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RELIABILITY ANALYSIS OF FIRE DETECTION AND ALARM SYSTEMS

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Abstract The aim of this paper is to determine the reliability of fire detection and alarm systems using fault tree quantitative analysis. The analysis is performed using analytical and matrix procedures for determining minimal cut sets and minimal path sets. The quantitative analysis focuses on a system installed in a production hall, which contains a heat detector, a smoke detector, and a manual fire alarm. The top event analyzed was the event "the fire detection and alarm system has not detected a fire". Based on the analysis and the evaluation of importance of the minimal cut sets, we were able to conclude that events such as line interruption, manual fire alarm push-button failure, and short circuits are the most significant events as they are the biggest contributors to fire detection and alarm system failure.

Keywords: reliability; fault tree analysis; minimal cut set; minimal path set; fire detection and alarm system.

1. INTRODUCTION

According to SRPS A.A2.005 (1986), reliability is the ability of a product to perform its required function under specified conditions over a specified time period. It is expressed through probability of faultless operation. A system failure refers to the incompatibility of a specific system's function with the function it provides to the user. In terms of reliability, failure refers to the inability of a product (a part, an assembly, a subsystem, a system, or a device) to perform its required function; alternatively, it refers to situations when specific product features fall outside a specified domain that constitutes satisfactory functioning of a product (SRPS A.A2.005:1986).

With regard to safety systems, as specific technical systems that maintain the safety of another system, there are no differences in the definition of failure in terms of reliability and safety. Namely, any disturbance of safety system functioning (failure in terms of reliability) implies the loss of ability to reduce risk of the system being protected (failure in terms of safety). This is why reliability is understood as a fundamental performance of any safety system.

The chief advantage of predicting reliability of complex systems does not lie in the absolute predicted numerical value but in the possibility to repeat the assessment for different maintenance time, different design redundancies, and different values of component failure frequency. This became feasible with the appearance of computers, e.g. with fault tree analysis software, which allows fast repetition of predictions. Thus, it is possible to make an assessment based on relative predictions with a higher degree of certainty compared to absolute values. In addition, the complexity of modern design products and systems results in the system failure not always being a consequence of simple failures of components and the system. The factors influencing system unreliability are the following: failure due to software elements, failure due to human factor or operative documents, failure due to weather conditions, standard manners of failure, and the like.

2018, Volume 2, Issue 2, 30-39, DOI: 10.6722/TES.201812_2(2).0005

Fire detection and alarm systems are fairly efficient with regard to warning people about a fire. The primary purpose of fire detection and alarm systems is to warn the user as soon and as reliably as possible about a fire breakout in order to avoid human casualties and protect property. Fire detection and alarm systems are supposed to detect fires in their earliest stage of development, immediately after the process of uncontrolled combustion is initiated [1].

Manual fire alarms are a necessary part of a fixed fire alarm installation, regardless of whether the system contains an automatic fire alarm or not. Since manual alarms are activated by people, the signal originating from such alarms is considered as a reliable notification of the occurrence of a fire and is not additionally verified by the system [1].

Constant increase of heat release is characteristic of the early stages of fire development, which is accompanied by temperature increase in the room. Heat detection in fire alarm systems can be performed with or without measuring, and due to simplicity of construction, heat detectors can be either point detectors or linear detectors, depending on the area they cover. With any detector type, only two conditions for generating the alarm signal are used: the predefined temperature value is exceeded or the temperature change rate is exceeded [1]

The fact that most fires are preceded by smoke, and that flames and temperature change occur later, is responsible for the extensive use of smoke detectors in fire alarm systems. Smoke detectors are the most efficient in situations where the composition of combustible material is such as to create smaller or bigger quantities of smoke at the very beginning of a fire. Their construction is based on two principles of smoke detection – radioactive and optical, only the detectors with a radioactive element are not in use anymore. They are produced as point or linear detectors, but there are special smoke detector types for special purposes [1].

2. METHODS OF SYSTEM RELIABILITY ANALYSIS

Literature provides numerous examples of methods for system reliability analysis, which mostly pertain to systems with a simple topology. One such example is the network reduction method and the fault tree method [2]. The essence of network reduction lies in the reduction of the whole system to a single equivalent element, by systematically combining appropriate series and parallel branches of the reliability network. Finally, reliability of the remaining equivalent element is equal to the reliability of the original system.

One of the most important methods of determining the reliability of complex networks is based on minimal cut and path sets [4].

The network in Figure 1 represents the use of minimal cut and path sets for system reliability evaluation. The system will function if there is one of the minimal paths (A,C) or (B,D) or (A,E,D) or (B,E,C).

2018, Volume 2, Issue 2, 30-39, DOI: 10.6722/TES.201812_2(2).0005

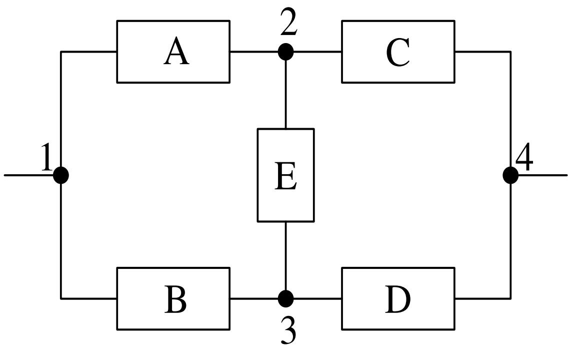

Figure 1. Bridge structure reliability network.

Reliability network is widely used to determine the reliability of fire detection and alarm systems as well as fire suppression systems.

Qualitative analysis is the determination of minimal cut sets and minimal path sets. Minimal cut sets and minimal path sets represent two equivalent sources of information on the state of the system.

Minimal cut sets are those sets of events that are necessary for the occurrence of the top event. A cut is minimal when it does not contain any other cuts itself.

A minimal path set is the smallest set of events, which must not occur if the top event is to be avoided, i.e. minimal path sets are the smallest sets of events, on which reliable functioning of the system (absence of the top event) is dependent. A path is minimal when it does not contain any other paths itself.

Initial derivation can be non-minimal or minimal, so that each cut set containing a minimal cut set is not minimal. Table 1 shows these differences: minimal sets can only include sets 1, 3, and 6, because they do not contain other cut sets. Set 2 is non-minimal because it contains set 3. Set 5 is also non-minimal, because it contains sets 1, 3, and 6 [6].

Table 1. Minimal cut sets

Set	Cut set	Minimal cut set
1	AB	Yes
2	ACD	No
3	AD	Yes
4	CDE	No
5	ABDE	No
6	DE	Yes

Cut sets shown in Table 1 can be represented as causes of system failure by means of Boolean OR operator, whereby Boolean algebra theorems and axioms are used (Table 2):

$$AB + ACD + AD + CDE + ABDE + DE = AB(1 + DE) + DE(1 + C) + AD(1 + C) = AB + DE + AD \quad (1)$$

2018, Volume 2, Issue 2, 30-39, DOI: 10.6722/TES.201812_2(2).0005

Table 2. Boolean algebra theorems and axioms

Boolean algebra theorems	
$a+0=a$	$a \cdot \bar{a}=0$
$a+1=1$	$a+\bar{a}=1$
$a \cdot 0=0$	$a+ab=a$
$a \cdot 1=a$	$a(a+b)=a$
$a \cdot a=a$	$a+\bar{a}b=a+b$
$a+a=a$	
Boolean algebra axioms	
$a \cdot b=b \cdot a$	Commutative law
$a+b=b+a$	
$(a+b)+c=a+(b+c)=a+b+c$	Associative law
$(ab)c=a \cdot (bc)=a \cdot b \cdot c$	
$a(b+c)=ab+ac$	Distributive law

When creating a minimal cut set using a matrix procedure, the following steps should be taken:

- Ignore all tree elements except the basic ones;
- Begin immediately below the top event, assign a unique letter and/or number to each event;
- Proceed downward ‘step by step’;
- Create a matrix using letters and/or numbers. The letter representing the top event gate becomes the initial matrix input. Subsequent steps include:
  - replacing the letter of every AND gate with a letter/number for all gates/events serving as its inputs and representing this horizontally in matrix rows;
  - replacing the letter of every OR gate with a letter/number for all gates/events serving as its inputs and representing this vertically in matrix columns. Each newly-formed row has to contain all other inputs as in the initial row.
- The final matrix contains only the numbers representing initial events. Each row of this matrix is a cut set. Eliminate by verification every row containing all elements from a lower-row set. Also, delete redundant (repeated) elements in rows and repeating rows. The remaining rows constitute a minimal cut set.

Based on the created minimal cut set, it is possible to create an equivalent fault tree, as shown in Figure 2. Fault trees have two event levels: the primary event level connected by AND gates and the event level directly leading to the top event, connected by an OR gate.

2018, Volume 2, Issue 2, 30-39, DOI: 10.6722/TES.201812_2(2).0005

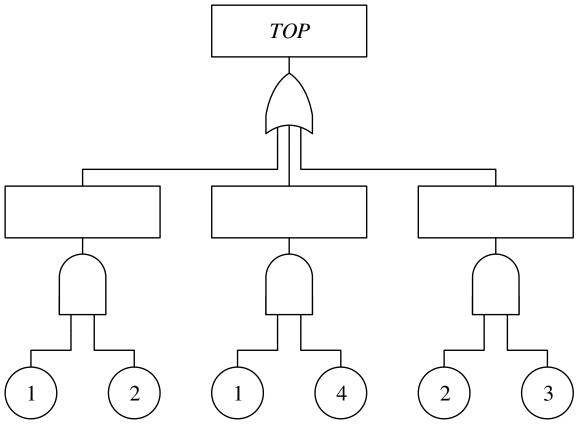

Figure 2. Equivalent fault tree created based on minimal cut sets [3].

Cut sets can be used to establish the vulnerability to shared causes and for qualitative evaluation of the importance of minimal cut sets and events.

The procedure for creating a minimal path set involves the following steps [6]:

- Replace all AND gates with OR gates and all OR gates with AND gates.
- Replace all events with opposite events.
- Apply same procedure as in creating the cut set matrix.
- The procedure yields path sets, specifically minimal path sets.

3.QUALITATIVE FAULT TREE ANALYSIS OF A FIRE DETECTION AND ALARM SYSTEM

A fire detection and alarm system comprises the following components: monitoring and control device, signalling and alarm elements, manual and automatic detectors and alarms, and auxiliary devices. The performed qualitative fault tree analysis of a fire detection and alarm system is represented using minimal cut sets and minimal path sets.

The analysis was performed for a fire detection and alarm system installed in a production hall, comprising heat and smoke detectors and a manual fire alarm. The top event (T) is “the fire detection and alarm system has not detected a fire”. The top event is preceded by event A (no signal from automatic detectors) and event B (no signal from manual alarms), which can be the result of human error (1) or push-button failure (2). Event A is caused by heat detector (C) and smoke detector (D) failure. Heat detector failure (C) can be caused by an interruption in the switch signal (E) (due to line interruption (3) or inertness (4)), central signal interruption (F), and signal interruption through the installation (G). Central signal interruption (F) occurs due to central software failure (7), central hardware failure (8), and power supply failure (I), which can be caused by the interruption of the main (9) and auxiliary (10) power supply. Signal interruption through the installation (G) is due to line interruption (3) and a short circuit (6). Smoke detector failure (D) can be due to central signal interruption (F), signal interruption through the installation (G), and signal interruption from the detectors and alarms (H), which in turn can be due to line interruption (3) and poor calibration (5) [5].

2018, Volume 2, Issue 2, 30-39, DOI: 10.6722/TES.201812_2(2).0005

Figure 3 shows a fault tree of a fire detection and alarm system, where all events are represented by numbers or letters, depending on whether they are primary or intermediate events.

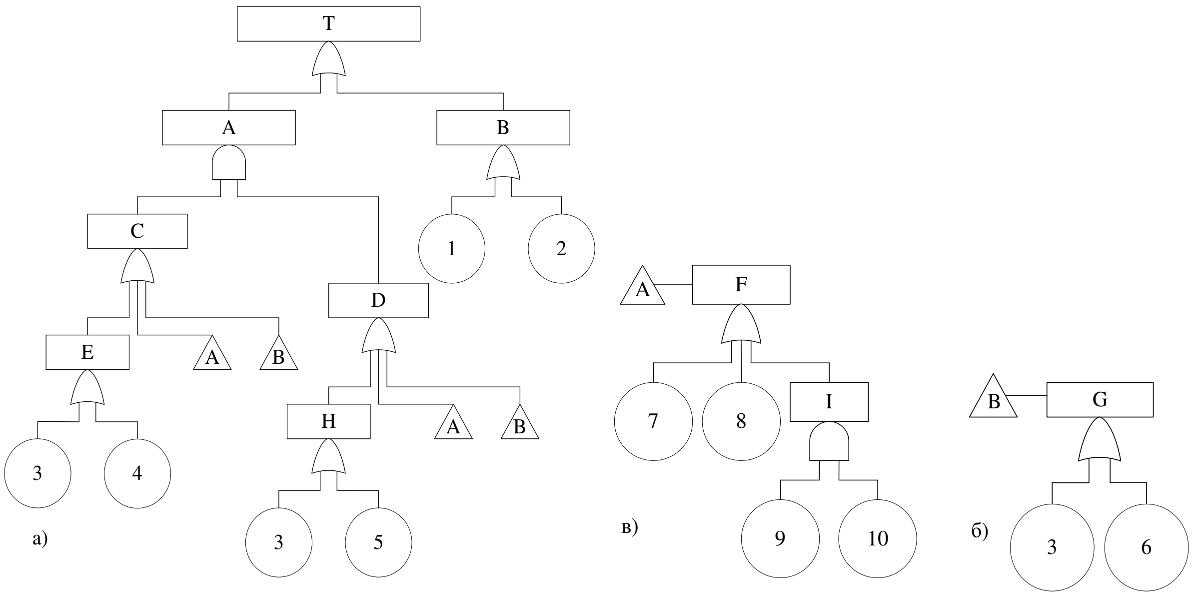

Figure 3. Fault tree of a fire detection and alarm system for qualitative analysis.

Figure 4 shows the creation of minimal cut sets using a matrix procedure for a portion of the fault tree of a fire detection and alarm system.

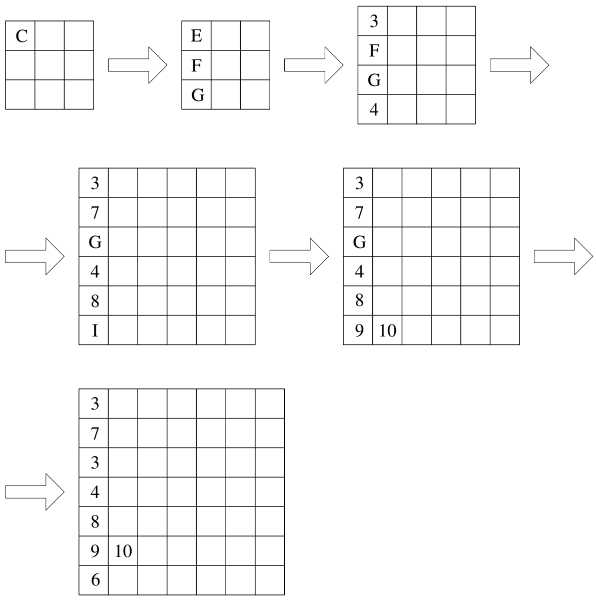

Figure 4. Creation of minimal cut sets using a matrix procedure.

Creation of a minimal cut set using Boolean algebra demonstrates that the failure of specific elements, or specific individual events (“line interruption”, “inertness”, “human error”, “push-button

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failure", "poor calibration", "short circuit", "central software failure", "central hardware failure"), can cause overall system failure.

$$T=A+B \tag{2}$$

$$A=C\cdot D \tag{3}$$

$$B=1+2$$

$$C=E+F+G \tag{4}$$

$$D=H+F+G \tag{5}$$

$$E=3+4$$

$$H=3+5$$

$$F=7+8+I$$

$$G=3+6$$

$$I=9\cdot 10$$

$$F=7+8+9\cdot 10$$

$$D=3+5+7+8+9\cdot 10+3+6$$

$$C=3+4+7+8+9\cdot 10+3+6$$

$$A=(3+4+7+8+9\cdot 10+3+6)\cdot\cdot(3+5+7+8+9\cdot 10+3+6)$$

$$A=3\cdot 3+3\cdot 5+3\cdot 7+3\cdot 8+3\cdot 9\cdot 10+3\cdot 3+3\cdot 6+4\cdot 3+4\cdot 5+4\cdot 7+4\cdot 8+4\cdot 9\cdot 1+4\cdot 3+4\cdot 6+7\cdot 3+7\cdot 5+7\cdot 7+7\cdot 8+7\cdot 9\cdot 10+7\cdot 3+7\cdot 6+8\cdot 3+8\cdot 5+8\cdot 7+8\cdot 8+8\cdot 9\cdot 10+8\cdot 3+8\cdot 6+9\cdot 10\cdot 3+9\cdot 10\cdot 5+9\cdot 10\cdot 7+9\cdot 10\cdot 8+9\cdot 10\cdot 9\cdot 10+9\cdot 10\cdot 3+9\cdot 10\cdot 6+3\cdot 3+3\cdot 5+3\cdot 7+3\cdot 8+3\cdot 9\cdot 10+3\cdot 3+3\cdot 6+6\cdot 3+6\cdot 5+6\cdot 7+6\cdot 8+6\cdot 9\cdot 10+6\cdot 3+6\cdot 6$$

$$A=3+3\cdot 5+3\cdot 7+3\cdot 8+3\cdot 9\cdot 10+3\cdot 6+4\cdot 3+4\cdot 5+4\cdot 7+4\cdot 8+4\cdot 9\cdot 10+4\cdot 6+7\cdot 3+7\cdot 5+7+7\cdot 8+7\cdot 9\cdot 10+7\cdot 6+8\cdot 3+8\cdot 5+8\cdot 7+8+8\cdot 9\cdot 10+8\cdot 6+9\cdot 10\cdot 3+9\cdot 10\cdot 5+9\cdot 10\cdot 7+9\cdot 10\cdot 8+9\cdot 10+9\cdot 10\cdot 6+3+3\cdot 5+3\cdot 7+3\cdot 8+3\cdot 9\cdot 10+3\cdot 6+6\cdot 3+6\cdot 5+6\cdot 7+6\cdot 8+6\cdot 9\cdot 10+6$$

$$A=3+3\cdot 5+3\cdot 7+3\cdot 8+3\cdot 9\cdot 10+3\cdot 6+4\cdot 3+4\cdot 5+4\cdot 7+4\cdot 8+4\cdot 9\cdot 10+4\cdot 6+7\cdot 5+7+7\cdot 8+7\cdot 9\cdot 10+7\cdot 6+8\cdot 5+8+8\cdot 9\cdot 10+8\cdot 6+9\cdot 10\cdot 5+9\cdot 10+9\cdot 10\cdot 6+6\cdot 5+6$$

$$A=3+3\cdot 4+3\cdot 5+3\cdot 7+3\cdot 8+3\cdot 9\cdot 10+3\cdot 6+4\cdot 5+7\cdot 4+7\cdot 5+7+7\cdot 8+7\cdot 9\cdot 10+7\cdot 6+8\cdot 4+8\cdot 5+8+8\cdot 9\cdot 10+8\cdot 6+9\cdot 10\cdot 4+9\cdot 10\cdot 5+9\cdot 10+9\cdot 10\cdot 6+6\cdot 4+6\cdot 5+6$$

$$A=3\cdot(1+4+5+7+8+9+10+6)+4\cdot 5+7\cdot(4+5+1+8+9+10+6)+8\cdot(4+5+1+9+10+6)+9\cdot 10\cdot(4+5+1+6)+6\cdot(4+5+1)$$

2018, Volume 2, Issue 2, 30-39, DOI: 10.6722/TES.201812_2(2).0005

$A=3+4\cdot5+6+7+8+9\cdot10$

$T=3+4\cdot5+6+7+8+9\cdot10+1+2$

$T=1+2+3+4\cdot5+6+7+8+9\cdot10$

Analytical determination of minimal path sets for a fire detection and alarm system is provided below.

$$T=A\cdot B \tag{6}$$

$$A=C+D \tag{7}$$

$B=1\cdot2$

$$C=E\cdot F\cdot G \tag{8}$$

$$D=H\cdot F\cdot G \tag{9}$$

$E=3\cdot4$

$H=3\cdot5$

$$F=7\cdot8\cdot I \tag{10}$$

$G=3\cdot6$

$I=9+10$

$F=7\cdot8\cdot(9+10)=7\cdot8\cdot9+7\cdot8\cdot10$

$D=3\cdot5\cdot(7\cdot8\cdot9+7\cdot8\cdot10)\cdot3\cdot6$

$C=3\cdot4\cdot(7\cdot8\cdot9+7\cdot8\cdot10)\cdot3\cdot6$

$A=3\cdot4\cdot(7\cdot8\cdot9+7\cdot8\cdot10)\cdot3\cdot6+3\cdot5\cdot(7\cdot8\cdot9+7\cdot8\cdot10)\cdot3\cdot6$

$A=3\cdot4\cdot6\cdot7\cdot8\cdot9+3\cdot4\cdot6\cdot7\cdot8\cdot10+$

$+3\cdot5\cdot6\cdot7\cdot8\cdot9+3\cdot5\cdot6\cdot7\cdot8\cdot10$

$T=(3\cdot4\cdot6\cdot7\cdot8\cdot9+3\cdot4\cdot6\cdot7\cdot8\cdot10+3\cdot5\cdot6\cdot\cdot7\cdot8\cdot9+3\cdot5\cdot6\cdot7\cdot8\cdot10)\cdot1\cdot2$

$T=1\cdot2\cdot3\cdot4\cdot6\cdot7\cdot8\cdot9+ 1\cdot2\cdot3\cdot4\cdot6\cdot7\cdot8\cdot10+1\cdot2\cdot3\cdot5\cdot6\cdot7\cdot8\cdot9+ 1\cdot2\cdot3\cdot5\cdot6\cdot7\cdot8\cdot10$

Figure 5 shows the reliability network for a fire detection and alarm system created based on the fault tree of a fire detection and alarm system.

2018, Volume 2, Issue 2, 30-39, DOI: 10.6722/TES.201812_2(2).0005

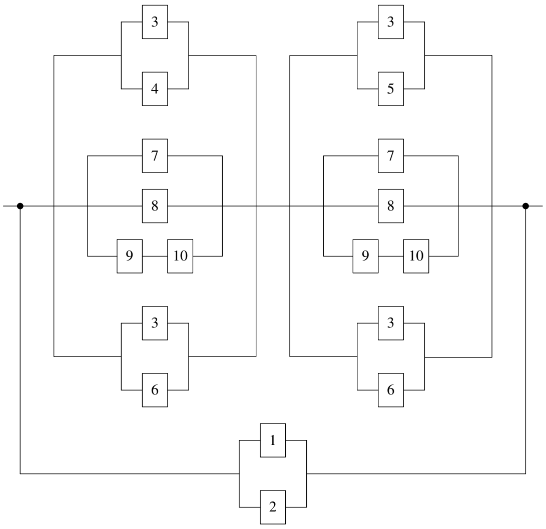

Figure 5. Reliability network for a fire detection and alarm system.

Based on the performed analysis and evaluation of the importance of minimal cut sets, it can be concluded that events such as line interruption, manual fire alarm push-button failure, and short circuit are the most important events and they contribute the most to fire detection and alarm system failure.

3. CONCLUSION

Fault tree analysis is one the most frequently used methods for system reliability analysis. Fault tree analysis can be used to calculate the probability of an unwanted top event as a probability function of failing components. The advantage of fault tree analysis is that it can be applied to any system, regardless of it complexity. On the other hand, the drawback of this approach is that it does not consider the interactions between system components.

The paper presented a qualitative analysis of a fault tree of a fire detection and alarm system using minimal cut sets and minimal path sets. Creation of a minimal cut set using Boolean algebra revealed that the failure of specific system components, or individual system events, can lead to the overall system failure and that some events are the greatest contributors to overall system failure.

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