclusion is that the fire safety level is not satisfactory due to the comparison between the accepted risk profile and the calculated risk profiles. The probability for a fire occurring and exposing people inside the assembly hall in the electrical installations has be calculated to one starts per 3905 years. The fire safety level can be increased either by decreasing the number of people allowed inside Amager Bio or by decreasing the probability of starts of fires exposing people. By decreasing the allowed number of people inside Amager Bio the consequences can be lowered - not examined. The probability of starts of fire - exposing people inside the assembly hall - can be decreased by educating staff in fire fighting, by regular inspections of electrical installations, by implementing a automatic fire alarm system etc. The above-mentioned solutions are not examined and therefore no further conclusion is drawn.

One could discuss the probability of fire starting in the room for electrical installations. The calculated probability covers fire in any electrical installation inside the assembly hall. However this probability is used for the room for electrical installations. This means that the probability is perhaps overestimated but even a minor change in the probability will not affect the fact that the over all risk profile lays way beyond what can be accepted.

5. Economical expenses

The economical expenses for implementing the natural smoke ventilation is not determined exact. The economic expenses are presented in Table 0.1.

Improvement	Economical expense
Natural smoke ventilation (12 m^2) with automatic opening device	45,000 DKr
Implementation of extra exits in Amager Bio (price per door)	6,000 DKr
Engineering expenses (including report typing)	25,000 DKr

Table 0.1: Economical expenses for the suggested solutions.

It is assumed that the time required for this analysis - only the risk assessment - is approximately 35 hours of work including writing this report - the price for a fire protection engineer is set to 700 DKr per hour.

If the fire safety analysis is not carried out before the risk assessment the cost of the consultant will be greater than the one listed in Table 0.1.

The cost of a complete risk assessment analysis will be larger because of the larger amount of calculations there will have to be done.

6. References

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