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THE PROBLEM OF SPRINKLER RELIABILITY

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Annotation. Sprinkler systems allow a considerable reduction of fire risk in buildings. Unfortunately, sprinklers are not fail-safe technical systems. Relatively high rates of sprinkler failures evoke the problem of reliability. A solution to this problem is considered from several viewpoints. The diversity of sprinklers' failure modes is the first challenge for estimating reliability (failure probability). It is found that the use of the available data for estimation is problematic. The second challenge is that the published data is insufficiently described to allow a verification of its relevance to the specific case of failure probability estimation. It is suggested to apply the published data with partial relevance to Bayesian inference about failure probabilities. The data is used for developing prior distributions of the unknown values of the probabilities. Bayesian inference is carried out on the basis of binomial distribution used to model the operation of sprinklers on demand basis. A problem of aging and a possible increase in failure probability in the course of sprinkler service is shortly discussed.

Keywords: spriklers, fire, Bayesain approach, multi-attribute selection.

Introduction

It is more than obvious that sprinkler systems can substantially contribute to the prevention of heavy fires and mitigation of fire consequences. When applied in combination with another protective systems, (e.g. fire alarm), sprinkles can considerably reduce risk posed by fires (e.g. Rasbash *et al.* 2004). Unfortunately, another obvious fact is that sprinkler systems are not fail-safe technical objects. The percentage of fires where sprinkler systems do not carry out their extinguishing function is relatively large. The data on sprinkler failures collected over the past 50 years indicate that in some cases, a chance of failure is unacceptably high (Rasbash *et al.* 2004; Rönti *et al.* 2004).

The problem of sprinkler reliability was addressed by many authors who applied various approaches to dealing with the potential sprinkler failure. The approaches range from a simple calculation of country-specific failure rates to the assessment of reliability by applying methodological means of quantitative risk assessment (QRA). The latter methodology is based on Bayesian reasoning widely applied to dealing with rare and dangerous events (Apostolakis 1990; Aven 2003; Apeland *et al.* 2002). A heavy fire and a failure of a sprinkler system to extinguish this fire are undoubtedly such events. Siu and Apostolakis (1986, 1988) suggested utilising the Bayesian approach estimating the probabilities of various modes of sprinkler failures, for instance, demand unavailability. A further methodological means of QRA used for assessing sprinkler failure probability is fault tree analysis suggested by Rönti *et al.* (2004) and Hauptmans *et al.* (2008).

The quality of decision-making concerning specific sprinkler systems will increase along with the precision of the estimates of sprinklers' failure probabilities. This quality can be assured in several ways the first of which is applying local data on sprinkler failures used as new evidence for Bayesian updating. Another improvement in estimation can be a better development of the prior distribution for the probabilities of specific failure modes.

The present paper considers the problem of sprinkler reliability from several standpoints. It is suggested that the quantitative measure of reliability, namely, failure probability can be decomposed according to the possible modes of sprinkler failure. A short review of data potentially suitable to assess failure probability is presented. The discussion leads to applying the Bayesian approach to the estimation of failure probability. The problem of a possible increase in this probability in the course of sprinkler's service is addressed. The findings presented in the paper are viewed as knowledge that should facilitate decision-making with respect to fire risk.

The phenomenon of Sprinkler Failure

A sprinkler system (or sprinklers, in brief) is a relatively complicated technical object that can fail in a variety of ways (modes). Specific modes are also related to the specific type of sprinklers having four principal arrangements that differ in terms of how water is put into the area of fire and certainly the set of subsystems and

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system components having their individual failure modes (SFPR 2002: 4–73).

The contribution of failures on the component level to the system failure is usually represented by means of fault tree diagrams (Rönti *et al.* 2004; Hauptmans *et al.* 2008). However, sprinkler failures can occur as specific events even in the case where all system components are in
the operational state. The failure can also occur due to:

– failure of water supply to the system from the water main (autonomous water tank);
– off-site failure of external power supply to the sprinkler system;
– unavailability of the system due to system shutdown in consequence of a human error or carelessness;
– failure of the system when fire exceeds the design capacity of sprinklers.

As regards failure that can be traced back to the component failures, two modes of failure are mentioned in literature (Siu and Apostolakis 1986, 1988; Linder 1993; Rönti *et al.* 2004):

– failure to actuate the system given a demand (fire) (demand failure in terms of Kumamoto and Henley (1996: 60));
– failure to continue operating given that the system is actuated (run failure in terms of Kumamoto and Henley (1996: 60)).

In case where the sprinkler system is activated on demand and does not commit run failure, the failure can be classified according to the hazard it protects:

– failure to control (put out) fire;
– start with an unacceptable delay;
– failure to suppress fire before a critical set of equipment is damaged;
– failure to provide exposure protection.

Generally, potential failures listed above may be represented by four random events:

1. random event F_1 representing demand failure due to inadvertent system shutdown or the failure of supply from the water main (external water piping network);

2. random event F_2 expressing demand failure of the sprinkler system caused by one or more failures of system components;

3. random event F_3 standing for run failure of the sprinkler system;

4. random event F_4 expressing form sprinkler failure due to insufficient capacity.

Events F_1 to F_4 can be considered mutually as exclusive ones. In this case, the conditional failure probability of the sprinklers can be expressed as a sum of individual probabilities of F_1 to F_4:

$$p_f = P(F_{sys} \mid \text{fire}) = P\left(\bigcup_{i=1}^{4} F_i \middle| \text{ fire} \right) = \sum_{i=1}^{4} P(F_i \mid \text{fire}), \quad (1)$$

where F_{sys} is the random event denoting the failure of the sprinkler system. As a simple illustration in Eq. 1 by a fault three gate 'OR' is shown in Fig. 1.

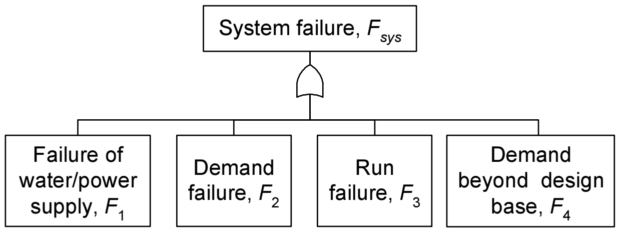

Fig. 1. A fragment of a fault tree diagram listing the main causes of sprinkler system failure

It follows from expression (1) that the estimation of failure probability will require to collect statistical data on occurrences of all four failure events F_i. A part of this data will be related to the behaviour of the components of the sprinkler system (demand failures), whereas some data will reflect such processes as sprinkler maintenance and random occurrence of fires in the course of exploiting a sprinklered building (room).

To answer the question what specific data is needed to estimate p_f requires a detailed definition of probabilities $P(F_i|$ fire). At least one of these definitions can be found in literature, namely, the definition of the failure event 'failure to suppress fire before a critical set of equipment is damaged' (Siu and Apostolakis 1986). Unfortunately, data on sprinkler failures has been collected in a passive way, which is, without any theoretical preconception such as the one expressed by Eq (1). Nevertheless, a substantial amount of data on sprinkler failures has been collected over the last 50 years. A short review of this data is presented in the next section. At least in part, this data can be applied to estimating some of failure probabilities $P(F_i|$ fire).

Table 1. A brief summary of data on sprinkler failure probability

Country	Reference	Reliability	Failure probability
UK	Rutstein and Cook (1979)	97,8 %	2,2 %
		For various types occupancies 92…97 %	3…8 %
		For all industrial buildings 95,6 %	4,4 %
Australia nad New Zealand	Marryatt (1988)	All building categories 99 %	1 %
US	Rasbash et al. (2004)	All building categories 96 % (for the period 1897 – 1964, NFPA data)	4 %
	FMRC	85 % (for the period 1970-1972, FMRC data)	15 %
	US Navy	95 % (for the period 1966-1970, US Navy data)	5 %
		Wet-pipe 86 %	14 %
		Dry-pipe 83 %	17 %
		Deluge 63 %	37 %
	Anon (1970)	All building categories 90 %	10 %

Table 2. Individual sprinkler failures with corresponding failure probabilities (Moelling *et al.* 1980)

Failure mode	Point estimates and 90% confidence estimates of probability per demand		
	Lower bound	Point estimate	Upper bound
Sprinkler heads fail to open	Not reported	$<1\times10^{-6}$ (0,0001 %)	Not reported
Fire detectors fail to function	$1{,}89\times10^{-3}$ (0,189 %)	$2{,}97\times10^{-3}$ (0,297 %)	$4{,}45\times10^{-3}$ (0,445 %)
Deluge valves fail to open	$8{,}9\times10^{-4}$ (0,089 %)	$1{,}90\times10^{-3}$ (0,19 %)	$3{,}58\times10^{-3}$ (0,358 %)
Fire pumps fail to start	$4{,}47\times10^{-3}$ (0,447 %)	$1{,}40\times10^{-2}$ (1,4 %)	$2{,}39\times10^{-2}$ (2,39 %)
Check valves fail to open	3×10^{-5} (0,003 %)	1×10^{-4} (0,01 %)	3×10^{-4} (0,03 %)
Alarms fail to function	$2{,}681\times10^{-2}$ (2,681 %)	$3{,}62\times10^{-2}$ (3,62 %)	$4{,}81\times10^{-2}$ (4,81 %)
Personnel fail to trip manual release	Not reported	0,2	Not reported
Frequency of the event "valves closed inadvertently"	$5{,}47\times10^{-3}$ year^{-1} (0,547 %)	$5{,}475\times10^{-2}$ year^{-1} (5,475 %)	0,5475 year^{-1}

Data on Sprinkler Failures

Sources of data on sprinkler failures are investigation reports cited in articles and books of fire engineering. The sources range between 1960s and 1990s. A brief review of this data is presented in Tables 1 and 2. According to this generic data, the probability of sprinkler failure ranges between 1 % and 37 %. The largest available study on the reliability of sprinklers shows that the generic estimate of failure probability is about 10 % (Anon 1970). Moelling *et al.* (1980) collected data on sprinkler failure from four nuclear power plants and made models and sensitivity analyses. Their estimates of failure probability are reproduced in Table 2. One can conclude that sprinkler systems used in this kind of buildings are more reliable as compared to generic data given in Table 1.

The cause of failure for any type of system is typically classified according to several general categories such as installation errors, design mistakes, manufacturing/equipment defects, lack of maintenance, exceeding design limits and environmental factors (Linder 1993). A large number of such classifications are presented by Rönti *et al.* (2004). Table 2 is an example of such classifications and contains point estimates and interval estimates of failure rates (frequencies). The interval estimates were calculated as confidence intervals of a binomial distribution parameter. In principle, such data can be applied to obtaining estimates of probabilities $P(F_i|\text{ fire})$ or related frequencies, for example, frequencies $P(F_i|\text{ fire})\times Fr(\text{fire})$. However, the estimation of probabilities and frequencies from data on fire incident is far from being straightforward.

A closer look at the relatively large amount of data on specific sprinkler failures raises several questions concerning the applicability of data for assessing failure probability p_f in highly case specific circumstances:

1. Is data collected in a specific type of buildings applicable to different types of occupancy (e.g. can data on fires in sprinklered nuclear power plants be applied to common office building)?

2. Can the failure of a sprinkler system produced and supplied by a specific manufacturer be considered as a representative observation in the entire population of sprinklers?

3. Can the estimates of the rates of specific low-level failure events be grouped into (added to) the estimates of the rates of higher level events when this data comes from different databases, countries, manufacturers, etc.?

(e.g. can data on water supply failures coming from one country be combined with data on water freezing in sprinkler pipes collected in another country)?

These questions allow to preliminary conclude that the estimation of failure probabilities p_f and $P(F_i|$ fire) using data from the past and from different data sources is problematic when the standard frequentist's approach is applied. At the least, a very careful analysis of data sources and consideration of applying this data to the case of the specific sprinkler system is required for such estimation. However, such data may be sparse and the frequentist's approach can be difficult to apply (Rönti *et al.* 2004). Some attempts to carry out fault tree analysis of sprinkler systems were made in 1979 by Watanabe (see references in Rönti *et al.* 2004). Recently, it has been investigated by Hauptmanns *et al.* (2008).

One can assume that data on sprinkler failures, where it is not fully relevant to the specific case of failure probability estimation, can be utilised in the framework of Bayesian reasoning. First and foremost, such data can be used for supporting engineering judgement which is indispensable to Bayesian analysis. For instance, data collected in foreign countries (different types of occupancies) can be used for developing Bayesian prior distributions for the case under analysis.

Bayesian Approach to Estimating the Probability of Sprinkler Failure

The standard 'model of the world' for the case of sprinkler failure is binomial distribution. This model assumes that sprinkler responses to demands (fires) are 'exchangeable', i.e. the probability of observing r failures in n fires is independent of the order in which successes and failures occur. Using binomial distribution, the conditional probability of observing r failures in n fires is given by:

$$P(r \text{ failures in } n \text{ fires} \mid \varphi) = \frac{n!}{r!(n-r)!}\varphi^r(1-\varphi)^{n-r}, \quad (2)$$

where ϕ is the parameter of the binomial model interpreted according to the nature of 'failure'. If this means 'failure to be actuated', parameter ϕ will be the probability of no actuation in one demand. If 'failure' stands for general even F_{sys}, parameter ϕ means any possible failure represented by events F_i.

For parameter ϕ, Bayes's theorem expressed in the form of probability densities takes the form (Congdon 2006):

$$\pi_1(\varphi|\mathrm{E}) = \frac{L(\mathrm{E}|\varphi)\pi_0(\varphi)}{\int_\theta L(\mathrm{E}|\varphi)\pi_0(\varphi)d\varphi}, \quad (3)$$

where $\pi_0(\phi)$ is the prior probability density function for the unknown parameter ϕ (prior to obtaining new evidence E), $L(\mathrm{E} \mid \phi)$is the likelihood function. The latter function is either proportional to the conditional probability of observing E given ϕ. The left-hand side of equation, $\pi_1(\phi \mid \mathrm{E})$ is the posterior probability density function for ϕ after E is obtained. The integral in the denominator ensures that $\pi_1(\phi| \mathrm{E})$ integrates to unity over all possible values of ϕ (i.e. that the posterior density function is indeed a proper density function). It is the expectation of $L(\mathrm{E}|\phi)$ with respect to prior distribution $\pi_0(\phi)$. Evidence E will have the form of empirical data on the responses of sprinklers to fires.

It is extremely important to note that as the amount of evidence increases, the numerical results of Eq (3) will converge with those of classical statistics. More precisely, posterior distribution for ϕ will become increasingly peaked about the maximum likelihood estimator for ϕ, i.e. that value of ϕ that maximizes the likelihood function

L(E | ϕ) (e.g. Congdon 2006). One can intuitively say that as we collect more evidence, the information contained in this evidence should overwhelm the information contained in prior distribution $\pi_0(\phi)$.

Binomial distribution (2) treats the Bernoulli (or 'coin-flip') process in which events (failures and no failures) are generated on a demand basis. This model is appropriate if sprinkler failures are independent and if there is no aging, i.e. failure probability ϕ is constant. If aging is an important phenomenon over the time scale of interest, a different process model should be used.

In the standard case of binomial distribution, the likelihood function $L(\mathrm{E} \mid \phi)$ has been derived for several standard form of evidence (Siu and Kelly 1998). If evidence E has the form E = {r failures in n trials}, the likelihood function is expressed by Eq (2). If evidence E is more detailed and expresses a specific sequence of failures 'F' and fire extinguishings 'S', the likelihood function is simply derived using the laws of probability:

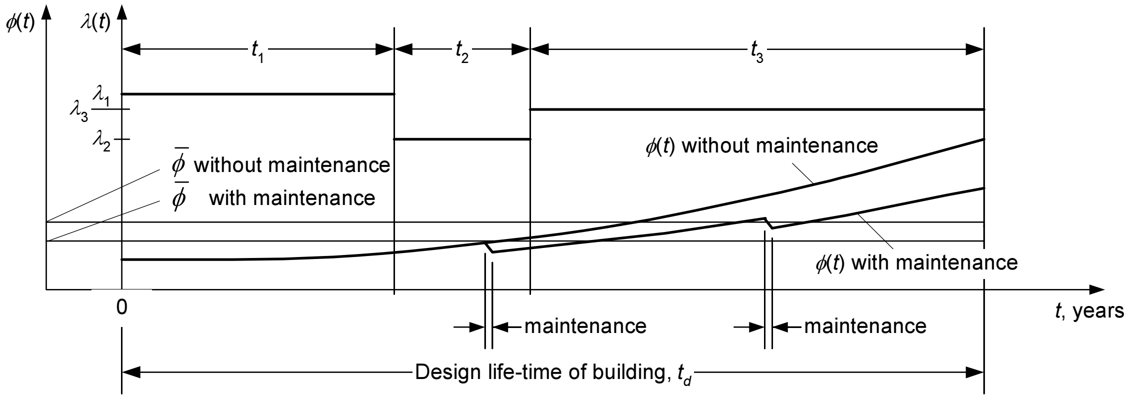

Fig. 2. Two evolutions of sprinkler failure probability $\phi(t)$ during the life-time of the building divided in three periods with different fire hazards expressed by annual fire rates λ_1, λ_2, and λ_3 (parameters of Poisson distribution)

$$L(E_i|\varphi) = (1-\varphi)\cdot(1-\varphi)\cdot\varphi\cdot\varphi\cdot(1-\varphi) = \varphi^2(1-\varphi)^3. \quad (4)$$

In the case of multiple, conditionally independent sets of evidence E_i, the likelihood function is given by

$$L(E|\varphi) = \prod_i L(E_i|\varphi). \quad (5)$$

Other forms of evidence E that fit within the framework of Eq (3) include expert opinions, model predictions and 'fuzzy' or imprecise data (Siu and Kelly 1998; Kelly and Smith 2009).

The assumption of the independence of subsequent sprinkler failures is relatively difficult to verily as these failures are rare events. Despite the considerable amount of generic statistical data on sprinkler failures, this data will hardly be sufficient for the formal proof of independence. However, the assumption of the absence of aging (no aging) seems to be not correct in the case of sprinklers. This requires expanding the 'model of the world' (2) for the case of a graduate decrease in sprinkler reliability with time.

The Treatment of Sprinkler System Aging

Some components of sprinkler systems are subjected to aging which can, in theory, increase a chance of sprinkler failure given fire. One can assume that aging is a gradual process leading to a monotonic increase in some of sprinkler failure probabilities $P(F_i|\text{ fire})$ (Fig. 2). In case that sprinklers are maintained repaired or replaced during the life-time of building, t_d, a monotonic change in failure probabilities $P(F_i|\text{ fire})$ may be interrupted. Let us, for simplicity, system failure probability p_f be represented by the time-dependent parameter $\phi(t)$as shown in Fig. 2.

The monotonic increase of $\phi(t)$ allows estimating failure probability either by the conservative estimate $\phi(t_d)$ or by an average value

$$\bar{\varphi} = t_d^{-1} \int_0^{t_d} \varphi(t)\, dt. \quad (6)$$

The mean value $\bar{\phi}$ represents the entire life-time t_d and is applicable to the case of the maintained system (non-monotonic evolution of $\phi(t)$. A derivation of the functional form of $\phi(t)$ is a complicated problem because:

1. the life-time of sprinklers is relatively long and can extend over several decades; the acquisition of data on sprinkler performance in fires is complicated by such a length of service life.

2. the number of demands (fires) per life-time of sprinklers is relatively low; in many cases this number is equal to zero; thus, the numbers of the failures of specific sprinkler systems within preset periods (years, decades) can be also very small and insufficient to assess failure rates within these periods with sufficient accuracy.

The aforementioned difficulties encumber a derivation of the functional form of $\phi(t)$ for sprinklers. In the simple case of the Bernoulli process, the function $\phi(t)$ is a time-independent parameter ϕ. The expected number of sprinkler failures in n fires is given by $n\phi$. In the theory, the functional form for $\phi(t)$ can be adopted from the corresponding expression using the time-dependent parameter of a Poisson distribution based on the non-homogenous Poisson process (Kelly and Smith 2009). The form of $\phi(t)$ can be expressed by the power law process

$$\phi(t) = \frac{\alpha}{\beta}\left(\frac{t}{\beta}\right)^{\alpha-1}, \quad (7)$$

the loglinear model

$$\phi(t) = \exp\{a + b\,t\}, \qquad (8)$$

and the linear model

$$\phi(t) = a + b\,t. \qquad (9)$$

Pulkkinen and Simola (2000) proposed the Bayesian approach to estimating the time dependent parameter of binomial distribution on the basis of the linear functional form of $\phi(t)$. Unfortunately, this approach rests on a somewhat different scheme of data acquisition and non-explicit representation of aging time. Consequently, it is not directly applicable to the specific case of sprinklers.

Field or test data that could allow fitting a specific form of $\phi(t)$ seems not to be available. At present, one can only guess about the rate of aging during different periods of sprinklers' life-time. Clearly, this guess can be formalised in the Bayesian format; however, a virtual lack of data on the time-dependency of failure probability will confine Bayesian modelling only to the educated guess.

Conclusions

The assessment of the reliability of sprinkler systems has been considered. The probability of sprinkler failure was used as a quantitative measure of reliability. Sprinklers can fail in a variety of modes, and therefore an estimation of sprinklers' failure probability is a relatively complicated task. In addition, failures in all modes are relatively rare events. This leads to a sparseness of data that could be applied to a direct estimation of specific failure probabilities in line with the frequentist's approach. Moreover, the collection of data is quite a chaotic process that did not undergo any world-wide or nation-wide standardisation. Row data on sprinklers' failures is usually hidden behind specific failure rates published in literature and not accessible to the analyst. Data is collected passively after failures take place. Data allowing to judge about the gradual aging of sprinkler systems seems not to be available. A theoretical model enabling the analyst to collect data in a consistent, systematic way and to obtain good estimates of failure probabilities has not been created until now.

The published rates of sprinkler failures allow a rough estimation of corresponding failure probabilities. These rates are generic data collected in specific countries or specific types of occupancy. Such estimates can be applied to Bayesian reasoning, namely, developing prior distributions for probabilities related to individual failure modes. Then, usually sparse albeit highly relevant data collected for a specific type of the sprinkler system in a particular country (region) can be applied as new evidence to updating the prior distributions. In case of sprinkler systems operating and failing on demand Bayesian failure probability estimation can be represented as a standard problem of Bayesian inferring about a parameter of binomial distribution. The binomial model assumes that there is no aging of sprinklers. Clearly, this assumption might be incorrect. Unfortunately, data on sprinkler failures is too sparse and diverse to allow a clear proof of an increase in failure probability in the course of sprinkler service, to say nothing of fitting a mathematical model quantifying the increase. At present, the aging and related potential increase of failure probability remains a theoretic assumption which is difficult to incorporate into the practical assessment of sprinkler reliability.

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SPRINKLERIŲ PATIKIMUMO PROBLEMA

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Santrauka

Nagrinėta sprinklerių sistemų patikimumo vertinimo problema. Patikimumo matu laikoma sprinklerių atsako tikimybė. Rasta, kad šios tikimybės vertinimas yra sąlygiškai sudėtingas uždavinys. Sprinkleriai gali patirti atsaką labai įvairiais būdais. Be to, šis atsakas patiriamas retai. Tai lemia duomenų apie sprinklerių neįsijungimo gaisro metu negausumą, neleidžia vertinti atsako tikimybės, remiantis klasikiniu santykinio dažnio požiūriu. Patikimumo vertinimą komplikuoja tai, kad duomenys apie sprinklerių atsakus renkami gana nesistemingai, be teorinio pagrindo ir standartizavimo šalies, regiono ar pasaulio mastu. Duomenys paprastai fiksuojami pasyviai, kai sprinkleriai neįsijungia gaisro metu.

Turimi empiriniai sprinklerių atsako dažniai gali būti naudojami kaip šiurkštūs tikimybių įverčiai. Juos galima taikyti Bajeso analizei, kai reikia formuoti apriorinį atsako tikimybės tankį. Šį tankį galima atnaujinti pasitelkiant negausius duomenis, surinktus konkrečioje šalyje, ir gautus stebint konkretaus tipo sprinklerius.

Teorinis modelis kuriuo galima nusakyti sprinklerių atsakų tikėtinumą per pasirinktą gaisrų skaičių, yra binominis skirstinys. Sprinklerių atsako tikimybės vertinimą galima atlikti taikant standartinę binominio skirstinio parametro vertinimo procedūrą Bajeso statistikos metodais. Pagrindinė binominio skirstinio prielaida yra ta, kad sprinkleriai nesensta ir jų atsako tikimybė nesikeičia laikui bėgant. Galima spėsti, kad ši prielaida yra neteisinga. Deja, duomenų, kurie galėtų patvirtinti arba paneigti tą prielaidą, trūksta. Be tokių duomenų, nebus galima parinkti modelio, kuris nusako atsako tikimybės didėjimą sprinklerius eksploatuojant. Taigi sprinklerių senėjimas ir jų atsako tikimybės didėjimas tėra tik teorinė prielaida, kurią sunku įtraukti į sprinklerių patikimumo vertinimą.

Reikšminiai žodžiai: sprinkleriai, gaisras, Bajeso požiūris, daugiakriterė atranka.