Fire safety aspects in cultural heritage – a case study in historical Delft

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Fire is an important threat to cultural heritage. Therefore 12 fire laboratories and consultants across the EU have joined together for the European Thematic-Network Fire Risk Evaluation to European Cultural Heritage (Fire-Tech). The final goal of this thematic network was to develop a decision making process in order to choose the most cost-effective fire safety measures when upgrading an object. This article presents the results of one of the case studies done in Fire-Tech. This case study consists of testing the decision making process on a building in the Netherlands. The building that was chosen is the Nieuwe Kerk (New Church) in Delft, which consists of three parts, the main church, the tower and a small shop. The total decision model involves seven steps, each will be presented in the article: Analysis of goal and budget; Analysis of the present level of fire safety; Risk Analysis; Possible fire safety actions; Decision model; Decision making; Results and comparison with existing practice. Emphasis will be laid on the risk analysis and on the decision making model. In the risk analysis an event tree approach was used combined with modelling of the fire spread, smoke spread and evacuation calculations. This showed that in the current configuration if there was a fire in the building there was a probability of 35% that people would be stuck in the tower and could only be rescued with a fire ladder and that there was a probability of 20% that the entire church would be destroyed. In the decision making step a number of measures were compared in order to find the most cost-effective solutions for an improvement of the fire safety of the church. This was done using an "Analytical Hierarchy Process" (AHP). In the AHP a number of measures can be compared in order to see which one has the most influence on a top goal (in this study defined as "Fire Safety"). In the AHP "grades of implementation" can be defined for existing fire safety measures as well as planned measures. With these values and the costs of each measure, the most cost-effective solutions to upgrade the fire safety of the building can be realized. This study showed that a number of the top measures, identified through the AHP, are organisational measures and are consequently easy and cheap to apply. This study is to be seen as an example, meaning a number of assumptions concerning the building itself and the acceptance criteria should be validated.

Key words: Cultural heritage, fire safety, risk analysis, decision model

1 Introduction

In the European project Fire-Tech the final goal is to develop an evaluation tool, taking into account all parameters expected to influence decisions when upgrading the fire safety of a cultural heritage building.

A case study into the fire safety of the Nieuwe Kerk in Delft has been made as a part of the Fire-Tech project in order to test the decision model designed in the project. This study includes a number of steps, among other a risk analysis model combined with fire safety engineering and a final decision making process, both that will be presented in this article.

This case study is to be seen as an example of the decision model, meaning a number of assumptions concerning the building itself and the acceptance criteria (i.e the acceptable size of the area within the building that is damaged during fire) may not be correct or validated.

2 Fire-Tech

Twelve fire laboratories and consultants across the EU have joined together for the European Thematic Network Fire Risk Evaluation to European Cultural Heritage (Fire-Tech). This Thematic Network, under the leadership of the University of Ghent, started in 2002 and will end in the beginning of 2005.

The main objective of the thematic network is to develop a decision model taking into account all parameters expected to influence design decisions when looking at the fire protection of cultural heritage buildings. In order to do so a number of pre-steps (or working groups) are necessary. These working groups focus on:

- Existing practices and regulations for fire safety of cultural heritage buildings
- Analyses of fires in cultural heritage
- Fire behaviour of archaic materials
- Fires safety techniques
- Risk analysis of cultural heritage

All information gathered from these steps has been put together in the decision model.
A number of case studies have then been performed in order to test and improve the model.

All information and results gathered in the project are accessible in a database on www.firetech.be and will be collected in a booklet, to be published in 2005.

3 Nieuwe Kerk, Delft

The Nieuwe Kerk is situated on the Market Square of the town Delft. It is one of the most important churches in the Netherlands as it contains the monument of William the Silent and the tomb of the Dutch royal family. The total length of the church is 100m and it also has an over 100m high tower. The church and the tower are open to the public during daytime all days except Sundays or on special occasions. On Sundays the church is used for religious service.

Figure 1. Engraving from 1675. "De Nieuwe Kerk in de 17e eeuw" (http://www.monument.delft.nl)

The tower is 109 m high and contains a staircase that is around 2m wide and has 360 stair steps. The tower has one opening to the shop downstairs, and three openings to higher platforms. There are no external staircases from the higher platforms.

The total ground floor area of the building is approximately 2025 m^2. The ground floor consists of two rooms, one 5 x 5 m^2 large shop and the main church that is approximately 80 x 25 m^2. The main construction of the church is made of masonry and the roof in the church is made of wood. The fire load in the church consists mainly of the wooden benches and the timber of the load-bearing structure (including the roof) of the church itself. In the shop the flammable contents are paper, desks, presents etc. The shop is not of cultural heritage value.

It is assumed that the maximum number of people in the tower, the shop, and the church during public opening hours will be 50, 25, and 100 respectively.
The maximum number of people that will be in the church during a religious service is assumed to be six hundred. However the church occupancy can vary between 300 and 1500.
In the rare occasion of a funeral of the Dutch royal family, up to 2000 people will be present in the church.

4 Decision Model

The decision model, developed within Fire-Tech, involves four steps: First of all an analysis of the goal of the study has to be made and the budget available has to be identified (4.1). Thereafter an analysis of the present level of safety of the building will be performed, including a risk analysis (4.2). After this step possible fire safety actions to improve the fire safety of the building will be identified (4.3). Finally the decision making will be performed using an hierarchy model and conclusions will be drawn as to the most cost-effective measures in the building (4.4).

4.1 ***Analysis of Goal and Budget***

In the first step one needs to identify the goal of the study (i.e. what is the need?). The assumed need in the Nieuwe Kerk is to minimize any damage by fire to the building and to people inside the building. One also needs to identify the time and money available for an eventual increase of the fire safety level of the building and for the study. The time available and the money available are not an issue in this example, although cost effectiveness of possible fire safety measures will be considered.

4.2 ***Analysis of the present level of fire safety***

To analyse the present level of fire safety, four points need to be addressed. The first is identifying the fires that have taken place in similar buildings, thereafter the behaviour of eventual critical ancient materials present in the church needs to be analysed. Furthermore the regulations that govern the use of the church need to be clear, the fire safety measures present in the church need to be identified. The information in this chapter can be used to perform a risk analysis (4.3).

4.2.1 Similar fires

In high buildings such as churches falling heavy objects such as church bells or parts of the roof could pose a problem for the firemen's intervention and for the historic contents in the church such as the tomb of William the Silent. Causes of fires in cultural heritage buildings can be seen in the FireTech WG2 report [1].

From a Dutch case, the Sint Petruskerk (Saint Peter's Church) in Oisterwijk, it appears that the evacuation of people in the church can be a problem. Close inspection reveals that it took the fire services approximately 20 minutes to evacuate 100 people with limited mobility from the church during a fire.

4.2.2 Behaviour of archaic materials

More information about the fire behaviour of critical parts of the church, such as the timber roof structure, the masonry walls, the wooden church benches and historical items in the church are needed. In the Fire-Tech project, information on fire behaviour of such material was gathered. Additionally, information was gathered about fire resistance of old doors. This can be used when old doors are important to the compartmentation of the fire, e.g. in the case of the *Nieuwe Kerk* the fire resistance of a separating door between the tower and the shop may be relevant. Also the fire resistance of the exterior doors can be of importance to avoid the spreading of exterior fires (due to arson) to the interior.

4.2.3 Regulations applicable

This church is situated in Delft, the Netherlands. In the Netherlands monuments fall under the "monuments law" and under the Dutch building decree for existing buildings. If a change in a monument needs to be made, a permit is required from the local government, who should consult the Netherlands department for conservation. Also other interests such as public health and safety have to be taken into consideration before the local government will decide on eventual changes.

4.2.4 Fire safety measures present

A number of fire safety measures are present in the church, such as sprinklers. The sprinklers are situated under the roof in the church. They have however to be opened manually by the fire services and vary in age from 70 years old to new. No detection or sprinklers are available in the shop. The fire services have equipment to rescue people from the lowest platform of the tower.

4.3 ***Risk analysis***

Seven steps are involved in the risk analysis. The first step is to identify the objectives of the risk analysis and the acceptance criteria. Thereafter the fire scenarios have to be identified. As a third step the events that can take place during a fire will be identified, and as a fourth step the event tree will be designed. Thereafter the quantification of the fire development and escape times should be made. Using all earlier steps the assessment of damage will be made and finally conclusions will be drawn. Hereafter the 7 steps are discussed in detail. In this study the risk analysis will be performed on the church as it is now to find problem areas. However a risk analysis can also be performed after having identified problem areas and thus including a number of fire safety measures.

Hereafter the 7 steps are discussed in detail.

4.3.1 Objectives and Acceptance criteria

No irreversible damage to persons (no persons even slightly injured) and the probability of having damage to more than 4% (in this case $80m^2$) of the building should be less than 10% in the case of a fire. Damage to the tower will not be taken into account in this report. These acceptance criteria have been chosen by TNO for the purpose of the study and have not been confirmed by the responsible authorities.

4.3.2 Definition of Fire Scenarios

• Scenario 1: fire in the church.

The fire in the church can be caused by arson, by candles or by faulty installations. It is assumed that an initial fire, in a church bench, will develop to surrounding church benches according to a medium growth rate ($0{,}012kW/s^2$). The fire in the church will be assumed to be fuel limited. According to the Natural fire safety concept (NFSC) [2] an office building will have a RHR of $250kW/m^2$ if the fire is fuel bed controlled. Thus it will be assumed that when 250kW is reached, $1m^2$ is involved in the fire. The fire will be in the growth phase at least during the first twenty minutes, because of the size of the building. Using a zone model to calculate smoke temperatures Halfill [3]calculations showed that the smoke temperature in the church was not high enough to ignite the wooden structure of the roof during the first 20 minutes of the fire.

• Scenario 2: fire in the shop.

The fire in the shop could be caused by a faulty installation or by arson. A rapid fire development is suggested for a shop in NFSC. The fire in the shop will be assumed to have a RHR of 250 kW/m2 when it is fuel bed controlled. The amount of combustible material is less than in a normal book, clothes or souvenir shop and therefore this value will be seen as sufficient. The growth phase will go on until a value of approximately 6,25 MW is reached. When the fire reaches this level it is assumed that the fire will spread from the shop compartment to the church, where the fire continues according to a medium fire growth. The fire in the shop is assumed to be stable until 70% of the fuel is burned, this will be after the first 20 minutes.

4.3.3 Selection of Events

As a starting point a developing fire is assumed. Thereafter selection of events (or branches for the event tree) has been done as follows: Fire location - > Time of day -> Fire detected - > Extinguished by staff - > Sprinkler control the fire - > Fire brigade control the fire

Fire location: It is assumed that the probability of the fire to start in the shop is 50% and in the church is 50%.

Time of day: The probability of a daytime fire or a night time fire will be assumed as 70-30 as more people are present during the day than during the night.

Fire detected at early stage: An early stage means at a time early enough to allow extinguishing by staff. The probability of detecting the fire in the church during an early stage will be 70% during the day, and 0% during the night. The probability of detecting the fire in the shop during an early stage will be 70% during the day. During the night because of the burglary alarm in the shop a value of probability of early detection of 50% will be used.

Extinguished by staff: This event only takes place during the daytime and if the fire is successfully detected in an early stage. Even though in these cases the staff is technically in the position to extinguish the fire, it is assumed that the staff has not had any fire fighting training and a value of 50% should be used.

Fire brigade to control the fire: If the fire brigade is able to control the fire the damage will not extend beyond the area where it was when the fire service's operation began to be effective. If the fire services are unsuccessful to extinguish the fire it is assumed that the fire will spread to the entire fire compartment. The probability of the fire brigade to control the fire when they arrive depends also on the detection time. If the staff detects the fire in an early stage, it is assumed that the firemen will be present and effective after 10 min and the assumed probability that they will be able to control the fire is 80%. If the fire is detected by staff at a later stage it is assumed that the firemen will be present and effective after 15min. The probability that the firemen will be able to control the fire will equally be assumed to be 80%.
During the night the time to detection of the fire depends on if passers-by see the fire or if the sprinklers already present inside the roof are activated by the fire. The church is in a busy place in the centre of Delft and it is assumed that a passer-by will see a fire and alarm the fire services within the first 15 minutes. It is then assumed that the firemen will be present and effective after 20 min. The probability that the firemen will be able to control the fire is assumed to be 50%.

4.3.4 Design of Event tree

The information above leads to the following event tree (table 1) that applies to the situation in which no additional fire safety measures are implemented.

Table 1. Event tree for no additional fire safety measures

	Place	Time	Detected Early stage	Extinguished by staff	Extinguished by Fire Brigade	Probability	Nr. Scenario
No additional measures	Shop (0.5)	Day (0.7)	Yes (0.7)	Yes (0.5)	-	0.1225	1
				No (0.5)	Yes (0.8)	0.098	2
					No (0.2)	0.0245	3
			No (0.3)		Yes (0.8)	0.084	4
					No (0.2)	0.021	5
		(0.3)	Yes (0.5)		Yes (0.8)	0.06	6
					No (0.2)	0.015	7
			No (0.5)		Yes (0.5)	0.0375	8
					No (0.5)	0.0375	9
	Church (0.5)	Day (0.7)	Yes (0.7)	Yes (0.5)	-	0.1225	10
				No (0.5)	Yes (0.8)	0.098	11
					No (0.2)	0.0245	12
			No (0.3)		Yes (0.8)	0.084	13
					No (0.2)	0.021	14
		Night (0.3)			Yes (0.5)	0.075	15
					No (0.5)	0.075	16

4.3.5 Quantification of Fire Development and Escape times

• Escape:

It is assumed that the staff will detect the fire after three minutes. At that time, the staff will immediately alarm the occupants, and the evacuation will start.

Church: In the church, both during religious service and during the opening hours to the public, the mobility of the occupants can be limited. Given the presence of a large escape door, and a number of other emergency exit doors, it is assumed that during religious service the church can be empty within the time it takes for a person with reduced mobility, sitting at the other end of the church to get out through the main door. The length of the church is 80 m and a speed of 0.5 m/s will be assumed. Also a time of 30 seconds will be allowed to get out of the bench row. A safe approximation of the time to escape is 5 minutes if only a normal number of persons present with reduced mobility are present.

Shop: The evacuation of the shop will be rapid, the people can escape either into the church or out the main entrance, and is assumed to be finished maximum one minute after detection of the fire.

Tower: The tower contains around 360 steps to the highest platform 300 steps to the second platform and 200 steps to the first platform. The steps are very narrow. An initial velocity of 1 step/s is taken for the first 50 steps. After that a velocity of 0.5 steps / s is used until the bottom of the staircase is reached. This means that it will take approximately 11 minutes for the people from the top floor to escape, 9 minutes for the people from the middle platform to escape and 6 minutes for the people from the first platform to escape. The church will be empty before 6 minutes during daytime and thus no congestion will take place at the exit of the tower. It is emphasized again that the actual numbers are exemplary and further validation of the underlying assumptions should be made before general conclusion are drawn.
It is assumed that the fire becomes dangerous for people in the tower because of smoke or fire in the shop when the fire is so large that the staff cannot extinguish it or when firemen cannot control the fire in the church. From this point, no exit is possible from the tower anymore.
The evacuation from the tower can be completed within 14 minutes, (3 minutes detection time and 11 minutes escape) according to the calculations above. Therefore it can be safely stated that people present in the tower can always escape if a fire starts in the church if they are warned on time.
In the shop if the staff cannot extinguish the fire people will thus be trapped up in the tower waiting for escape by the high-rise ladder, or for the fire to be extinguished by the fire brigade.

• Fire Development:
The aim of quantifying the fire development is to derive information on how different fire related parameters vary with time. As said in the chapter fie scenarios, 4.3.2, according to NFSC a fuel bed controlled fire inside an office building will have a RHR of 250 kW/m^2. Thus, to make a simplification in this study, for every additional 250 kW that is produced another m^2 is assumed to be involved in the fire. In 4.3.2 a medium fire development was assumed for the church, and in the shop a rapid fire development was assumed until the entire shop was engulfed in flames, thereafter a medium fire growth rate in the church was assumed. This gives the following fire development (see figure 2), with the time represented on the horizontal axis and the area involved in the fire on the vertical axis.

4.3.6 Assessment of Damage

Combining the data from escape, fire development and the event tree the following table is obtained (table 2).
In the table, the 16 different scenarios that follow from the event tree have been characterised by the state of the fire (extinguished, controlled or total damage), the probability of occurrence of the scenario, the damaged area within the church and the shop, and the consequences for human beings. Since the event tree is based on the situation in which no additional fire safety measures are taken, this also applies to the table.

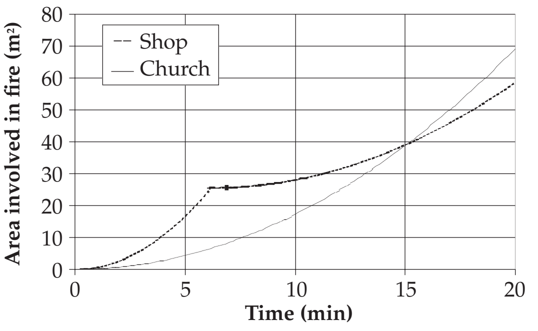

Figure 2. The area involved in the fire versus time

Table 2. The assessment of damage

Scenario	State	Probability	Consequence (m^2) Church	Consequence (m^2) Shop	Consequence persons
1	Extinguish by staff	0,1225	-	11	(1)
2	Control by fire brigade	0,098	3	Total Damage	(1)
3	Total Damage	0,0245	Total Damage	Total Damage	(2)
4	Control by fire brigade	0,084	14	Total Damage	(1)
5	Total Damage	0,021	Total Damage	Total Damage	(2)
6	Control by fire brigade	0,06	3	Total Damage	None
7	Total Damage	0,015	Total Damage	Total Damage	None
8	Control by fire brigade	0,0375	33	Total Damage	None
9	Total Damage	0,0375	Total Damage	Total Damage	None
10	Extinguish by staff	0,1225	3	-	None
11	Control by fire brigade	0,098	17	-	None
12	Total Damage	0,0245	Total Damage	Total Damage	None
13	Control by fire brigade	0,084	38	-	None
14	Total Damage	0,021	Total Damage	Total Damage	None
15	Control by fire brigade	0,075	70	-	None
16	Total Damage	0,075	Total Damage	Total Damage	None

(1): Evacuation stopped after 1 min. People left in tower to be evacuated when fire is extinguished or evacuation by high ladder firemen.

(2): Evacuation stopped after 1 min. People left in tower. Evacuation by high ladder firemen.

The previous table can be rearranged to give a clear picture of the probability of a category of scenarios, e.g. the probabilities for damaging a certain floor area, for trapping people in the tower, or other cumulative probabilities.
Cumulative probability versus fire damage area results in the following values in table 3.

Table 3. Probability of fire damage

Hazard	**Probability**
Total loss of church	22%
70 m^2 church damaged	7,5%
30 - 40 m^2 church damaged	12 %
10 - 20 m^2 church damaged	18%
3 m^2 church damaged	28%
No damage to church	12,5%

Cumulative probability versus consequences for persons (i.e. being trapped in the tower) results in the following values (table 4).

Table 4. Probability of consequences for persons

Hazard	**Probability**
People left in tower to be evacuated by high ladder firemen.	4,5%
People left in tower to be evacuated when fire is extinguished or evacuation by high ladder firemen.	30%
None	65,5%

4.3.7 Risk evaluation

The acceptance criteria for this study were that no people should be injured and that the probability of having damage to more than 4% (in this case 80 m^2) of the building should be less than 10% in the case of a fire.

One can see that the first acceptance criterion concerning the people can in principle be fulfilled in this case. This acceptance criterion could be checked with the fire brigade, checking how many people they can rescue with their ladder.
One can see that the second acceptance criterion cannot be fulfilled in case of any additional fire safety measures. Therefore a number of measures should be identified to improve the fire safety of the *Nieuwe Kerk*.

4.4 ***Possible fire safety actions***

In this chapter a number of measures useful for the protection of people and the building will be identified. The most appropriate measures for this case are listed below in table 5. For a description of the below mentioned measures, refer to the complete report of the *Nieuwe Kerk* in Fire-Tech [4].

Table 5. Possible fire safety actions

Technical Actions	**Technical actions specific for the Nieuwe Kerk**	**Non technical actions**
Automatic fire detection	CCTV	Control of installations
Alarm systems	Burglary alarm	Limit unnecessary flammable items
Visual signals / evacuation plans		Procedures for evacuation of people
Smoke control		Training of personnel
First-aid fire fighting equipment		Contact with fire services
Sprinklers		Guides with visitors in tower
Fire Resistant glazing		"Fire Guards" during large events
Inert insulating materials		Renovation Guidelines
Intumescent materials		

5 Decision making

5.1 Technical approach

In this chapter, first of all the structure of the decision method has to be decided on. Questions that need consideration are: What is the main goal or policy? What are the objectives, i.e. how can the policy be attained? What strategies can be used to obtain the objectives? Finally what measures/parameters have been defined. These questions can be considered as a hierarchy, in which the level of consideration ranges from very general (e.g. main goal: fire safety) to very detailed (e.g. one of the possible measures: training of personnel). From each of the levels to the level above there is a need to set a score or an effectiveness of the measure/strategy and objective on the level above.

In the next paragraphs, the allocation and processing of score figures will be shown.
The following variables will be used:

S(a,b)	the score (importance or effectiveness) of a on b,
I(a,1)	the normalised influence of a on the main goal,
G(a)	the "grade of implementation"; the extent to which a certain measure is present and effective,
EI	the "effectiveness index"; a measure for the overall fire safety,
CE_a	the cost effectiveness of measure a.

5.2 ***Structure of decision method***

In the following tables, all items have been numbered. The main goal is number 1, both objectives are numbers 2 and 3, the strategies are numbered 4 – 8, and finally the measures are numbered 9 – 27.

Table 6. Main goal

Main Goal	1. Fire Safety of Cultural Heritage Building

Table 7. Objectives

Objectives	2. Protect Building incl. immovable contents	3. Protect People in the building

Table 8. Strategies

Strategies	4. Avoid Ignition	5. Limit fire spread inside compartment	6. Limit fire spread outside compartment	7. Allow escape	8. Allow fire services to act

Scores Objectives – Main Goal

First of all, it needs to be defined to what extent each of the objectives (protection of the building and of the people) contribute to the main goal (fire safety). In this case it is assumed that it is equally important to protect the building (and its non-moveable contents) and the people inside. Because of the national importance of the building it is chosen to attribute the same importance to the building as to the people inside it. This is an arbitrary choice. Both these objectives can also be used as main goals. The different scores will be as follows:

S(2,1) = 0,5   S(3,1) = 0,5

Table 9. Measures

Measures (9-13)	Sprinklers	First-aid fire fighting equipment	Automatic fire detection	Alarm systems	Visual signals/ evacuation plans
(14-18)	Smoke control	Fire resistant glazing	Inert insulating materials	Intumescent materials	CCTV Control of
(19-23)	Training of personnel	Procedures for evacuation	Fire guards during large events	Guides with visitors in tower	installations
(24-27)	Guidelines during renovation	Burglary alarm	Limit flammable items	Contact with fire services	-

It should be noted that in the AHP model the influence of one measure on another is not taken into account. In the list of measures it would thus be useful to note any adverse effect one measure can have on another and take this into account when making a final selection.

The score represents the relative importance/effectivity. The notation is S(objective, main goal). The scores show that the importance of both objectives on the main goal are 50% each. Analogous notation will also be used on the lower levels.

Scores Strategy - Objectives

After the decision on the scores of the objectives on the main goal has been made, the scores (effectivity) of the strategies on the objectives have to be decided on.

Concerning the first objective (protecting the building), it is assumed that strategies 4, 5, 6 and 8 are equally important. Strategy 7 has no effect, because allowing escape does not help to protect the building.

S(4,2) =0,25 S(5,2) =0,25 S(6,2) =0,25 S(7,2) =0 S(8,2) =0,25

The second objective concerns the protection of people inside the building. Here strategy 7, allowing escape, is the most important. Thereafter strategies 4, 5 and 8 are equally important. Strategy 6 is the least important. Strategy 6, limit fire spread between compartments is considered less important than the rest because the only separate compartment in the church would be the shop, but if a fire starts in the shop people will be able to get out of the church anyways. If a fire starts in the church it is assumed that people will be able to get out of the shop and the tower and out of the church. It is thus more important to limit the fire spread inside a compartment than between them.

S(4,3) =0,2　　S(5,3) =0,2　　S(6,3) =0,1　　S(7,3) =0,3　　S(8,3) =0,2

Thereafter, one lever deeper in the analysis, scores from all measures to the strategies have to be set. These scores can be seen in table 10. The scores for the previous levels were normalised (always adding up to 1). For the scores of the measures however, a large number of scores needs to be assigned and therefore it would be impractical to normalise them right away. Instead, scores are given on a scale of 0 (no importance) – 10 (ultimate importance). These scores will be normalised hereafter.

Table 10. Scores from measures to strategies

Strategy \ Measure	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
4	0	0	0	0	0	0	0	0	0	0	5	0	3	3	9	9	5	7	3
5	9	8	7	0	0	5	0	4	3	3	5	0	4	2	2	4	1	5	5
6	7	3	2	0	0	6	7	5	5	1	3	0	2	1	1	3	0	3	6
7	5	4	7	8	7	6	2	1	1	5	6	9	7	7	3	3	1	3	6
8	7	3	6	4	2	7	5	6	6	4	4	5	3	4	1	1	2	3	9

After all scores on all the levels have been assigned, they are normalised and influence parameters are calculated (I). Whereas a score (S) represents the importance of a low level parameter to another parameter on the level directly above, the influence parameter (I) represents the importance of the low level parameter on the top parameter (main goal). In this way, the influence of all objectives, strategies and measures on the main goal are calculated. The results from this are shown below.

I(2,1)=0,5　　I(3,1)=0,5

As given in the scores it has been assumed that the safety of people and the protection of building are equally important in this example.

I(4,1)=0,225　　I(5,1)=0,225　　I(6,1)=0,175　　I(7,1)=0,15　　I(8,1)=0,225

From these numbers one can identify the most important strategies for obtaining the overall goal. Avoiding ignition, limiting fire spread within the compartment and contact with firemen are the most important strategies. Thereafter avoiding fire spread between compartments is important and last allowing escape.

From these results the classification of importance of measures is obtained (total 100%) and can be seen in table 11.

Table 11. Classification of importance of measures

n	Measure	I(n,1)	n	Measure	I(n,1)
1	Contact with fire services	8,6 %	11	Guides with visitors in tower	4.8 %
2	Sprinklers	8,0 %	12	Inert insulating materials	4,8 %
3	Renovation Guidelines	7,7 %	13	Intumescent materials	4,5 %
4	Limit flammable items	7,6 %	14	Fire resistant glazing	4,0 %
5	Training of personnel	6,0 %	15	Burglary alarm	3,6 %
6	Smoke control	6,5 %	16	CCTV	3,0 %
7	Control of installations	6,3 %	17	Procedures for evacuation	2,9 %
8	Automatic fire detection	5,8 %	18	Alarm systems	2,4 %
9	Fire guards	5,5 %	19	Visual signals/evacuation plans	1,7 %
10	Fire fighting equipment	5,1 %			

Out of the first five measures it is only sprinklers that will require a major investment. The rest of the measures are organisational measures.

5.3 ***Refinement of the technical effectiveness of each measure***

The above calculations were made assuming that in the present situation the measure was not implemented and in a future situation the measure will be fully implemented. In order to have a more refined approach so called "grades of implementation" (G) on a scale of 0 to 1 can be used, to represent both the present and future situations.

E.g. the old sprinkler system, present in the church, may not be very effective and is thus given a G = 0.1. If modern sprinklers would be fit in the church, they would be much more effective but still it might be hard to have reliable and effective sprinklers on a ceiling that is very high; this could be expressed by G = 0.8. Such present and future grade of implementation values have been defined for all possible measures, see table 12.

Thereafter with the increase of a grade of implementation an increase in the effectiveness index can be found, where the effectiveness index indicates the contribution of each measure to overall fire safety as calculated by AHP. The overall fire safety is represented by the effectiveness index EI, which is calculated as follows:

$$EI = \sum_n EI_n$$

$$EI_n = I(n,1) \cdot G(n)$$

$$\Delta EI_n = I(n,1) \cdot \Delta G(n)$$

In these formulae, n is the number of each measure. Using these formulae, again a ranking can be made of all measures based on their likely improvements of the fire safety (ΔEI).

5.4 *Refinement of the cost effectiveness of each measure*

The ranking from the previous paragraph, based on the contribution to EI of each improved measure (ΔG) does not include the costs of a specific measure. Therefore it will give a technically effective measure a high ranking, even if the costs are disproportionately high. In practice it is important to incorporate cost effectiveness in the calculation.
This done by calculating the ratio between improvement of the fire safety over the costs of a measure:

$$CE_n = \Delta EI_n \,/\, c(n)$$

in which n is the number of the measure, and $c(n)$ represents the total costs for implementing this measure.
Now it is possible to rank the measures for cost effectiveness. In Figure 3, the two rankings (based on technical optimisation and on cost effectiveness optimization) have been compared.

Table 12. Present and future grades of implementation

Nr.	Measure	Imple-mentation present / future	Nr.	Measure	Imple-mentation present / future
1	Sprinklers	0.1 / 0.8	11	Training of personnel	0.3 / 0.9
2	Fire fighting equipment	0.3 / 0.7	12	Procedures for evacuation	0.2 / 1.0
3	Automatic fire detection	0.0 / 0.5	13	Fire guards	0.0 / 0.9
4	Alarm systems	0.0 / 0.8	14	Guides with visitors in tower	0.0 / 0.7
5	Visual signals / evacuation plans	0.2 / 0.8	15	Control of installations	0.3 / 0.6
6	Smoke control	0.0 / 0.8	16	Renovation Guidelines	0.3 / 0.7
7	Fire resistant glazing	0.0 / 0.7	17	Burglary alarm	0.5 / 0.6
8	Inert insulating materials	0.0 / 0.7	18	Limit flammable items	0.6 / 0.9
9	Intumescent materials	0.0 / 0.7	19	Contact with fire services	0.7 / 1.0
10	CCTV	0.4 / 0.5			

On the horizontal axis, the figure shows the total costs of a set of measures. On the vertical axis the effectiveness index, achieved with those measures, is shown. The choice of the set of measures is based on the ranking of the measures. The triangular marks represent sets of measures that would be chosen if only the technical optimisation is carried out. The diamond marks represent the sets of measures that would be chosen after carrying out a cost effectiveness calculation.

In the current situation, the *EI* is 0.23. This can be seen in the figure: in the present situation no costs are made to take additional fire safety measures. At costs=0 both lines show an *EI* of 0,23, the diamond and triangular marks in the graph representing "empty sets" of additional fire safety measures. If all measures are applied to a credible level (G), the EI will reach 0.77. In the example, this would involve total costs of 1.100 k€. However, with an investment of only 475 k€, the *EI* can already be improved from 0.23 to 0.63 if the choice of measure is based on a cost effectiveness calculation. If only a technical optimisation is done, the choice of measures would be different and the same investment would give an *EI* of only 0.47.

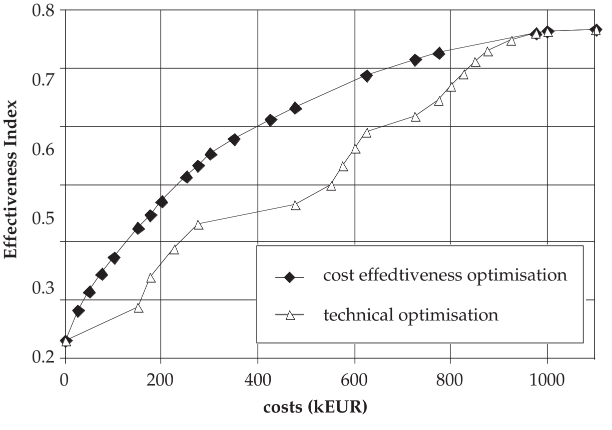

Figure 3. Overall fire safety versus costs with and without cost effectiveness calculation

6 Results and comparison with existing practice

It is not clear if sprinklers would be acceptable inside the church itself to limit damage to the church and allow escape. In the risk analysis done for the *Nieuwe Kerk* in the Fire-Tech study [5] it has been shown however that sprinklers would limit the damage to the church to an "acceptable" level according to the assumptions made by TNO.

A number of the top ten measures are organisational measures and easy and cheap to apply. Examples are: contact with fire services, guidelines during renovation to avoid ignition, a limitation of unnecessary flammable items and training of personnel.

The criterion of $80m^2$ damage in the risk analysis is a tougher recommendation than required by the building decree, which assumes a larger compartment size and will thus in principle allow the entire compartment to burn down. The reason for having the tougher criterion is because of the monumental importance of the church and its contents to the Netherlands.

7 Conclusions

The object of the study, the *Nieuwe Kerk* in Delft, has been used as an example. A number of assumptions concerning the church itself, the effectiveness of measures and the costs involved, should be validated. However the case study has provided a clear example of the possibilities that the methodology, developed within Fire-Tech, has to offer.

The methodology applied in the case study consists of five steps:
1. preliminary steps: definition of the fire safety objectives and the available time and budget.
2. survey of the present fire safety situation: which measures are present in the building?
3. risk analysis
4. survey of possible fire safety measures: which additional measures could be taken?
5. decision making: functional/technical and/or economical optimisation of the choice of measures to be taken. The optimisation is aided by computer models.

In Fire-Tech information has been collected concerning the identification of European regulations, identification of fires in cultural heritage, information regarding archaic materials and information on fire safety techniques. Also, methods for risk analysis and a decision model have been proposed. The case study of the Nieuwe Kerk in Delft has shown that the collected data, together with risk analysis can be combined with a decision model in order to compare a number of fire safety measures and to allow the cost-effective upgrading of a historical building.

Using the method is straightforward but nevertheless requires careful consideration. The all-determining factor is the selection of scores. The scores can be filled in using expert judgement or applying fire safety engineering techniques. The selection of these values can be done by multiple experts. Although these experts are supposed to be familiar both with fire safety and with cultural heritage, the scores assigned to the objectives, strategies and measures can be different. t is noted that the calculated effectiveness index is strongly dependent on expert judgement while entering all scores and grades. This can lead to subjective interpretation and inconsistencies between different individuals filling out the scores and grades.

It should be noted that, even though for any specific case it is possible to calculate an effectiveness index (EI) to represent the overall fire safety, this value of EI can only serve for comparison of different alternative sets of fire safety measures. It is impossible to define a universal threshold value, because in absolute terms the figure has little meaning.

A clear advantage of the AHP method is that it allows the user to oversee a large number of measures and to investigate the sensitivity to specific measures of the overall fire safety level (represented by the effectiveness index). Also, the reasoning behind the choice for a certain set of fire safety measures can be made transparent using this method.

An additional cost effectiveness calculation, as has been added to the spreadsheet AHP-model during the project, can clearly point out which measures per spent Euro contribute most to the overall fire safety level. The case study has shown that this can significantly improve the allocation of budget to an optimised set of fire safety measures.

Through this study this method has shown its potential to determine and upgrade the fire safety level of monumental buildings. It allows to determine the present fire safety level through risk analysis and further to decide on most cost-effective solutions for the upgrading of the building through decision modelling. It is recommended to further use this method for upgrading of cultural heritage buildings.

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