A Cost-Benefit Analysis of Fire Protection Systems Designed to Protect Against Exterior Arson Fires in Schools

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A Cost-Benefit Analysis of Fire Protection Systems Designed to Protect Against Exterior Arson Fires in Schools

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ABSTRACT

Fires in school buildings caused by arson are a major problem in Sweden. The costs of these fires are disproportionately high compared to the costs of fires in buildings in general, and it has been shown that fires that start outside of the building in connection with an exterior wall, so called exterior fires are especially problematic. However, technical systems can be used to mitigate the consequences of arson fires in school buildings. In this paper a cost-benefit analysis is used to calculate cost-benefit ratios for four technical systems used to detect these types of fires.

INTRODUCTION

Almost every day one or two school fires occur in Sweden. In most cases, arson is the cause of the fire and it accounts for more than 40% of the annual 400-500 fires in Swedish school buildings (schools and pre-schools) [1]. In contrast, national statistics supplied by the Swedish Civil Contingencies Agency (MSB) [2] show that 10 to 15% of all fires occurring annually in Swedish buildings (approximately 11.000) are caused by arson. This means that arson is almost four times as common in school building than in buildings in general. It must be pointed out that very few people are injured in fires in Swedish school buildings, making the many arson fires primary a property issue.

The costs of fires in school buildings are also disproportionately high compared to fires in buildings other than school buildings. According to statistics provided by insurance companies the costs of fires in school buildings are up to 500 million SEK annually, amounting to more than 10 % of the total cost of fires in Sweden [1]. It has been shown in studies of statistics [3] that many of the most costly arson fires occur in one-story school buildings where the fire starts outside the school building and spreads into the attic space via ventilation openings in the eaves. Thus, in order to reduce the overall cost of school fires, one important first step would be to reduce the number of this particular type of school fire.

In order to take this first step, almost 60 arson fires in Swedish schools have been investigated in a case study [4]. The objective of the case study was to identify means to minimize the damage of school arson fires in the future. It is concluded that fire detection systems can be used to reduce the consequences of fires in school buildings. An inventory of technical systems used for fire detection/mitigation in schools [5] has shown that there are several of technical systems suitable for detection of fires beginning at or close to an exterior wall, so called exterior fires. The efficiency and costs associated with these systems vary, and there are few comparisons made of the systems with regard to these aspects. Hence, when it comes to investments to prevent or mitigate the consequences of fires, decision makers (e.g. school principals, building owners or local politicians) have limited information to base a decision upon.

This paper shows how cost-benefit analysis [6] can be used to evaluate the positive (benefits) and negative (costs) effects of a technical system. If the benefits outweigh the costs, the measure should be taken. A cost-benefit analysis alone could be used to guide decision makers in their choice of technical system, but there are a lot of uncertainties associated with the calculations e.g. the size of fire damage and effects of the technical systems, which must be taken into account. These uncertainties must be addressed and discussed. This paper aims to contribute to the provision of better information that will assist decision makers face with decisions concerning investments in fire detection systems.

Technical Systems

Four technical systems for detecting exterior fires are analysed in this paper: two types of linear heat detectors (maximum temperature detection and differential heat detection), smoke detectors and thermo sensors. Their characteristics are discussed below.

The maximum temperature linear detector is composed of two copper-coated steel wires that are individually insulated with a heat-sensitive polymer and when the polymer insulation is heated to a specified temperature, the conductors will create a short circuit and detection will take place [5, 7]. The differential linear heat detector [5] consists of a very thin sealed steel tube connected to a pressure sensor. When the tube is heated the sensor will register the rapid increase in pressure and detection takes place. Both types of linear heat detectors are usually placed on the eaves of one-story school buildings and they will detect a growing fire along the entire length of the cable.

One-storey school buildings in Sweden are in many cases fitted with small un-insulated attics that are naturally ventilated with ventilation openings in the eaves. Smoke detectors can be placed in these types of attics to detect smoke that flows into the attic from the outside through the ventilation openings [5]. Both linear heat detectors and smoke detectors can be connected to an automatic fire alarm system. It can be an existing automatic fire alarm system or a local manual fire alarm system

The thermo sensor uses thermal imaging for infrared surveillance and can be used to detect suspicious actives around buildings [5]. Normal closed circuit camera surveillance (CCTV) around public buildings is problematic due to issues of privacy and it has therefore, in contrast to other countries, been difficult to obtain permission to install such cameras from the Swedish regulatory agencies. Since it is very hard to identify individuals with thermo sensors are the issues of privacy decreased and therefore have several authorities approved the installation of thermo sensors around school buildings. Thermo sensors are usually connected to a security company through an Ethernet connection. If the sensor detects suspicious activity it alerts personnel or guards that can take actions accordingly.

METHOD

A comparative cost-benefit analysis is presented in this paper by deriving a cost benefit ratio for each technical system. The analysis has been conducted in the following steps:

- Estimated benefit based on the time to detection
- Estimated cost of the technical system

The efficiency of the systems has been evaluated with qualitative reasoning in the discussion section. The analysis has been conducted as a case study on a small school building where all the systems could be applied.

Cost-Benefit analysis

It is necessary to study the costs and benefits during the whole lifetime of the technical system and this can be done by using a life-cycle cost analysis. In such an analysis, both the initial investment costs (e.g. cost of planning, materials and labour) and future costs (e.g. cost of repairs, service, running and maintenance) are included.

Costs incurred at various times during the economic lifetime of the system are not directly comparable, and it is important to know when the costs occur to be able to take them into account. The net present value method is one method that can be used to compare costs that have occurred at different times [6, 8]. The net present value method is based on the assumption that the running costs are not tied up when the system is installed and thus can it be used for other investments. Costs at different times are moved in time by the aid of an interest rate in order to compare them, i.e. to when the system was installed. The real rate of interest for calculating purposes, r, reflects the potential income and inflation (see equation 1).

$$r = \left(\frac{1+r_c}{1+I}\right) - 1 \qquad \text{equation 1}$$

Where r_c is the interest rate calculated for costing purposes and I is the inflation. It is difficult to find an interest rate suitable for these purposes. A real interest rate of 5% has been used in previous cost-benefit analyses of fire protection systems performed in Sweden [6, 9] and therefore it is also used in the present analysis. The following equation is used to calculate the life-cycle cost (LCC) of each technical system:

$$LCC = I_{in} + \sum_{i=0}^{n} \frac{R_i}{(1+r)^i} \qquad \text{equation 2}$$

Where I_{in} is the initial investment cost (e.g. material and installation) and R_i is the running costs in year i. Costs of reinvestments and liquidation are not considered in the present analysis. The estimated annual cost, A, is calculated as the annuity of the life-cycle cost with the following equation:

$$A = LCC \cdot \frac{r}{1-(1+r)^{-i}} \qquad \text{equation 3}$$

Description of case study

A typical pre-school in Sweden consists of a one-storey construction with an un-insulated attic under a gable roof. The buildings usually consist of a wooden stud structure with a wooden façade. The building can have two to four children's wards each with 10 to 20 children and cover a total of 1000-2000 m^2. There are no special fire safety requirements for this type of building to protect the school for loss of property, i.e. the buildings usually consists of one single fire compartment with no automatic fire alarm system requirements.

In the present study, a 1200 m^2 building as described above is used as a reference for cost estimates. The lifetime of all the systems has been set to 20 years and the real interest rate is 5% as mentioned before.

RESULTS AND ANALYSIS

Estimated benefit due to a shorter detection time

Detection time of the each one of the technical systems

Small-scale experiments have been performed previously to study maximum temperature linear detectors [7]. However, there are weather effects that will have a large influence to the detection time. To obtain an estimation of detection times in real-scale outdoor environments data from a series of experiments has been used. A detailed description of the experiments can be found in an experimental report from Lund University [9], but a brief description of the experimental setup is give here.

The real-scale experiments were conducted against the façade of a one-storey building mock-up. Two types of façade cladding were used in the experiments: an incombustible Minerit board and planks of pine. The height to the eaves was 2.5 m above the fire source. The eaves were 300 mm wide and there was a ventilation opening that connected the attic space under the gable roof with the outside. Two sizes of ventilation opening were used (30 mm and 60 mm). The distance from the ceiling to the floor in the attic was 1.2 m and the entire attic was 3.5 m wide and 6 m long. All experiments were ignited at the same place on the façade; however, the wooden cladding on the façade was replaced between the tests conducted using this facade.

Temperatures were measured with type K thermocouples (0.26 mm). Both maximum temperature detection and differential heat detection cables together with smoke detectors were used in the experiments. Both linear heat detectors were placed on the eaves. The smoke detectors were placed in the attic space. The smoke detectors were placed close to the highest point in the attic, immediately above the fire source and 2.5 m laterally of fire source.

Typical design fires for initial fires around school buildings have been identified in a previous case study [4], and literature study [11]. Typical fire sources in arson fires at façades include various combustible materials that can be found in and around the school, such as waste material. However, a heptane fire was used in the experiments to limit the variation of the fire source between tests. Four fire sizes were investigated: 260 kW, 140 kW 65 kW and 8 kW. The mass loss of the fuel was recorded with a load cell during all experiments. The experimental setup in the different tests is described in Table 1.

Table 1: Experimental setup

Test	HRR (kW)	Facade	Ventilation opening (mm)	Number of tests
1	140	Incombustible	30	4
2	65	Incombustible	30	3
3	140	Combustible	30	2
4	65	Combustible	30	2
5	140	Incombustible	60	3
6	65	Incombustible	60	4
7	8	Incombustible	30	2
8	260	Incombustible	30	1

Table 2: Range of time to detection for the tested technical systems

Type of technical system	Detection time (s)			Test series	Number of tests
	Min	Max	Average		
Maximum heat detector cable	64	400	179	1,3,4,5,6,8	9
Differential heat detector cable	16	27	22	3,5,8	4
Smoke detector 1	88	478	162	1,2,3,4,5,6,7,8	21
Smoke detector 2	77	316	168	1,2,3,4,5,6,8	18

The range of time to detection is large in every test series (see Table 2) and it is not possible to see that the façade type or ventilation opening has any effect on the detection time. However, there is a quite clear trend indicating that a higher heat release rate will yield in a faster detection. Another important issue is the reliability of the detection systems. It is clear that a sudden increase in temperature is needed for the differential cable to detect because in many of the tests the temperature increase has been too low even though a pool of heptane (which has a much more rapid fire growth than a waste basket fire) was used as the fire source. The differential heat detector cable detected the fire in only 4 out of the 21 tests (19%) while the maximum heat detector detected the fire slower but in 9 tests (43%). The smoke detector closest to the fire (smoke detector 1) detected all fires and the smoke detector further away detected all fires except the fires in test series 7 and one fire in test series 2.

The detection times given in Table 3 have been used in the present cost-benefit analysis presented here based on the results summarised in Table 2.

Table 3: Used detection time for the technical systems in the case study.

Type of technical system	Detection time (s)
Maximum heat detector cable	180
Differential heat detector cable	30
Smoke detector	180

The fourth system to be analysed is a system with thermo sensors. Since it is possible to detect people before a fire is ignited the detection time for thermo sensors was set to 0 s.

Money saved due to the decreased detection time

The main benefit of detection systems is that an early detection is obtained. Thus it is desirable to translate a decrease in detection time to monetary terms. Juås [13] and Jaldell [14] have used response time data from fire service reports [2] and cost estimate of different extents of fire damage to quantify how much money a decrease of 5 minutes in fire service response time (see Figure 1) will save for a community. The purpose of these analyses was to provide support for cost-benefit analysis of fire service staffing, i.e. if money could be saved by having a part-time fire service (5 minute longer response time) or not.

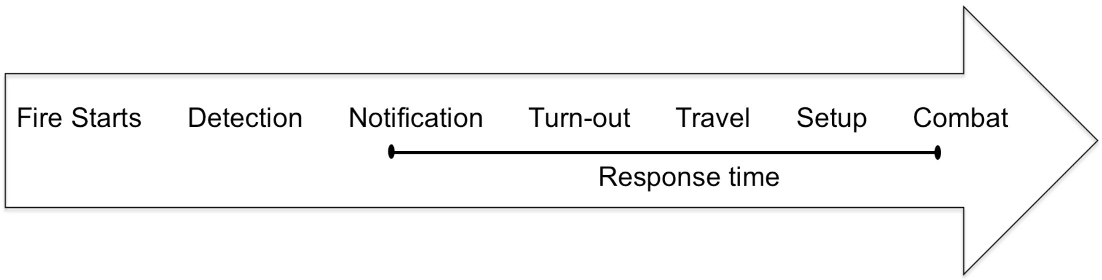

Figure 1: Description of the different events in fire service operation.

The total time for the fire service to intervene (time to appear at the fire scene) can also be described with the following expression:

Time to detection + Time for fire service notification + Response time = Time to intervene

The same type of approach has been used in the present paper to quantify detection time in monetary terms. It is assumed that the time for the fire service to intervene can be decreased with the time that is saved by a faster detection system.

Data from a Swedish insurance company together with fire investigation reports have been used to obtain an estimate of costs associated with a given size of fire damage. The data from the insurance company gives the cost associated with specific fires, and in the fire investigation reports from these fires one obtains a qualitative measure of the level of fire damage when the fire service arrives. Five categories of fire damage have been used (see Table 4). These five categories are used in the Swedish statistics on building fires that is provided by MSB.

Table 4: Costs associated with different fire sizes at fire service arrival

Size of fire	Costs associated with the fire (kSEK)*			Number of fires
	Min	Max	Average	
Extinguished/only smoke	0	5.5	1.8	3
Fire in object of origin	0	1.1	0.9	5
Fire in room of origin	0	87.0	41.4	4
Fire in several rooms	274	1070	631	3
Fire in several fire compartments	36,400	161,100	90,100	3

* The costs in the table have been transformed into the monetary value of 2011.

Jaldell [14] used different values that were considerable lower for the larger fire sizes. The reason for this is that the fires in schools will be larger than in on or two family houses, which were the object studied by Jaldell, due to the different size of buildings. The expected total cost of school arson fires in Sweden can be calculated to approximately 240 million SEK with the average costs in Table 4 and statistics on the number of fires for each fire size. This number is rough but within the ball park of data from insurance companies [1].

Table 5: Fire service response time from fire service reports [2] for arson fires in Swedish schools and kindergartens 2000-2010.

Size of fire	Share of fires at different response time (s)					
	200-299	300-399	400-499	500-599	600-699	700-799
Extinguished/only smoke	0.65	0.54	0.46	0.50	0.44	0.39
Fire in object of origin	0.22	0.28	0.30	0.25	0.33	0.29
Fire in room of origin	0.13	0.13	0.19	0.19	0.17	0.25
Fire in several rooms	0.00	0.03	0.04	0.04	0.05	0.05
Fire in several fire compartments	0.01	0.02	0.02	0.01	0.01	0.03
Sum	1	1	1	1	1	1

The expected costs of arson fires in Swedish schools and kindergartens at specific response times can be calculated with the help of Table 4 and Table 5. A rough estimate of the saving per second in decreased response time can be retrieved with the help of a linear regression analysis of the expected losses at different time points. The slope of that regression line yields that there will be a saving of approximately 2100 SEK/s for response times between 200 and 800 seconds. Jaldell [14] calculated that a decrease of 5 minutes in response time would yield in a saving of 352.400 SEK (in the monetary value of 2004) in public buildings (including school buildings) this corresponds to an average of approximately 1320 SEK/s in the monetary value of 2011.

To be able to use this approximation it is necessary to know the detection time for the benchmark case, i.e. when no detection system is present. This time will of course vary with time and location. It can be expected that people detect a fire more rapidly during the daytime and when they are in public places and more slowly during the night time and in places that are protected from view. A benchmark detection time of 5 minutes has been used in the case study.

Number of exterior fires in schools in Sweden

To be able to estimate the expected benefit of the technical systems it is necessary to know the expected number of exterior fires in school buildings (see Table 6).

Table 6: Average number of annual fires in schools in Sweden and in three Swedish cities between 2000 and 2010 [2] that starts on the exterior of the building.

City	Number of fires (2000-2010)	Number of schools*	Fires per school
Stockholm	38	168	0.021
Gothenburg	68	160	0.039
Malmoe	26	83	0.028
Sweden	297	5641	0.005

*The number of schools is in 2011.

Estimated cost of the technical systems

The total cost of technical systems will of course vary between countries, manufacturers and contractors. The costs presented in Table 7 must therefore be regarded as rough estimates. The values in Table 7 are based on information from suppliers and system designers in Sweden.

Table 7: Cost of technical systems

Technical System	Material costs SEK/unit	Installation cost (SEK)	Running cost (SEK/year)
Central fire alarm panel	50.000	5.000	5.000 *
Maximum temperature detection cable	100 /m	10.000	0
Differential linear heat detector	12.000 + 100 /m	10.000	1.000
Smoke detectors on attic	2.000	5.000	5.000
Thermo sensor	40.000	5.000	15.000

* Including cost of connection to emergency-answering centre.

The running cost of the central fire alarm panel includes connection to an emergency-answering centre. The cost of maintenance of the fire alarm panel is included in the running cost of the detectors. To be able to calculate the real cost of these systems it is necessary to preform a life cycle cost analysis of each system with the help of the present value method.

Certain technical systems may have a shorter lifetime than others, but in this analysis the lifetime of all systems has been assumed to be 20 years. The costs for de-commissioning a system are not considered in this analysis although this could be included if deemed necessary or important.

RESULTS OF THE CASE STUDY

Estimated benefit of decreased detection time

The time saved is the difference between the detection time in the benchmark case (i.e. 5 minutes) and when a technical system is used (Table 3). The benefit can be estimated by using the calculated value saved per second in decreased detection time above.

Table 8: Estimated benefit of decreased detection time

Technical System	Time saved (s)	Benefit (SEK)
Maximum temperature detection cable	120	252.000
Differential linear heat detector	270	567.000
Smoke detectors on attic	120	252.000
Thermo sensor	300	630.000

Table 6 in combination with Table 8 is used to derive the expected benefit of decreased detection time (see Table 9).

Table 9: Expected benefit of decreased detection time

Technical System	Expected benefit in Sweden and three cities (SEK/year)			
	Stockholm	Gothenburg	Malmoe	Sweden
Maximum temperature detection cable	5.200	9.700	7.200	1.200
Differential linear heat detector	11.700	21.900	16.100	2.800
Smoke detectors on attic	5.200	9.700	7.200	1.200
Thermo sensor	13.000	24.300	17.900	3.100

Estimated cost of the technical systems

The cost of installing and running the technical systems during a 20-year period can be estimated for the case with the help of the information in Table 7. The estimated annual costs are taken as the annuity of the present value of the life cycle cost (see equation 3).

Table 10: Estimated cost of the technical systems in the case study.

Technical System	Material costs SEK/unit	Installation cost (SEK)	Running cost (SEK/year)	Total cost (SEK/year)
Central fire alarm panel	50.000	5.000	5.000	9.400
Maximum temperature detection cable	14.000	10.000	0	1.900
Differential linear heat detector	38.000	10.000	1.000	4.900
Smoke detectors on attic	24.000	5.000	5.000	7.300
Thermo sensor	160.000	5.000	15.000	28.200

If the systems are going to be installed in a building with an existing central communication unit, the cost of the maximum temperature detection cable, differential linear heat detector and smoke detectors on attic will be as in Table 10. If a new central fire alarm panel is needed must the yearly total cost of the panel be added to the cost of each system.

Expected cost-benefit ratio

By dividing the expected benefit (see Table 9) with the estimated cost (see Table 10) a cost-benefit ratio (see Table 11) can be derived. The higher the ratio is the more beneficial is the system, and ratios under 1 are not beneficial.

Table 11: The expected cost-benefit ratio of the systems.

Technical System	Stockholm	Gothenburg	Malmoe	Sweden
Maximum temperature detection cable	2.69	5.06	3.73	0.65
Differential linear heat detector	2.40	4.52	3.33	0.58
Smoke detectors on attic	0.71	1.33	0.98	0.17
Thermo sensor	0.46	0.86	0.64	0.11

The cost of the central fire alarm panel is not included in the cost-benefit ratio of the first three systems in Table 11. If it is necessary to install a central unit the expected cost-benefit ratio will be a third for the differential linear heat detector and smoke detectors and a sixth for the maximum temperature detection cable. Thus will the differential linear heat detector be the most beneficial in that case.

DISCUSSION

From Table 11 it is clear considering the fire risk for the whole of Sweden, if it is statistically rare that a fire event occurs none of the studied systems result in a high cost-benefit ratio. This indicates that it is important to identify high-risk areas when using cost-benefit methods to determine which of various different technical systems would be most advantageous to install. Low risk buildings probably should stick to low cost systems if, indeed, detection systems are installed at all.

The maximum temperature detection cable and the differential linear heat detector has a cost-benefit ratio higher than 1 in the three studied cities. Smoke detectors in the attic has a cost-benefit ratio higher than 1 only in Gothenburg, the studied city with the most exterior fires. Table 11 shows that thermo sensor do not have a high cost-benefit ratio from a strict fire prevention point of view but there are additional benefits of this system in terms of prevention of other vandalisation activities or theft.

No account has been taken to the reliability of the different systems when doing the calculation. In the mentioned real-scale experiments the differential linear heat detector did only detect in 19% of the tests, this indicates that the detection time of 30 seconds is only valid for a couple of cases. The same goes for the maximum temperature detection cable even though it detected fire in 43% of the tests. If that reliability were accounted for the expected benefit of these systems would drop as well as the cost-benefit ratio. The estimate of the smoke detector detection time is considered to be more reliable than the others since it detected fire in all of the real-scale experiments. A prerequisite for using smoke detectors on the attic is that there are ventilation openings in the eaves. It is important to point out that the detection times used in this paper are based on a single experimental setup and will of course vary between buildings and weather conditions. However, the setup used is considered to be representative for a majority of one-storey school buildings in Sweden.

Thermo sensors have not been tested in the real-scale experiments and no evaluation on the reliability of them has been made. A detection time of zero seconds might seem like an un-conservative approximation, but thermo sensors can detect movement of people before a fire is lit which means that actions can be taken much earlier and ignition might be prevented entirely. Thermo sensors are also a system that can have benefits in other areas than reducing the costs of fires, which makes thermo sensors particularly beneficial in areas with a lot of vandalism and fires.

The method used in this paper has the benefit of resulting in a quantitative estimate of each system and thus also a relative comparison of the systems. However, the method is highly dependent on statistics and the estimation of cost associate several important parameters. One of the key parameters is considered to be the expected saving per second in decreased response time. This parameter is estimated to be 2100 SEK/s but if an estimate from previous research (1300 SEK/s) is used will the cost-benefit ratio decrease with one third. In this approach it is assumed that fire damage will increase linearly with time, and this contradicts the commonly used exponentially growth of fires used in fire safety design. Another important parameter is the real interest rate. If an interest rate of 1 % were used instead would the cost-benefit ratios increase with 10 to 45 % depending on systems. A third important variable is the cost of the technical systems. Information from suppliers and system designers has been used to do the approximation of system costs, but it is clear that these costs can vary depending on manufacture, contractor and method of procurement. Moreover are system costs associated with reinvestments and de-commissioning not included in the estimate total cost. Finally, the benchmark detection time will have a linear influence on the cost-benefit ratio; a longer benchmark detection time will result in higher cost-benefit ratios. It is desirable to look further into how the uncertainties associated with these parameters will affect the results.

The focus of this paper is detection of exterior arson fires. But there are other technical systems that should be evaluated as alternatives or complements to the systems studied to be able to get a complete picture of the economics of fire protection systems in the entire school building. Sprinkler systems and even passive systems such as fire rated eaves should be added to this type of cost-benefit analysis in future research.

CONCLUSION

In this paper the cost-benefit ratio and efficiency of different detection systems used for detecting exterior fires has been studied. It is a first attempt based on one set of values without any extensive sensitivity or uncertainty analysis of the input parameters. Four different types of detection systems have been studied in a case study. The case study was conducted on a typical Swedish one-story school building with an un-insulated attic under a gable roof.

A case study has been used in this paper to study the benefits of installing four different types of technical systems to detect exterior fires. The study shows the some systems have clear cost-benefit advantages for protection of buildings in high-risk areas and this method can be used as one basis for determining which system to install. However, detection systems cannot be rationalised from a cost-benefit standpoint for low risk buildings and that in such cases the cheapest system should be chosen if an installation is planned

The results are based on estimations of several key parameters, and this means that the results are associated with a high degree of uncertainty. It is therefore important that a sensitivity analysis is included in a full implementation of this methodology in a real school design.

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