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PROBABILISTIC ANALYSIS OF INDUSTRIAL EQUIPMENT ACCIDENT REGISTERS THROUGH BAYES' RULE AND BAYESIAN NETWORKS

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Abstract

The paper aims to develop a probabilistic model of a register of industrial equipment accidents. For this purpose, the register of accidents is presented by a probability tree diagram in which the conditional probabilities of the events are denoted. From the diagram and the indicated probabilities, by using the Bayes' rule the probabilities of specific events belonging to different levels of the diagram are determined. Especially valuable is the ability for a certain outcome of the accident to determine the probability that it is caused by a certain machine and a certain cause. To automate the probability determination activity, a Bayesian network consisting of three variables with several states was developed, which was also used to determine the probabilities of events.

Key words: *Accident, Probability tree diagram, Bayes network.*

1 INTRODUCTION

In recent years, the increased amount of used industrial equipment worldwide has inevitably led to an increase in the number of accidents. Although accident monitoring and prevention systems are becoming more sophisticated and produce a definite effect, the analysis of the statistical data for the accidents and the adoption of precautionary measures according to the results of the analysis remains the main means of reducing the accidents rate. In practice, diverse approaches are employed for the statistical data analysis and prognosis of the occurrence of accidents – classical statistical analysis, regression analysis, machine learning, Markov analysis, reliability analysis, etc.

One widely used method for analysing probabilistic data are the Bayesian networks. Bayesian networks are a class of graphical models that allow a concise representation of the probabilistic dependencies between a given set of random variables as a directed acyclic graph [1].

Because of their universal nature, Bayesian networks have found application in the modelling of a wide variety of systems, including accidents. In [2] Bayesian networks are used for risk analysis in construction projects, and in the paper [3] modelling for risk assessment in case of working at heights was performed using Bayesian network. Chan et al. [4] developed a decision-making system based on a Bayesian network used to reduce the risk of conducting electrical and mechanical works in construction. The Bayesian networks are widely used in the investigation of vehicle accidents. The paper [5] presents a basic model for analysing the causes of ship collisions. A similar approach was employed in [6] to analyse the causes of road accidents. The study [7] investigate train derailment by presenting an event tree using a Bayesian network. A methodology for statistical analysis of the causes for accidents with hoisting cranes is developed in [8]. Other applications have been established in forensic science [9] and the reliability of systems [10].

Based on the need for an in-depth analysis of the data from accidents of industrial equipment, the present paper aims to develop a probabilistic mathematical model of a register of accidents, based on a Bayesian network, through which to obtain more information on the causes of the accidents.

2 MODELING OF ACCIDENT REGISTERS BY A PROBABILITY TREE DIAGRAM

Usually, the occurrence of industrial equipment accidents is recorded in registers of accidents. These registers are kept by the owners, state or private organizations. In most cases, the dangerous industrial equipment (boilers and pressure vessels, gas equipment, elevators, cranes, etc.) are controlled by state organizations - in Bulgaria, it is the State Agency for Metrology and Technical Supervision. The registers of the accidents are the most reliable source of information on the causes, events and outcomes of the accidents.

A sample of a register of accidents, in which a particular accident is recorded using the type of machine, the type of causes of the accident and the outcome of the accident, is shown in Table 1.

Table 1 Example of register of accidents

Accident №	Type of the machine	Cause of the accident	Outcome of the accident
1	Type 1	Cause 1	Outcome 1
2	Type 2	Cause 2	Outcome 2
…	…	…	….
z	Type *f*	Cause *n*	Outcome *k*

The accidents recorded in each row of the table, are distinguished from each other by the attributes "type of the machine", "cause of the accident" and "outcome of the accident". This register contains a minimum amount of information about the accidents, but it can be extended through the addition of other specific accident attributes such as weather conditions, qualification of the operator and the supporting personnel, etc. Also, such a type of register can be continuously extended over time by increasing the number of records *z*. This way of presenting the register is problematic for the extraction of systematic statistical information for the accidents, which can be used for in-depth analysis of the causes and decision-making. Most often, the information from such type of register is presented in the form of a simple summary “bar” or “pie” diagrams of some of the parameters [11], for example - the number of accidents per year or causes for accidents.

An in-depth analysis of the recorded statistical data for the accidents is possible through their representation in a systematic form and additional statistical processing. This will make it possible to indicate the causal links and develop a statistical model of the events related to the operation of industrial equipment. For this purpose, the register is presented as a probability tree diagram [12,13], which contains as many levels as the attributes of the accident. The last level in the tree diagram is the outcome of the accident. Figure 1 shows a sample probability tree diagram built using records of accidents taken from a hypothetical register of accidents with lifting cranes. The attributes of the accidents are: "Crane type", "Cause of the accident" and "Outcome of the accident". The values of the attributes are as follows (f=6, n=6, k=2) [8]:

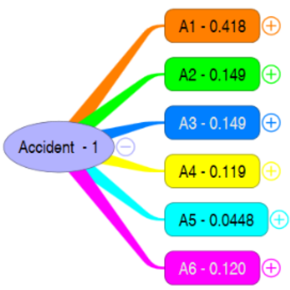
• **Level A** - "Crane type" with 6 values (events) - overhead crane *A1*, gantry crane *A2*, truck crane *A3*, tower crane *A4*, portal crane *A5*, other type *A6*;

• **Level B** – “Cause of the accident” with 6 values – a mistake of the supporting personnel *B1*, a mistake during the installation of the crane *B2*, a destruction of the mechanical or hydraulic transmission *B3*, a mistake of the operator *B4*, a destruction of a structural element *B5*, an absence or malfunction of a safety device *B6*;

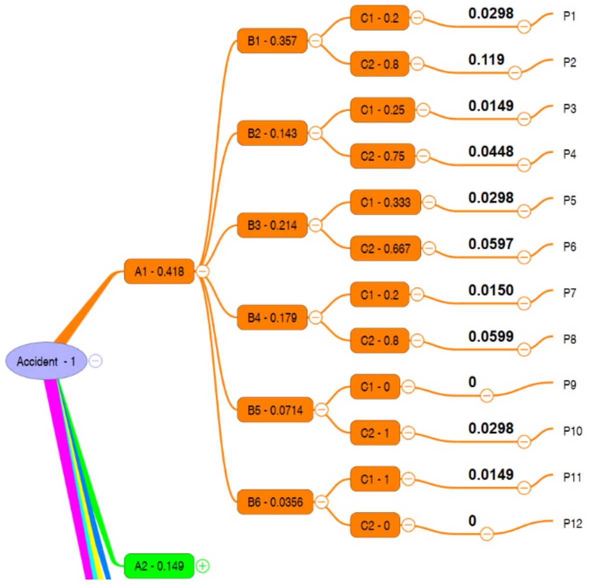
• **Level C** – “Outcome of the accident” with 2 values – an accident with injury to people *C1* and an accident without injury to people *C2*.

The notation C1B2A3 can be interpreted as an occurred accident with outcome “accident with injury to people” due to “a mistake during the installation of the crane” and the machine was “truck crane”.

In Figure 1 a) ÷ Figure 1 g) is shown the probability tree diagram of the accidents with cranes. The conditional probabilities (statistical relative frequencies) for the occurrence of the corresponding events are indicated on the tree diagram, provided that the parent event from the previous level has occurred. The conditional probabilities are easily obtained by statistical processing of the register of accidents. The automation of this processing is performed by suitable software tools, for example, the *Pivot Table* and *Pivot Chart* tools in Excel software.



a)



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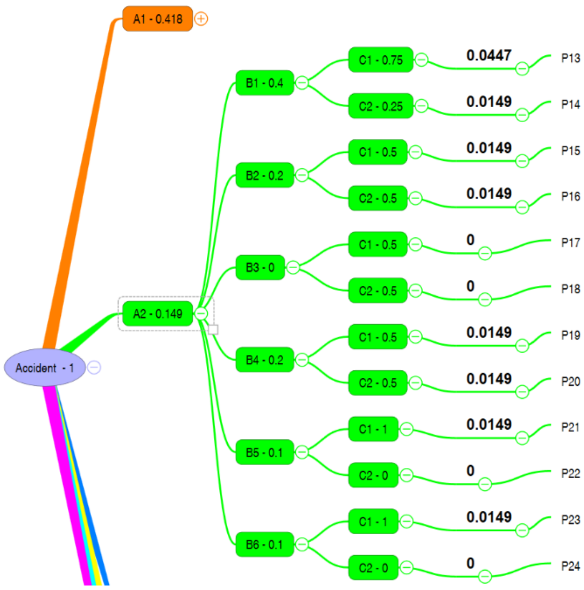

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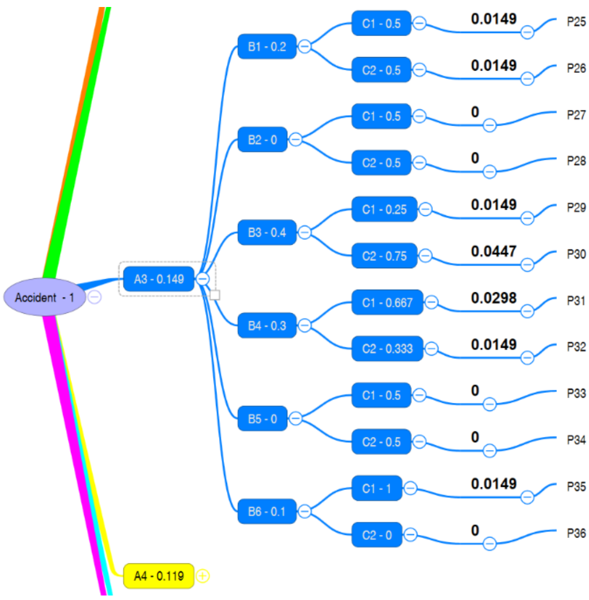

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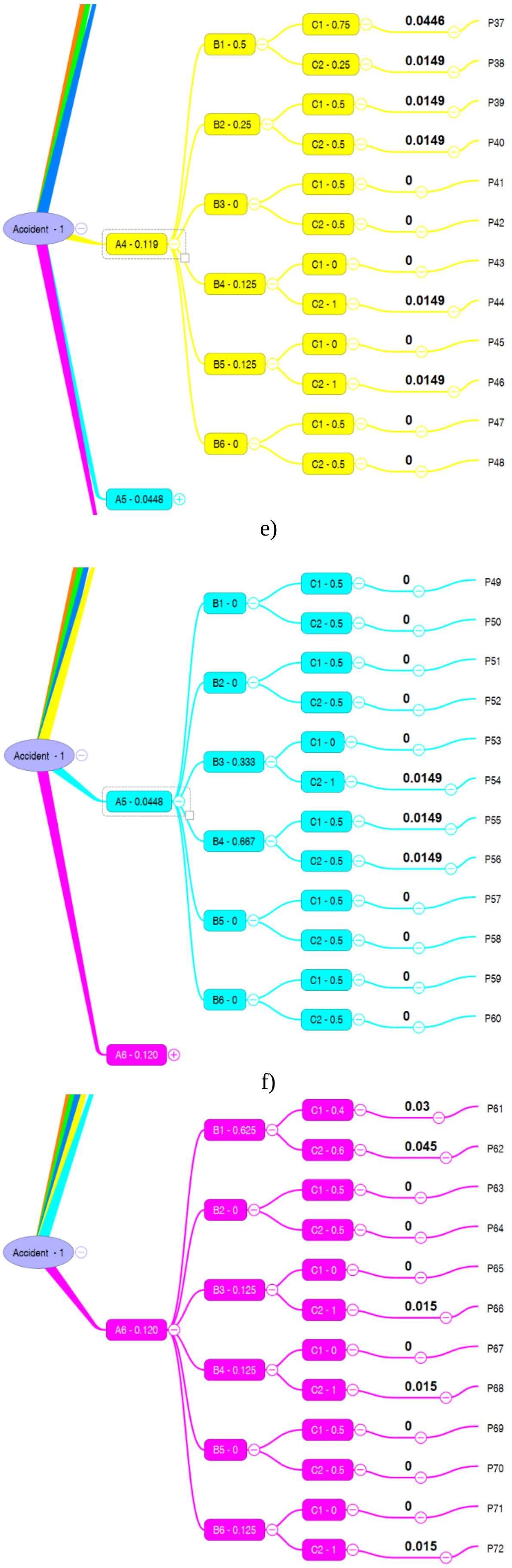

***Fig.1** Probability tree diagram for the accidents with cranes*

3 DETERMINING THE PROBABILITIES OF ACCIDENTS USING BAYES' RULE

An important question arises: how the probability tree diagram can provide further information about the accidents? A fundamental approach is by using the classical Bayes' rule by which the probabilities of occurrence of certain events can be obtained.

The Bayes' rule [8,12,13] is used for this purpose:

$$P(H_i \mid A) = \frac{P(H_i)P(A \mid H_i)}{P(A)} \tag{1}$$

where: $P(H_i \mid A)$ is the conditional probability of the event H_i occurrence given the event A; $P(A) = \sum_{k=1}^{n} P(H_k)P(A \mid H_k)$ is the probability of occurring of event A; $P(H_i)$ is the probability of occurring of event H_i, $(i=1,n)$; $P(A \mid H_i)$ is the conditional probability of the event A given the event H_i.

Using the Bayes' rule, the following sample probabilities can be obtained from the tree diagram.

Case 1: If the event *C1* has occurred then the probability $P_{C_1}^{A_1 \cap B_1}$ that it is caused by the events *A1* and *B1* (i.e. by the certain tree branch) is:

$$P_{C_1}^{A_1 \cap B_1} = \frac{P^{A_1 \cap B_1} \times P_{A_1 \cap B_1}^{C_1}}{P^{C_1}} \tag{2}$$

Here, the following short notations are used:

$P_{C_1}^{A_1 \cap B_1} \equiv P(A_1, B_1 | C_1)$ $P_{A_1 \cap B_1}^{C_1} \equiv P(C_1 | A_1, B_1)$,

$P^{A_1 \cap B_1} \equiv P(A_1, B_1)$, $P^{C_1} \equiv P(C_1)$.

Using the values of the conditional probabilities for the events shown in Figure 1 b), the following values are obtained: $P^{A_1 \cap B_1} = 0.418 \times 0.357 = 0.149$, $P_{A_1 \cap B_1}^{C_1} = 0.2$,

$P^{C_1} = P_1 + P_3 + P_5 + \ldots + P_{71} = 0.3876$,

$$P_{C_1}^{A_1 \cap B_1} = \frac{0.149 \times 0.2}{0.3876} = 0.07688.$$

The joint probabilities P_1, P_3,…,P_{71} are shown in Figure 1. They are calculated as the probabilities for the occurrence of the events *C1*:

$$P_1 = P(C_1 | A_1, B_1) = 0.418 \times 0.357 \times 0.2 = 0.0298;$$

$$P_3 = P(C_1 | A_1, B_2) = 0.418 \times 0.143 \times 0.25 = 0.0149;$$

…

$$P_{71} = P(C_1 | A_6, B_6) = 0.120 \times 0.125 \times 0 = 0.$$

The probability $P_{C_1}^{A_1 \cap B_1}$ can be interpreted as: if an accident with outcome "accident with injury to people" is occurred, what is the probability that the cause is "a mistake of the supporting personnel" and the crane type is "overhead crane"?

Case 2: If the event *C1* occurred, the probability $P_{C_1}^{A_3\cap\forall B_j}$ that it is caused by the event *A3* without taking into account the events from the level *B* is calculated as:

$$P_{C_1}^{A_3\cap\forall B_j}=\frac{\sum_{j=1}^{6}\left(P^{A_3\cap B_j}\times P_{A_3\cap B_j}^{C_1}\right)}{P^{C_1}} \tag{3}$$

$$\sum_{j=1}^{6}\left(P^{A_3\cap B_j}\times P_{A_3\cap B_j}^{C_1}\right)=P_{25}+P_{27}+...+P_{35}=0.0745\ ,$$

$$P_{C_1}^{A_3\cap\forall B_j}=\frac{0.0745}{0.3876}=0.1922\ .$$

The probability $P_{C_1}^{A_3\cap\forall B_j}$ can be interpreted as: if an accident with outcome “accident with injury to people” is occurred, what is the probability that the crane type is “truck crane”?

Case 3: If the event *C1* occurred, the probability $P_{C_1}^{\forall A_i\cap B_2}$ that it is caused by the event *B2* without taking into account the events from level *A* is:

$$P_{C_1}^{\forall A_i\cap B_2}=\frac{\sum_{i=1}^{6}P^{A_i\cap B_2}\times P_{A_i\cap B_2}^{C_1}}{P^{C_1}} \tag{4}$$

$$\sum_{i=1}^{6}P^{A_i\cap B_2}\times P_{A_i\cap B_2}^{C_1}=P_3+P_{15}+...+P_{63}=0.0447\ ,$$

$$P_{C_1}^{\forall A_i\cap B_2}=\frac{0.0447}{0.3876}=0.1153\ .$$

The probability $P_{C_1}^{\forall A_i\cap B_2}$ can be interpreted as: if an accident with outcome “accident with injury to people” is occurred, what is the probability that the cause is “a mistake during the installation of the crane”?

Case 4: If the event *B3* occurred, the probability $P_{B_3}^{A_1}$ that it is caused by event *A1* without taking into account the events from the level *C* is:

$$P_{B_3}^{A_1}=\frac{P^{A_1}\times P_{A_1}^{B_3}}{P^{B_3}} \tag{5}$$

$$P^{A_1}\times P_{A_1}^{B_3}=0.418\times 0.214=0.0895\ ,$$

$$P^{B_3}=\sum_{i=1}^{6}P^{A_i}\times P_{A_i}^{B_3}=0.418\times 0.214+0.149\times 0+$$
$$+0.149\times 0.4+0.119\times 0+0.0448\times 0.333+$$
$$+0.120\times 0.125=0.179,$$

$$P_{B_3}^{A_1}=\frac{0.0895}{0.179}=0.5\ .$$

The probability $P_{B_3}^{A_1}$ can be interpreted as: if an accident due to the cause “a destruction of the mechanical or hydraulic transmission” is occurred, what is the probality that the crane is of type “overhead crane”?

Case 5: If the events *A2* and *C2* occurred then the probability $P_{C_2\cap A_2}^{B_2}$ that they are caused by event *B2* is:

$$P_{C_2\cap A_2}^{B_2}=\frac{P^{B_2}\times P_{B_2}^{C_2\cap A_2}}{P^{C_2\cap A_2}} \tag{6}$$

$$P^{B_2}\times P_{B_2}^{C_2\cap A_2}=0.2\times 0.149\times 0.5=0.0149\ ,$$

$$P^{C_2\cap A_2}=P_{14}+P_{16}+...+P_{24}=0.0447\ ,$$

$$P_{C_2\cap A_2}^{B_2}=\frac{0.0149}{0.0447}=0.333.$$

The probability $P_{C_2\cap A_2}^{B_2}$ can be interpreted as: if an accident with outcome “accident without injury to people” is occurred and the crane type is “gantry crane”, what is the probability that the cause is “a mistake during the installation of the crane”?

Case 6: If the events *B2* and *C2* occurred, then the probability $P_{B_2\cap C_2}^{A_2}$ that they are caused by event *A2* is:

$$P_{B_2\cap C_2}^{A_2}=\frac{P^{A_2}\times P_{A_2}^{B_2\cap C_2}}{P^{B_2\cap C_2}} \tag{7}$$

$$P^{A_2}\times P_{A_2}^{B_2\cap C_2}=P_{16}=0.0149\ ,$$

$$P^{B_2\cap C_2}=P_4+P_{16}+...+P_{64}=0.0746\ ,$$

$$P_{B_2\cap C_2}^{A_2}=\frac{0.0149}{0.0746}=0.1997\ .$$

The probability $P_{B_2\cap C_2}^{A_2}$ can be interpreted as: if an accident with outcome “accident without injury to people” is occurred and the cause is “a mistake during the installation of the crane”, what is the probability that crane type is “gantry crane”?

Case 7: The probability $P^{A_2\cap B_1\cap C_1}$ of occurring of event *C1* if the events *B1* and *A2* occurred is:

$$P^{A_2\cap B_1\cap C_1}=P^{A_2}\times P_{A_2}^{B_1}\times P_{B_1\cap A_2}^{C_1}=$$
$$=0.149\times 0.4\times 0.75=0.0447.$$

The probability $P^{A_2\cap B_1\cap C_1}$ can be interpreted as: what is the probability of outcome “accident with injury to people” if the cause is “a mistake of the supporting personnel” and the crane type is “gantry crane”?

Case 8: The probability $P_{B_2\cap(A_2\cup A_5)}^{C_1\cup C_2}$ of the occurrence of the event *C1* or *C2* caused by the event *B2* and events *A2* or *A5* can be calculated as a sum of the following probabilities:

$$P_{B_2\cap(A_2\cup A_5)}^{C_1\cup C_2}=P^{A_2}\times P_{A_2}^{B_2}\times\left(P_{B_2\cap A_2}^{C_1}+P_{B_2\cap A_2}^{C_2}\right)+$$
$$+P^{A_5}\times P_{A_5}^{B_2}\left(P_{B_2\cap A_5}^{C_1}+P_{B_2\cap A_5}^{C_2}\right) \tag{8}$$

The probability $P^{C_1 \cup C_2}_{B_2 \cap (A_2 \cup A_5)}$ can be interpreted as: if the outcome "an accident with injury to people" or outcome "an accident without injury to people" are occurred, what is the probability that the cause is "a mistake during the installation of the crane" and the type of the crane is "gantry crane" or "portal crane"?

The probabilities of similar specific events can be calculated similarly.

4 MODELING THE PROBABILITY TREE DIAGRAM USING A BAYESIAN NETWORK

In the presence of conditional probabilities of individual events, the Bayesian network makes it possible to automate the activity of determining probabilities of specific events. The graph representing a tree diagram with *n* levels by a Bayesian network has the form [7] shown in Figure 2 and is represented by an adjacency matrix (9).

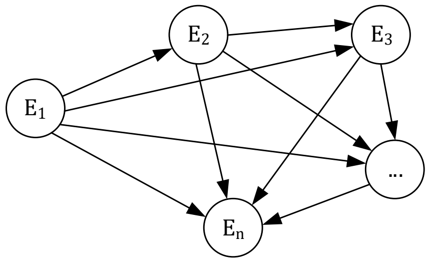

Fig.2 *A graph, representing the Bayesian network for the tree diagram*

$$Adj = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{9}$$

In Figure 2 by $E_1, E_2, \ldots, E_j$ are denoted the probability variables corresponding to the levels (attributes) in the tree diagram. The variable E_j is a successor of the parent variable E_{j-1} (j=2,3,…,n). The joint probability of the events $E=\{E_1, E_2, \ldots, E_n\}$ is calculated as [1,14]:

$$P(E) = \prod_{i=1}^{n} P^{E_i}_{Pa(E_i)} \tag{10}$$

where by $P^{E_i}_{Pa(E_i)}$ is denoted the conditional probability for the event E_i given the parent event $Pa(E_i)$, i.e. $P^{E_i}_{Pa(E_i)} \equiv P\left(E_i \middle| Pa\left(E_i\right)\right)$.

The conditional probabilities of the individual events are defined by conditional probability Tables 2, 3 and 4.

Table 2 Conditional probabilities for level *A* events

Event	Probability
A1	P^{A_1}
A2	P^{A_2}
...	…
A_n	P^{A_i}

Table 3 Conditional probabilities for level *B* events

A		*A1*	*A2*	...	*Ai*
B	*B1*	$P^{B_1}_{A_1}$	$P^{B_1}_{A_2}$	...	$P^{B_1}_{A_i}$
	B2	$P^{B_2}_{A_1}$	$P^{B_2}_{A_2}$	...	$P^{B_2}_{A_i}$
	B3	$P^{B_3}_{A_1}$	$P^{B_3}_{A_2}$	...	$P^{B_3}_{A_i}$
	...	...	...	...	...
	Bj	$P^{B_j}_{A_1}$	$P^{B_j}_{A_2}$	...	$P^{B_j}_{A_i}$

Table 4 Conditional probabilities for level *C* events

		B1				*B2*				...	*Bj*			
A		*A1*	*A2*	...	*Ai*	*A1*	*A2*	...	*Ai*	...	*A1*	*A2*	...	*Ai*
C	*C1*	$P^{C_1}_{B_1,A_1}$	$P^{C_1}_{B_1,A_2}$	…	$P^{C_1}_{B_1,A_i}$	$P^{C_1}_{B_2,A_1}$	$P^{C_1}_{B_2,A_2}$	…	$P^{C_1}_{B_2,A_i}$	…	$P^{C_1}_{B_j,A_1}$	$P^{C_1}_{B_j,A_2}$	…	$P^{C_1}_{B_j,A_i}$
	C2	$P^{C_2}_{B_1,A_1}$	$P^{C_2}_{B_1,A_2}$	…	$P^{C_2}_{B_1,A_i}$	$P^{C_2}_{B_2,A_1}$	$P^{C_2}_{B_2,A_2}$	…	$P^{C_2}_{B_2,A_i}$	…	$P^{C_2}_{B_j,A_1}$	$P^{C_2}_{B_j,A_2}$	…	$P^{C_2}_{B_j,A_i}$
	...	…	…	…	…	…	…	…	…	…	…	…	…	…
	Ck	$P^{C_k}_{B_1,A_1}$	$P^{C_k}_{B_1,A_2}$	…	$P^{C_k}_{B_1,A_i}$	$P^{C_k}_{B_2,A_1}$	$P^{C_k}_{B_2,A_2}$	…	$P^{C_k}_{B_2,A_i}$	…	$P^{C_k}_{B_j,A_1}$	$P^{C_k}_{B_j,A_2}$	…	$P^{C_k}_{B_j,A_i}$

SpiceLogic Inc.'s Bayesian Doctor software [15] was used for computer modelling of the Bayesian network and it has the layout shown in Figure 3. The random variables *A, B* and *C*, corresponding to the tree diagram levels, have multiple states, corresponding to the events in the levels.

The conditional probability Tables 5, 6, and 7 for every variable are compiled using the conditional probabilities shown in the probability tree diagram in Figure 1.

Using the computer model of the developed Bayesian network and the available tool "Joint Conditional Probability Calculator" the determination of the probabilities of the events for the cases from 1 to 8 (see Section 3) was performed.

Figure 4 a) and Figure 4 b) show the windows of the tool when calculating the probabilities for the cases 1 and 2. In Table 8 are shown the determined probabilities for all cases. As can be seen, they coincide with the probabilities determined by the Bayes' rule (see Section 3), and the differences in the values are due to the roundings made during the calculations.

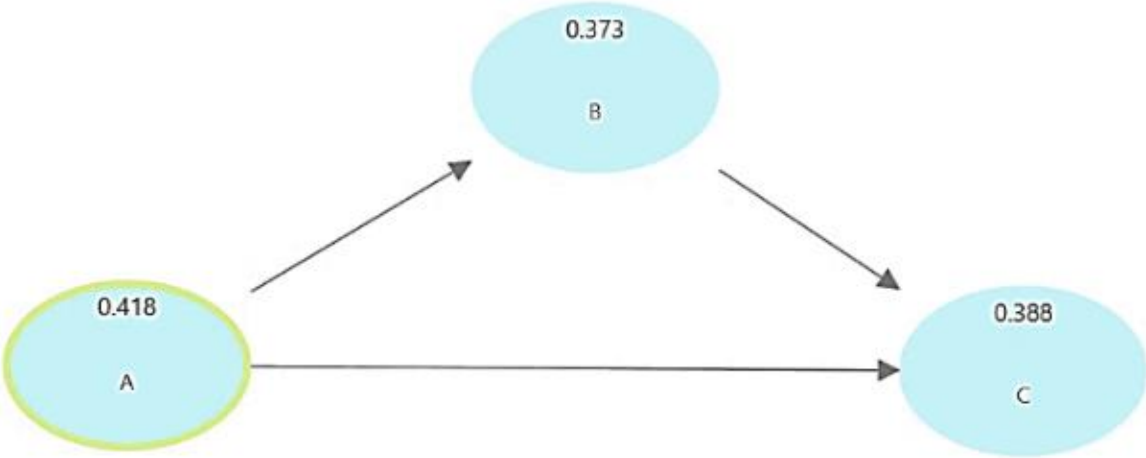

Fig.3 *Bayesian network for the tree diagram with three levels*

Table 5 Conditional probabilities for level *A* events

Event	Probability
A1	0.418
A2	0.149
A3	0.149
A4	0.119
A5	0.0448
A6	0.12

Table 6 Conditional probabilities for level *B* events

A		*A1*	*A2*	*A3*	*A4*	*A5*	*A6*
B	*B1*	0.357	0.4	0.2	0.5	0	0.625
	B2	0.143	0.2	0	0.25	0	0
	B3	0.214	0	0.4	0	0.333	0.125
	B4	0.179	0.2	0.3	0.15	0.667	0.125
	B5	0.071	0.1	0	0.125	0	0
	B6	0.036	0.1	0.1	0	0	0.125

Table 7 Conditional probabilities for level *C* events

B1							
A		*A1*	*A2*	*A3*	*A4*	*A5*	*A6*
C	*C1*	0.2	0.75	0.5	0.75	0.5	0.4
	C2	0.8	0.25	0.5	0.25	0.5	0.6

Table 7 Conditional probabilities for level *C* events – continuation 1

B2							
A		*A1*	*A2*	*A3*	*A4*	*A5*	*A6*
C	*C1*	0.25	0.5	0.5	0.5	0.5	0.4
	C2	0.75	0.5	0.5	0.5	0.5	0.5

Table 7 Conditional probabilities for level *C* events – continuation 2

B3							
A		*A1*	*A2*	*A3*	*A4*	*A5*	*A6*
C	*C1*	0.333	0.5	0.25	0.5	0	0
	C2	0.667	0.5	0.75	0.5	1	1

Table 7 Conditional probabilities for level *C* events – continuation 3

B4							
A		*A1*	*A2*	*A3*	*A4*	*A5*	*A6*
C	*C1*	0.2	0.5	0.667	0	0.5	0
	C2	0.8	0.5	0.333	1	0.5	1

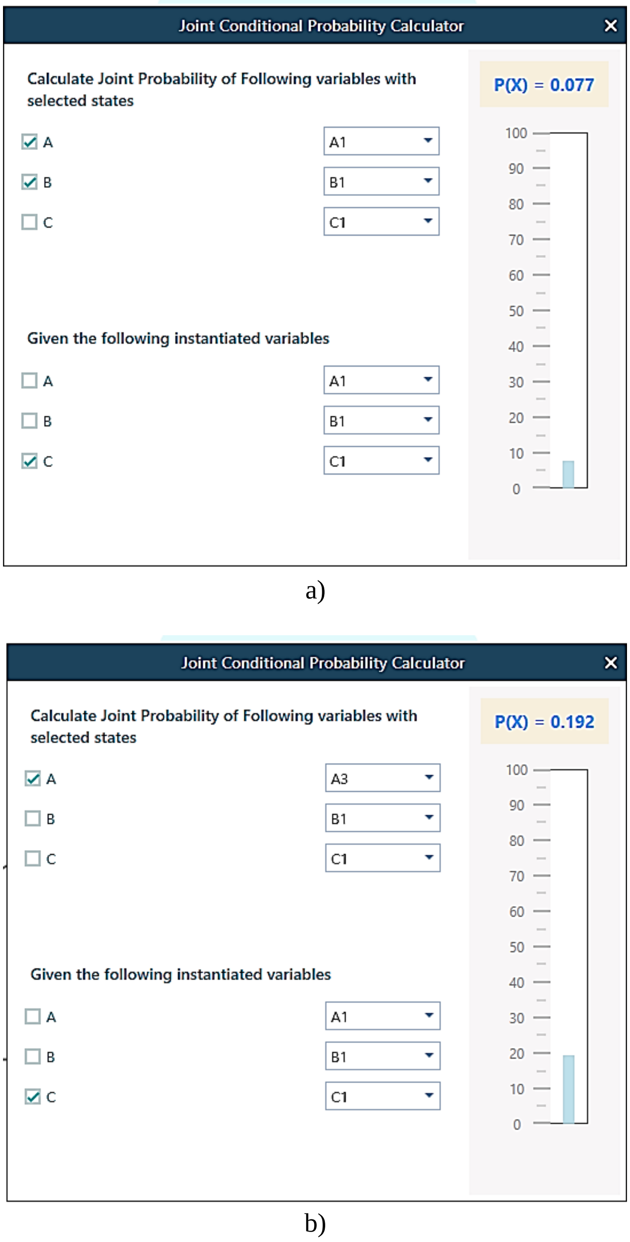

Fig.4 *Joint Conditional Probability Calculator: a) Case l; b) Case 2*

Table 8 The computed probabilities using the Bayesian network

Case	Probability
1	0.077
2	0.192
3	0.115
4	0.5
5	0.333
6	0.2
7	0.045
8	0.03

5 CONCLUSIONS

The paper develops an approach for analysis of registers of accidents of industrial equipment in order to determine the causal relationships between the events and the outcomes of the accidents on a probabilistic basis. For this purpose, the register of accidents is presented in the form of a probability tree diagram and the conditional probabilities for the various events are determined. The demonstration of the developed approach is based on a tree diagram built for a hypothetical register of crane accidents. Bayes' rule is used to determine the probabilities of specific events, belonging to different levels of the tree diagram. Because this approach is difficult to apply in the presence of multiple variables with multiple states, the tree diagram is presented by a Bayesian network. The developed computer model of the network automates the obtaining of individual events probabilities.

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