OPTIMISING SMOKE DETECTORS ON PASSENGER SHIPS

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ABSTRACT

The effectiveness of smoke detectors arrangement in a ship restaurant is examined, considering probabilistically generated design fires. The main parameters investigated for their effect are, sensors' covered area and their obscuration sensitivity. The achieved level of safety is quantitatively expressed for an assumed nominal arrangement in the space, incorporating also fire extinguishment by ship's crew. The presented methodology could be extended for assessing, from an early design stage, the effectiveness of all active and passive fire systems on board.

KEY WORDS

Fire Safety; Smoke detection; probabilistic

INTRODUCTION

Effective fire detection is one of the most crucial elements of passenger ship fire safety: the faster the identification of an ignition event, the lesser the likelihood of fire growth and escalation. In accommodation areas smoke detectors are usually installed according to SOLAS Chapter II-2 (Part C-Regulation 7) in combination with the FSS code (chapter 9). These provide design specifications, namely smoke detectors arrangement in space plus their type and component characteristics (IMO 2009; 2007).

Regulations specify however only the maximum covered area and detectors maximum distance from each other. Specifically, the FSS code specifies that the maximum covered area should be 74 m^2, while the maximum distance apart between centres should be 11 m. Furthermore, SOLAS prescribes an acceptable range for their sensitivity. It is required that they are activated "...before the smoke density exceeds 12.5% obscuration per meter, but not until the smoke density exceeds 2% obscuration per meter". However, the response time of a smoke detector depends also on the type of the ignited fuel source and the time parameter of growth does not seem to be fully addressed. Therefore it is not clear the true level of safety that a specific design arrangement of smoke detectors practically offers considering the dynamic evolution characteristics of fires.

A common type of smoke detectors used in accommodation areas and public spaces is the "spot-type". They are usually "optical" (photoelectric) or "ionization - based". The key element of the analysis of a smoke detector system is the calculation of its response time. Detection relates to optical density and optical obscuration, which in turn are mainly determined by visibility and light attenuation. On the other hand, smoke depends on various parameters, such as the type of fuel, the combustion mode and the ventilation conditions. It is quite essential to know how detection efficiency depends on such parameters. In the current study we are seeking an optimal response time of smoke detectors in terms of: a) their distribution in space and b) their sensitivity characteristics, specifically their obscuration rating

For the calculation of the detector's response time, we assume that a smoke detector behaves like a low-temperature fast response heat detector. This is a usual engineering methodology, following NPFA 72 (2000) and British Standard PD 7974-4 (2003). Optical density in a space and mass concentration of smoke particles are quantitatively related with temperature rise, for a given type of ignited fuel. However, for an examined onboard space, there exist many parameters that affect fire development, such as the type, quantity and growth characteristics of the fuel sources, the type of ignition sources, the ventilation conditions and others. Furthermore, there is uncertainty, both epistemic and aleatory, concerning the values of these parameters, resulting in various computationally possible fire realizations. As well known, the key element of fire

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evolution is the heat release rate time history. In a recent paper the authors have proposed a methodology for the probabilistic generation of heat release rate curves (HRR) or else, for the generation of *design fires* (Themelis and Spyrou 2010). This concept will be applied also here for investigating, in a probabilistic framework, smoke detector efficiency.

The investigation is based on a large restaurant space of a cruiser. Firstly, a set of HRR curves that are realistic for a restaurant will be developed, considering the available fire load (i.e. the energy that can be potentially released), fuel´s composition and fire growth characteristics. It should be noted that in fire engineering, a fuel source corresponds to any combustible material present in the considered space. Then, a parameterized smoke detector system is tested against various HRR curves, focusing on the calculation of the response time. A sensitivity analysis is performed with respect to the smoke detector's covered area and obscuration rating. We define detector's response as tautochronous to fire alarm's activation and subsequently coinciding with fire patrol's call. A fire unit (a crew member or fire patrol) could extinguish the fire with some probability of success which depends on the fire size at the time of intervention and also on unit's capability. Relevant statistics are available for buildings (McDaniel 1997). Similar statistics for ships concerning fire unit's effectiveness as function of fire size, would be very useful and would enable one to optimize smoke detector's arrangement or obscuration sensitivity, for a target probability of fire extinguishment success.

SMOKE DETECTION MODELLING: RESPONSE TIME

A first objective of the current study is the estimation of the response of a smoke detector knowing the ignited fuels in the space and also the type and the characteristics of the detector, expressed by the percentage of smoke obscuration per meter. The modelling of the smoke detector follows NPFA 72 (2000) and British Standard PD 7974-4 (2003). The main principle can be found in Heskestad and Delechatsios (1977), Evans and Stroup (1985). Detector's response prediction is based on the assumption that, smoke concentration at the location of the detector and temperature rise due to the fire are proportional. As a matter of fact, their ratio will be constant. Practically, such assumption could hold if, the loss of energy from the flow due to convection to cool room boundaries and also, the radiation of smoke gases are not significant. At the same time, there should be no heat transfer among smoke particles during smoke's movement from the source to the detector. Also, the size of the particles should remain constant. Therefore, for a certain type of fuel and burning mode (e.g. flaming combustion), the optical density (*OD*) at a point is proportional to the mass concentration of smoke particles (C). Furthermore, the mass concentration of particles (C) will be proportional to the change of temperature (ΔT), given the validity of the above assumptions. So, there will be a constant ratio of optical density (*OD*) to temperature rise (ΔT) for each fuel and burning mode. Heskestad and Delechatsios (1977) carried out tests for various fuels in order to calculate this ratio. The average values are shown in Table 1.

Table 1: Average ratios of optical density to temperature rise for various fuels based on Heskestad and Delechatsios (1977).

Material	**10^2 OD/ΔT [1/m C^0]**
Wood	0.118
Textiles (cotton)	0.089
PVC	4.269
Polyurethane	2.397
Polyester	0.181
Foam PU	7.882

The percentage obscuration O_u and optical density OD per unit distance are defined by the following equations, respectively (Schifiliti et al (2002):

$$O_u = 100\left[1-\left(\frac{I}{I_0}\right)^{1/\ell}\right] \qquad [1]$$

$$OD = \frac{1}{\ell}\log_{10}\left[1-\left(\frac{I_0}{I}\right)^{1/\ell}\right] \qquad [2]$$

where I_0 is the initial intensity of a light beam reaching a photocell, I is the intensity of the light beam in the presence of smoke and ℓ is the distance from the source to the photocell. Then, for example, if we considered a detector with 6% obscuration per meter, then the optical density per unit distance should be 6.723 1/m. Assuming polyester as the burning material, the respective temperature rise will be 14.84 ^{0}C. Typical values of smoke detectors' obscuration rating, covering also the acceptable range mentioned in SOLAS, for both the ionization-based and optical (photoelectric) types, are shown in Table 2 (Brazzell 2009).

Table 2: Smoke detectors obscuration rating.

Type of detector	Obscuration level
Ionization	2.6–5.0 %/m
Photoelectric	6.5–13.0 %/m

As said, the smoke detector is basically modeled as a low-temperature, fast response heat detector. Therefore, the response will be defined as the time when the detector's instantaneous temperature reaches its activation temperature. Following the analysis presented in (Schifiliti et al 2002) for heat detectors, the differential equation for estimating sensor's temperature is given by the following equation:

$$\frac{dT_{det}}{dt} = \frac{\sqrt{u}}{\mathrm{RTI}}\left(T_{cj} - T_{det}\right) \qquad [3]$$

where T_{det} [^{0}C] and T_{cj} [^{0}C] are the sensor and ceiling jet temperature respectively, RTI [(m s)$^{1/2}$] is the response time index of the sensor and u [m/s] is the ceiling jet velocity (or else the flow velocity of the hot gases). According to Schifiliti et al (2002), T_{cj} and u can be calculated by the next formulae:

$$T_{cj} = \begin{cases} T_{amb} + \dfrac{16.9 \cdot \dot{Q}^{2/3}}{H^{5/3}}, \; R < 0.18H \\ T_{amb} + \dfrac{5.38 \cdot \left(\dot{Q}/R\right)^{2/3}}{H}, \; R \geq 0.18H \end{cases} \qquad [4]$$

$$u = \begin{cases} 0.96 \cdot \left(\dfrac{\dot{Q}}{H}\right)^{1/3}, \; R < 0.15H \\ \dfrac{0.195 \cdot \dot{Q}^{1/3}\sqrt{H}}{R^{5/6}}, \; R \geq 0.15H \end{cases} \qquad [5]$$

where H [m] and R [m] are respectively, the height of ceiling above the top of fuel and the radial distance from the fire centre line to the detector; whereas $\dot{Q}$ [kW] and T_{amb} [^{0}C] are the heat release rate and the ambient temperature. Therefore the response time, t_{det} [s] will be calculated by eq. 3, applying for example the Euler integration method with a time step δt.

The steps of the performed calculation are as follows. Firstly the required temperature rise at the detector will be found considering the obscuration level of the detector and the average ratio $OD/\Delta T$, specified by the fuels present and taking into account also their percentage of contribution to the total combustible mass. Then, the detection time is calculated by eqs. [3] to [5]. Recommended RTI values have been proposed by FESA (2010) and IFEG (2005), in the range 1-10 [(m s)$^{1/2}$]. The response time index for a smoke detector could be considered as his "entry resistance". This is the time delay experienced for the optical density inside the detector's chamber to become equal to the density value outside of it. This delay is an inherent property attributed to the design of a detector.

SCENARIO DESCRIPTION

Restaurant properties

The examined space onboard, as mentioned in the introduction, will be a large public space and specifically a restaurant which occupies horizontally the entire area of a main vertical zone (MVZ). The length of MVZ is 43 m, while the restaurant is 31 m wide and its height is 3.4 m. Therefore the floor area of the restaurant is 1333 m^2.

Concerning the available fuel sources (type and amount), we will use data from building statistics since respective information for ships is not available. From the statistical survey presented in Zalok et al (2009), it was found out that for restaurants with floor area bigger than 300 m^2, the main contribution (over 85%) to the combustible mass comes from wood/paper based materials. Specifically, in Table 3 is shown the derived average contribution to the total combustible mass of 4 generic groups of combustible materials. The mean fire load density for this type of restaurants was calculated equal to 106 MJ/m^2.

Table 3: Average composition of materials for restaurants

material type	% contribution (average)
textiles	3.7
plastics	5.2
wood/paper	84
food/misc	7

Heat release rate curves generation

For cruiser restaurants of this size, the capacity was found to be about 600 passengers. With simplicity in mind, one could assume a nominal arrangement of 100 tables with 6 chairs each. The tables provide areas of higher fire load density and we made the choice to produce a discretized distribution of fire load, by associating other burning material with its nearest table, thus producing 100 “fuel packages”. A “fuel package” is a technical quantity that represents some fraction of the total fire load and with specific burning properties (e.g. growth characteristics). For the generation of HRR curves, the total combustible mass was thus distributed uniformly in 100 “fuel packages”. The resulting fire load per fuel package is 1413 MJ. In Themelis and Spyrou (2010; 2012), a methodology for generating HRR curves has been developed, where each stage of fire development (incipient, growth, fully developed and decay) is treated probabilistically. It is remarked that, despite using a large space, there is no need to consider a mechanism of fire spreadover to adjacent fuel packages since smoke detection by the nearest sensor should occur much faster than an adjacent ignition. It also assumed that the detectors will work properly at all cases.

The incipient stage duration has been considered as a random parameter, taking into account the composition of the available mass (Table 3) and a typical range of ignition source heat flux (Fitzgerald 2004). The average and 95th percentile time duration were calculated equal to 2.31 and 6.39 minutes respectively.

Furthermore, the coefficients that characterize the intensity of growth have been derived from statistical analysis deriving from a survey of accidents in restaurants, performed by Holborn et al (2004). The obtained pdf was the log-normal distribution with average and 95th values 0.027 and 0.102 kW/s^2 respectively (Figure 1). Therefore, the assumed fires were rated from medium to fast according to the usual characterization of ISO (1999). Table 4 summarizes the definition of the considered random parameters for the generation of HRR curves.

Another worthy remark is that, due to the large enclosure space, there should be no ventilation limitation. Hence all fire scenarios can be considered as “fuel-controlled”. The generated set was comprised of 100 uncontrolled fires, depicted through their HRR curves in Figure 2. The maximum HRR was estimated to have a mean value 3.161 MW, with 95th percentile at 5.265 MW (Figure 3).

Table 4: Random parameters definition

parameter	value	type of distribution	most probable value
HRR at the end of incipient stage [kW]	20-30	uniform	-
Ignition source heat flux [kW/m^2]	20-40	uniform	
Growth coefficient [kW/s^2]	250 -550	log - normal	0.027
Percentage of fuel load consumed for decay to start (%)	45-60	uniform	-

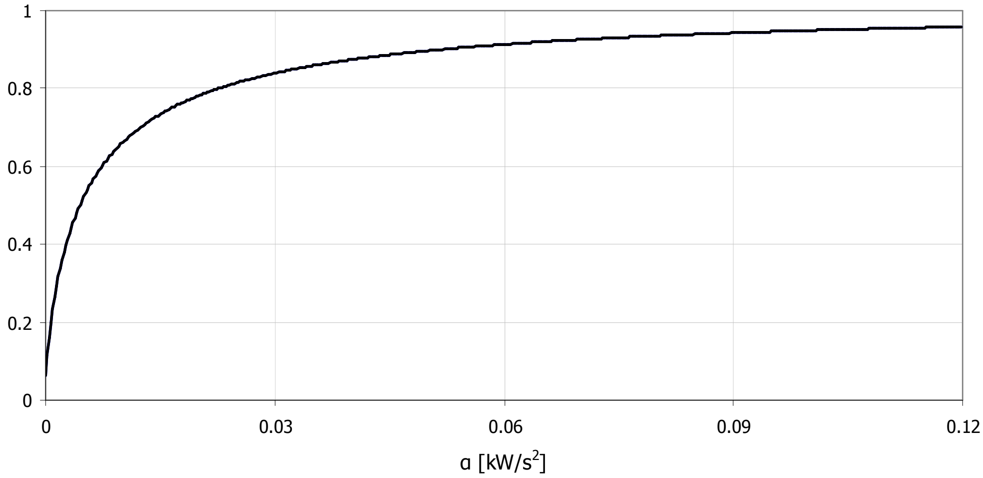

Figure 1: Cumulative pdf for growth coefficient.

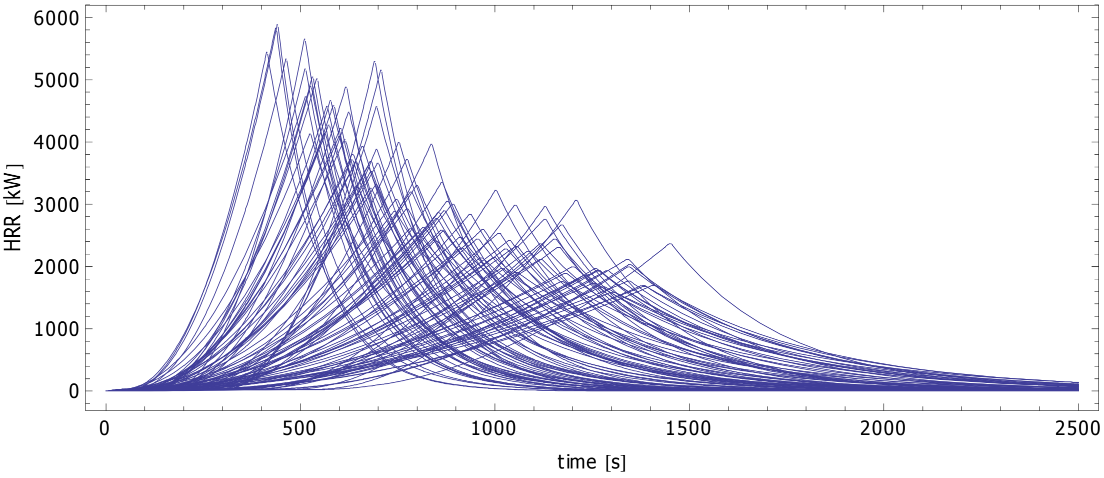

Figure 2: Generated set of HRR curves

Smoke detector characteristics

The percentage obscuration per meter of the considered smoke detectors was allowed to span the acceptable SOLAS range (2 - 12.5 %/m), while the covered area ranged from 8 - 74 m^2. Taking into account the type of combustible materials and their percentage contribution to the total mass, the ratio of optical density to temperature rise was calculated to an average $OD/\Delta T$ = 3.997 10^{-3} [1/(m^{0}C)]. In Figure 4 is shown the calculated temperature rise required, for the assumed obscuration level. RTI was set to 5 [(m s)$^{1/2}$] as the median of the recommended range of FESA (2010) and IFEG (2005).

Another parameter treated as random was the relative position of the fire to the detector. Specifically, on the horizontal plane, the relative position described by the radial distance *R* is uniformly distributed up to the radius of the covered area. The vertical distance *H* from the top of the fuel package to the detector was considered as uniformly distributed in the range 1.4 – 3.4 m.

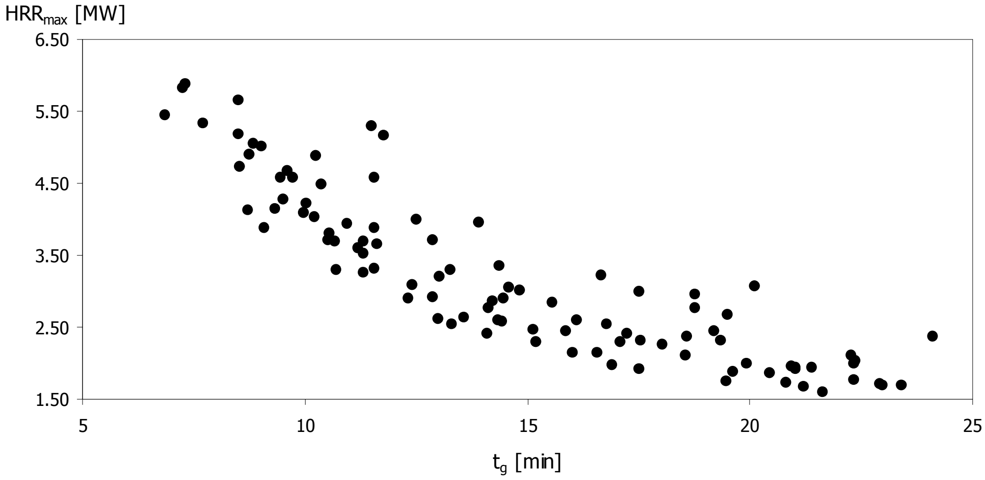

Figure 3: Maximum HRR values and respective times.

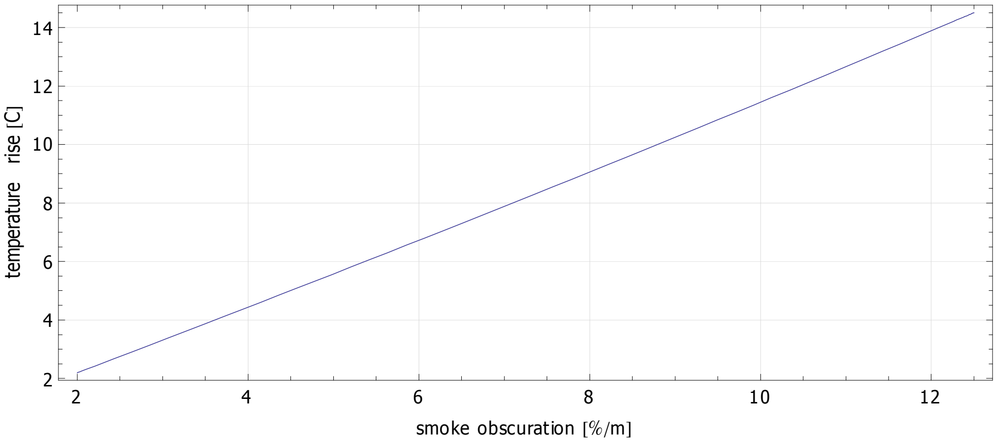

Figure 4: Temperature rise for the SOLAS smoke obscuration range for the considered restaurant.

Probability of fire units' extinguishment failure

As well known, smoke detection triggers the fire alarm and the subsequent call of a fire unit. Thus it affects critically the fire extinguishment process. Two cases have been studied:

- a crew member who attempts alone to fight the fire.
- Intervention by a trained fire patrol.

The time duration from alarm ringing to unit's arrival, usually called response time, depends on the readiness of the unit, the travel time and any decision making. Several uncertainties exist on these factors and for this reason the response time will be treated as a random parameter. Following Hakkarainen et al (2009), we have selected the "gamma" as representative distribution of this parameter. The input parameters for the shape of the pdf were selected empirically after some interaction with ship operators and they appear in Table 5. Fire patrol 1 is the base case; while fire patrol cases 2 and 3, representing a faster arrival, will be used later for a sensitivity analysis.

Table 5: Parameters for the definition of the gamma distribution for response time

	1 % percentile	50% percentile	95% percentile
Crew member	1 min	2.5 min	6 min
Fire patrol 1	3 min	6.5 min	12 min
Fire patrol 2	2.4 min	5.2 min	9.6 min
Fire patrol 3	2.1 min	4.55 min	8.4 min

Except from the arrival time of the fire unit, its effectiveness to fight and ultimately extinguish the fire should also be considered. It is common in the buildings literature (e.g. McDaniel 1997) to express the capability of a unit to extinguish a fire as a probability that depends on the fire size represented in turn by the flame area. Unfortunately, such statistics are not available for ship fires. We have assumed a 30% reduction of fire unit efficiency relatively to buildings' fires. The obtained pdfs seem to follow the Gamma distribution for the fire patrol and the Weibull for the single crew member (Themelis & Spyrou 2012) and are presented in Figure 5. The flame area is correlated with the HRR (Heskestad 2002). Thus, by entering the time of arrival on the spot and the respective HRR value, the probability of success (or failure) could be deduced. It is remarked that, for big fires, we have assumed as failure the outcome of those scenarios where the time of arrival happens after the HRR curve has reached its maximum.

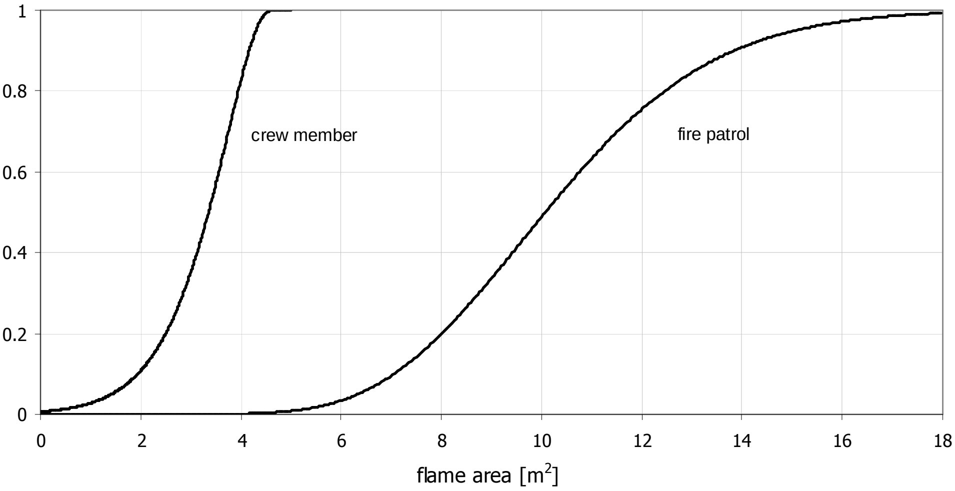

Figure 5: Fitted distributions of probability of extinguishment failure, considering 30% capability reduction in respect to McDaniel (1997). They follow the Weibull (α = 4.66, β = 3.56) for a crew member and the Gamma (α = 14.97, β = 0.69) for the fire patrol.

RESULTS

Detection and arrival times

Firstly the detection time was calculated, varying the obscuration level and keeping constant (24 m^2) the area covered. Statistical results (average and percentiles) for a crew member and for fire patrol are shown in Figure 6. In Figure 7 are shown the derived detection times when varying the covered area and keeping constant the obscuration (6%/m). Changing the obscuration rating in the examined range (2-12.5 %/m), detection can become faster 3 to 7 times. On the other hand, for the selected value of obscuration, the covered area seems to be relatively less influential (2-3 times faster).

In Figure 8 and Figure 9 are shown statistics of the arrival time of the crew member and fire patrol respectively, varying obscuration. It can be deduced that the most sensitive detector (2%/m) will result to (60 – 100) % faster arrival of the crew member. The respective difference for the fire patrol is about 3 minutes. On the other hand, in Figure 10 and Figure 11 are seen similar arrival time statistics, in terms of the covered area of the detector. Time differences of 1 – 1.5 minutes were found. In the next subsection, we will present how these time differences in detection and arrival transform into extinguishment failure probabilities.

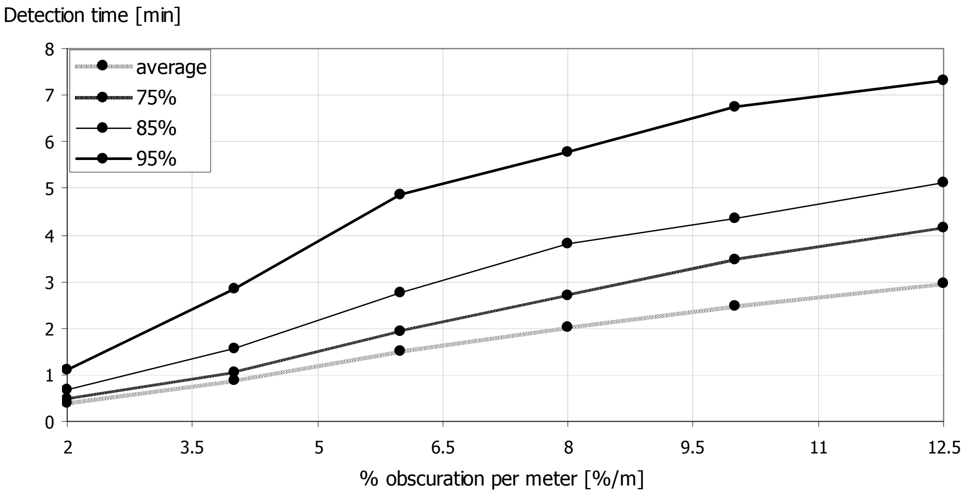

Figure 6: Statistics of detection time when varying obscuration (covered area 24 m^2).

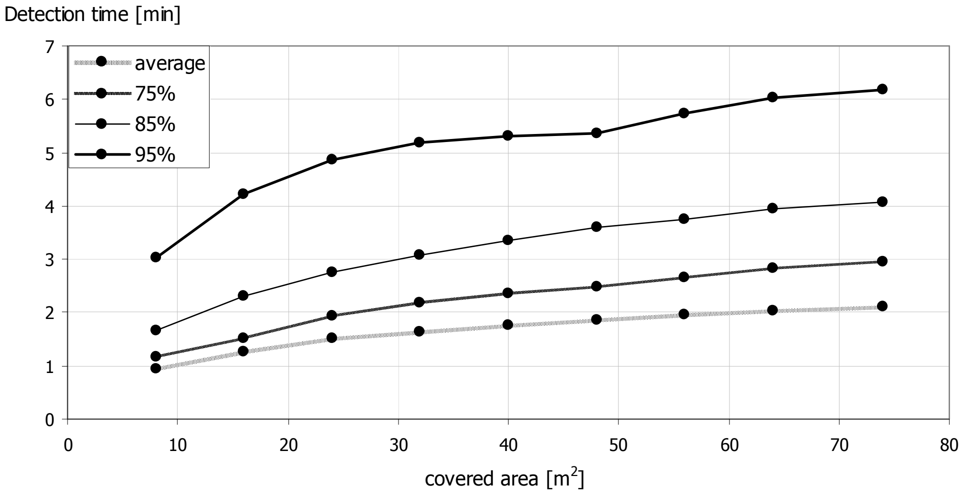

Figure 7: Statistics of detection time when varying detector's covered area.

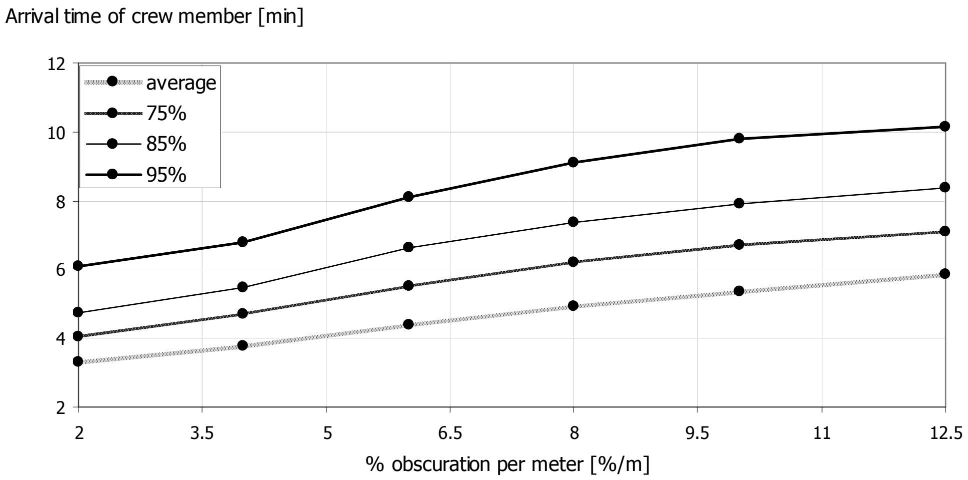

Figure 8: Statistics of arrival time for a crew member, varying obscuration.

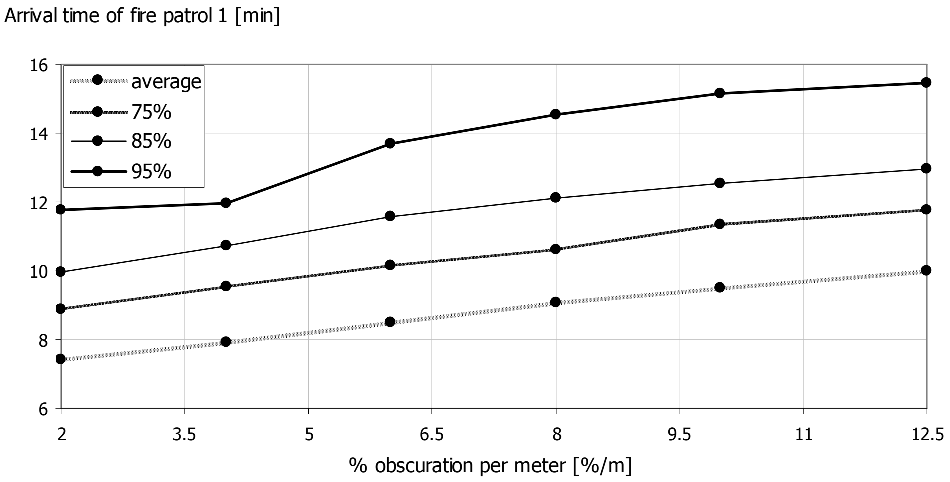

Figure 9: Statistics of arrival time for the fire patrol case 1, varying obscuration.

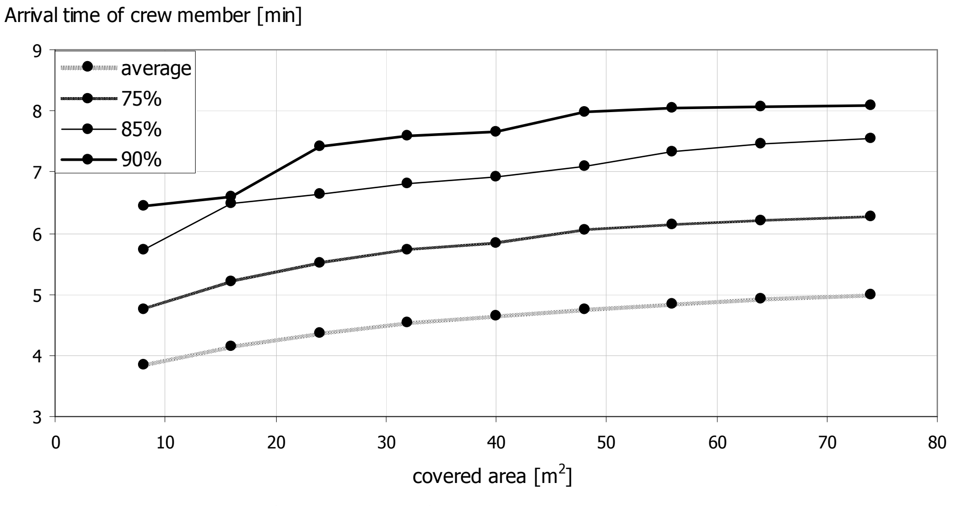

Figure 10: Statistics of arrival time for the crew member, varying covered area.

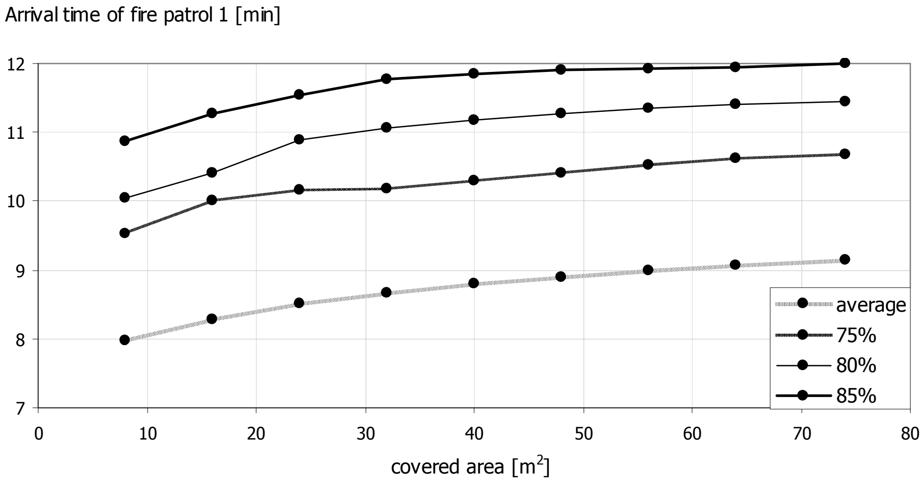

Figure 11: Statistics of arrival time for the fire patrol 1, varying covered area.

Extinguishment failure probabilities statistics

As the utilized data for the calculation of failure probabilities are in a statistical form (Figure 5), the respective results for the 100 considered scenarios will be presented in percentiles. Specifically, the 75% to 95% percentile will be produced.

Crew member

In Figure 12 are presented failure probabilities in terms of the detector's obscuration. It appears that from about 4.5-5 %/m, there is a rapid growth of the failure probability. That is more severe for the higher percentiles, where for the 95th there is total failure for all obscuration levels. In Figure 13 are shown results for the considered covered area range. Combing these results, one could reach the same level of safety with different smoke detection arrangements. For example, aiming at 90% success probability and designing with the 85% percentile (this could be regarded as a "confidence" parameter), two combinations can produce the same safety level:

- a 4%/m obscuration with 24 m^2 covered area spacing.
- a 6%/m obscuration with 8 m^2 covered area spacing.

For the considered space the required numbers of detectors are, for the respective cases, 56 and 167. Thus there is an obvious economic benefit to be achieved by optimizing the arrangement.

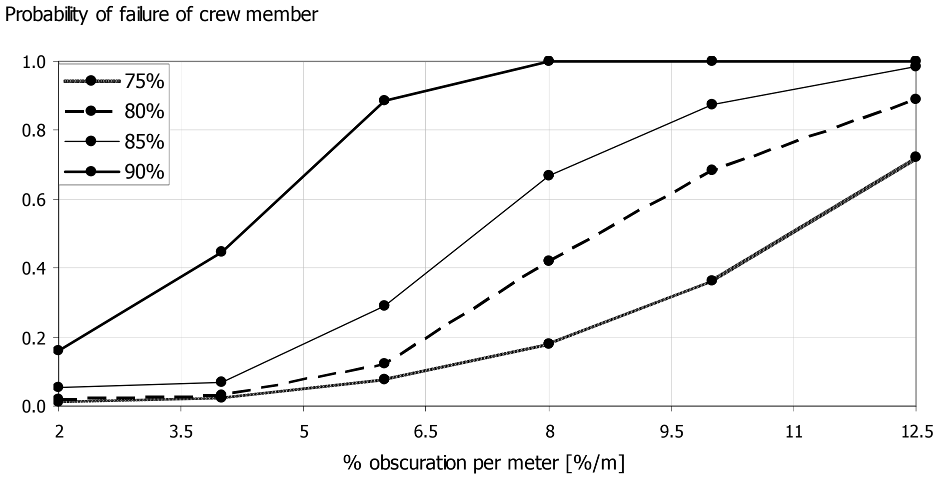

Figure 12: Statistics of failure probability of crew member, varying obscuration.

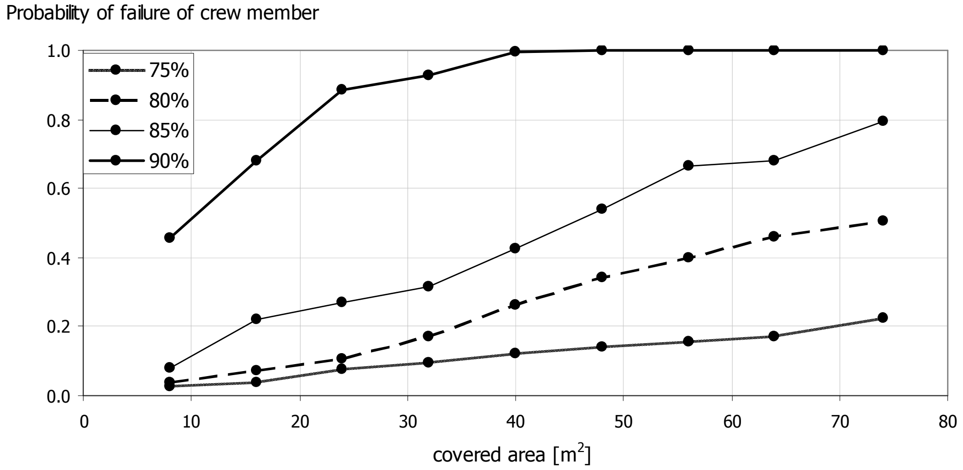

Figure 13: Statistics of failure probability of crew member, varying detector's covered area.

Fire patrol and sensitivity analysis of its response time

In Figure 14 and Figure 15 are shown the respective results for the fire patrol. It is observed that failure probability becomes less sensitive when varying the covered area. This could be explained from the (approximately) 1 minute difference in the arrival time in comparison to the 3 minutes difference associated with the selected obscuration range. Nevertheless we could deduce that for the specific patrol's response time range (fire patrol 1 - Table 5), the level of safety attained is not satisfactorily (less than 80% successful extinguishment for 80% and higher percentiles).

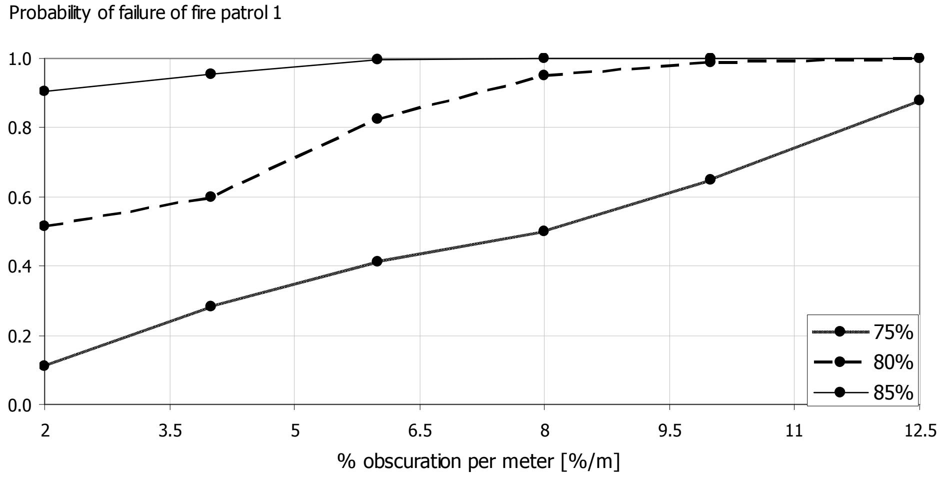

Figure 14: Statistics of failure probability of fire patrol 1, when varying detector's obscuration.

Subsequently we carried out a sensitivity analysis for the response time of fire patrol reducing the respective values by 20% and 30% (patrol 2 and 3, see Table 5). We focus on the 85% percentile results. In Figure 16 can be observed how lower the failure probability could be if the response time became faster. However it shows also the strong influence of detector's sensitivity. On the other hand, in Figure 17 is shown a less severe dependence from the covered area. The required covered area per detector for a 90% success level when relying upon the fire patrol's response and using detectors of 6%/m obscuration will be 15 m^2. For single crew member intervention the corresponding figure is 8 m^2.

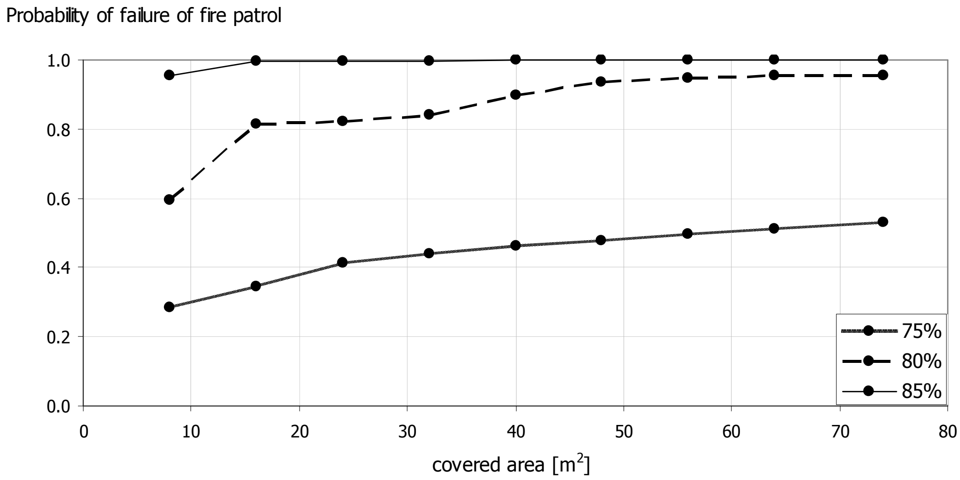

Figure 15: Statistics of failure probability of fire patrol member when varying detector's covered area.

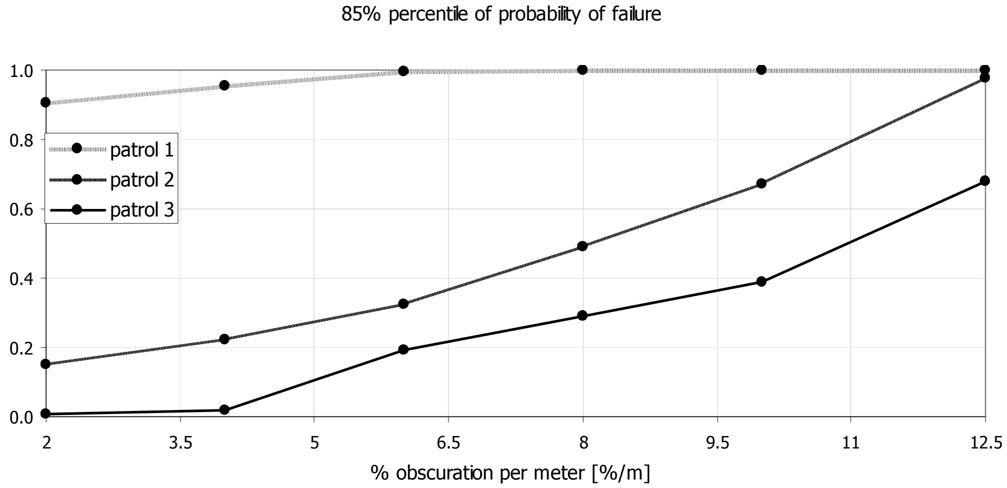

Figure 16: 85% percentile failure probability statistics, varying obscuration for 3 types of patrolling.

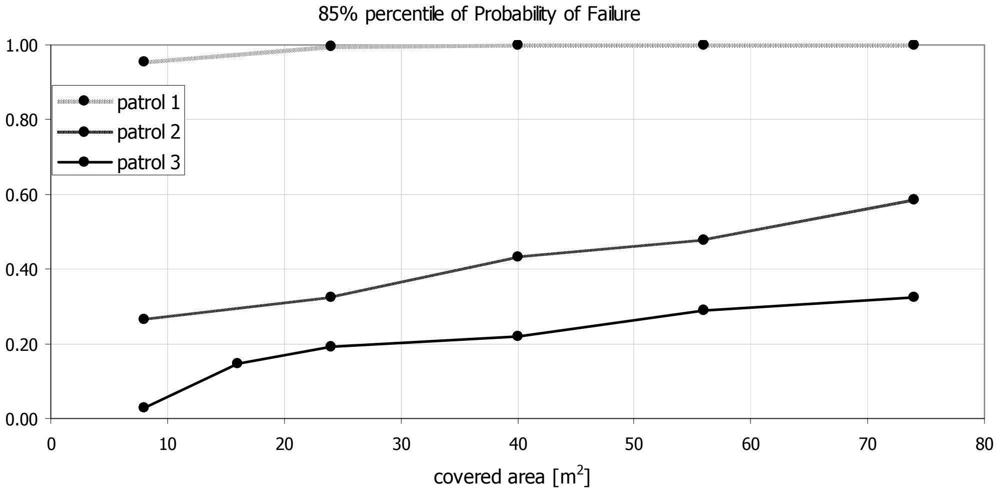

Figure 17: 85% percentile failure probability statistics, varying covered area for 3 types of patrolling.

CONCLUSIONS

Smoke detection normally occurs during the incipient and the fire growth stage. The effect that the detection time has on fire suppression efficiency has been considered. The relative position of the fire to the detector has been assumed as a random parameter, along with four other parameters characterising fire evolution. As random (in a range) is considered also the time instant of human intervention.

It was found that sensors obscuration sensitivity affects significantly the response time. Specifically, assuming a spacing of 24 m^2 , the response could be up to 7 times faster for the most sensitive sensor examined (2 %/m obscuration) compared to the least sensitive (12.5 %/m). On the other hand, assumption of a sensor with 6 %/m obscuration rating, and varying its covered area from 8m^2 up to the SOLAS acceptable limit of 74 m^2, produced up to triple delay of response. It should be mentioned here that, examining all possible combinations of obscuration rating and covered area would provide a more detailed insight about the distribution of these differences.

Detectors' response time was examined also for its effect on fire extinguishment probability of success, given the fire patrol intervention. For example, a 90% success level could be achieved either by a combination of 5%/m obscuration and 24 m^2 spacing; or by a 6%/m and 15 m^2 combination, respectively. Taking into account that the required number of detectors for the examined space is 56 and 89 respectively, and knowing the cost of each detector, optimization of the system in a risk-based and cost-effective manner is viable.

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