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MORT WorkSheet or how to make MORT analysis easy

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Abstract

The article is devoted to incident investigation, specifically to one of its aspects: the satisfactory identification of root causes. Management Oversight and Risk Tree (MORT) technique is exploited as a tool that helps to fulfill the task. However, since the application of traditional MORT diagrams was not considered satisfactory, a new software tool MORT WorkSheet was developed to make the MORT analysis easier. The article explains what led to the development of the software tool, how the tool works, and what results it is able to provide. An incident example is used in the article that illustrates how the new tool is applied during the investigation and how the results of its application look. Final comparison shows how different the obtained results may be with support of the MORT WorkSheet from the results of conventional incident investigation.
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1. Introduction

Recently, we studied a set of incident investigation reports from the seventies and eighties.

The article [3] describes an incident analysis process that we decided to follow. The process is divided into the four following steps:

(1) data collection;
(2) causal factor charting;
(3) root cause identification;
(4) recommendation generation and implementation.

The second step produces a graphic representation of the incident chronology and is finalized by the identification of causal factors, i.e. partial events for which the root cause identification should be performed. The third step utilizes a decision diagram, which is referred to in the article [3] as the Root Cause Map, in order to identify the underlying reasons for each causal factor.

We decided to use the Management Oversight and Risk Tree (MORT) diagram as the Root Cause Map.

The Management Oversight and Risk Tree is relatively old. It has been referred to as a respected tool already in the Lees's encyclopedia [1]. However, it is difficult to use. Obviously, many people have tried to create computer tools in order to make the MORT analysis easier. Usually, the attempts to computerize MORT are based on the fact that its structure is the structure of a fault tree so an FTA tool is used as a base for the computerized MORT analysis (this idea is expressed in the guidelines [2]). However, there is a pitfall to this: transfers in the MORT diagram do not have the same meaning as transfers in the standard FTA. In MORT, their meaning is only that the structure of the parts of the tree is identical but not that the parts of the tree are identical. Probably here is the reason why we have not indicated any MORT computerized tool representing complete MORT diagram without substantial simplifications. We are presenting here and offering to readers a MORT analysis tool that is based on the transcription of the diagram into the environment of spreadsheet. This transcription helped to create a MORT WorkSheet tool that is simple to use and that does not simplify the original structure of the MORT diagram. Our MORT WorkSheet is available from the webpage

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2. MORT analysis

The Management Oversight and Risk Tree is an analytical procedure for determining causes and contributing factors [4]. The original MORT program for assuring safety was written up by W.G. Johnson [5]. Included in this program was a method for investigating incidents that relied on a logic tree diagram. The MORT diagram served as a graphical index to Johnson's text, which was in excess of 500 pages. In order to help the investigators, the Noordwijk Risk Initiative Foundation distilled the original text into a forty-two-page question set in a manual [4]. The manual [4] is intended to be used with the MORT diagram [6]. We decided to use the sources [4,6] as a general guide to the investigative use of the MORT method.

As it was noted in the introduction, the MORT diagram is used in the article as the Root Cause Map in order to identify the underlying reasons for each causal factor produced by the causal factor charting. The MORT diagram is suitable for this purpose since it fulfills the two following conditions. First, it is a decisive diagram that serves to describe connections between an incident and individual features of the process safety management system. Second, according to [4] it is to be applied to key episodes in the incident sequence of events. Comparison of the terms key episodes in [4] and causal factors in [3] leads to the conclusion that the key episodes and the causal factors are identical.

MORT analysis is applied to the episodes/causal factors identified. Each episode/causal factor is characterized as a vulnerable target exposed to an agent of harm in the absence of an adequate barrier [4].

The manual [4] describes the MORT process as a dialogue between the generic questions of MORT and the situation that is under investigation. The questions are asked in a particular sequence. The MORT diagram acts as a prompt list that alerts the analyst to concentrate on the issues that are revealed through the process.

The MORT diagram itself represents an extensive graph that uses the conventions of Fault Tree Analysis. To make the process easier to review, the manual [4] recommends that the analyst uses one printed copy of the MORT diagram for one episode and colors it as he proceeds with his/her work. Customary color-code are the following: red, to indicate a problem; green, to highlight a satisfactory relevant issue; and blue, to indicate where there is not enough information to properly assess an issue.

Table 1 shows how the root cause identification procedure should look using the MORT diagram.

3. Drawbacks of the MORT analysis

The available MORT diagram [6] is extensive but not excessively so; it contains about 350 basic events. However, this relatively low number is a result of multiple uses of transfers in the diagram. If there were no transfers, the number of basic events would be above 2000. The diagram would be extremely

Table 1
Root cause identification procedure using the MORT diagram

1. Identify key episodes of the incident
2. For each of the key episodes:
   2.1. Determine the vulnerable target, the agent of harm, and the absent barrier
   2.2 Take a printed copy of the MORT diagram, passage through all its branches in the established sequence
   2.3 At each of the branches:
       2.3.1 Ask the relevant generic questions of MORT
       2.3.2 Color the branch using the customary color-code
   2.4 Review the blue parts of diagram after the whole diagram is colored. For each of the blue branches of the diagram:
       2.4.1 Provide supplementary information
       2.4.2 Make color of the branch red or green
3. Red part of a colored MORT diagram printed copy represents root causes of relevant episode. Set of red parts of the colored MORT diagrams represents multiple root causes of the incident

unpractical without any transfers —its printed copy would be very large, hardly legible and unsuitable for printing, copying and archiving.

The disadvantages of the transfers become visible as soon as we try to accomplish step 2.3 of the above procedure. Due to the transfers, we have to pass through many parts of the diagram repeatedly and this results in repeated coloring of relevant branches. Of course, the colors assigned to different individual passages through a specific part of the diagram may be varied. However, it may be difficult to keep track of what colors belong to each of the individual passages. Reviews according to step 2.4 may make the matter even more complex.

Obviously, the application of the procedure copes with drawbacks of the available MORT diagram. Its printed form makes the use of transfers necessary that further leads to the uncomfortable work not assuring the highest quality of results. It is therefore difficult to assure transparent color marking of diagram branches, to make an echo check of coloring and to control the completeness of the analysis. Documentation of results (filled diagram) may be unambiguous and is not easy to read. Archiving and retrieval of old results is impractical and their comparison with new ones is difficult.

4. Focus of the article

The incident analysis was transformed into three consecutive tasks: drawing a chart, applying a diagram and creating a table.
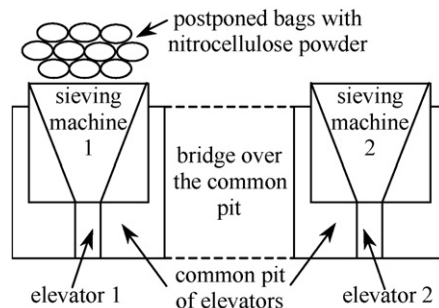

Fig. 1. Plot of the equipment involved in the incident.

As soon as we began to solve the tasks, we recognized that while the chart and the table can be easily created on a PC monitor, the computer will not support the application of the diagram. The MORT diagram had been developed before the appearance of personal computers, which afforded the comfort of office work to which we grew accustomed. But the use of personal computers does not only make our work more comfortable. It makes the work more effective and its results more satisfactory. Therefore,

we focused our efforts on the possible computerization of the root cause identification using the MORT diagram.

Properties of the final product of our effort —the software tool MORT WorkSheet— are described below. An incident example is used in the article to provide material for illustrations. Numerous figures show how the new tool is applied during the investigation and how the results of its application look. The description of the MORT WorkSheet properties is com-
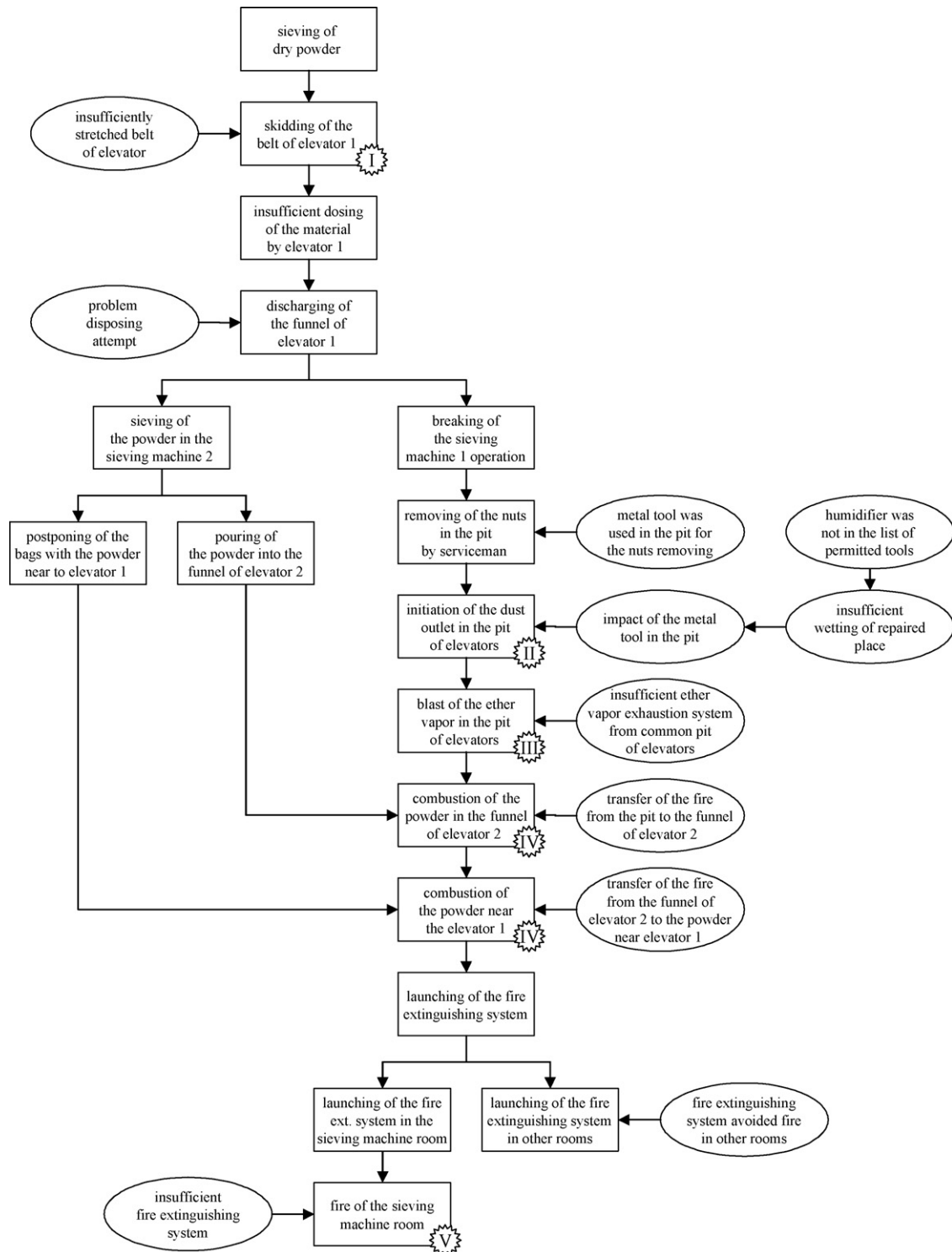
Fig. 2. Causal chart of the incident example.

plemented by a comparison in the final part of the article that shows how different results may be obtained with the MORT WorkSheet from those of conventional incident investigation. The comparison (which also exploits the above-mentioned incident example) demonstrates that the application of the created software tool helps to remove excessive concentration on only one or a few causal factors of the incident from the incident investigation report.

5. Incident example

An incident that occurred at a nitrocellulose smokeless powder production plant on 29 November 1983 was chosen as the incident example. The incident occurred in the operational room of a one-story building for powder sieving.

There were two sieving machines (denoted 1 and 2) in the operational room. Raw nitrocellulose powder packed in bags was transported to the sieving machines on manual trucks. Each of the sieving machines was equipped with a bucket elevator that dosed the powder and transported it to the sieves. Both elevators were situated in a common pit. Since the raw powder contained residual ether solvent, both the sieving machines were vented into a common ether vapor exhausting system.

Before the incident, an elevator belt attached to the sieving machine 1 began to skid. The staff of the operational room could not fix the problem so they called up a serviceman from the factory workshop. The staff stopped the sieving machine 1 and cleaned it while the sieving machine 2 continued to work. After the machine 1 was cleaned, a serviceman came in the building to evaluate the problem. The serviceman examined the skidding belt and decided to repair the equipment immediately. He took a wrench from his haversack and descended to the common pit of elevators. A moment later, combustion of the dust outlet present there was initiated. A fire overrun the whole pit, which atmosphere was probably filled with the ether vapor, and spread to the funnel of the operating sieving machine 2 and to the bags of raw powder that were situated at the sieving machine 1. The equipment involved in the incident is shown in Fig. 1. Timeline of the most important events and conditions of the incident example is shown in Fig. 2. Asterisks with roman figures denote the identified causal factors.

6. MORT diagram transformation into a sequential table

Fig. 3 shows a subtree of the MORT diagram. The diagram is branched from the top down. Every branch of the MORT diagram is described by a title and has two references —an identifier code and a number that refers to the relevant page of the manual [4]. E.g., the branch SB2 is shown in the figure. It is titled Vulnerable People or Objects and refers to page 5. Logical gates serve to define logical relations of branches. One condition (titled Barriers LTA) and two assumed risk events (denoted R3 and R4) are visible in Fig. 3.

We transformed the MORT diagram into a sequential table. Table 2 illustrates the way in which it was performed. The transformation of the subtree SB2 is shown. The left part of the table
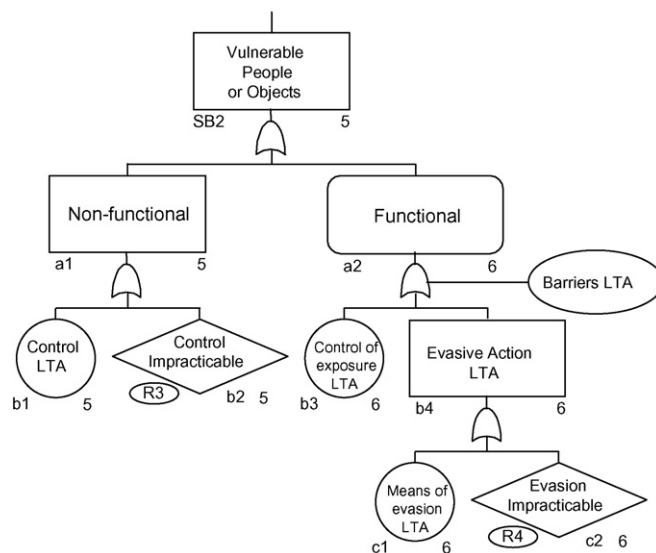

Fig. 3. Subtree SB2 in the MORT diagram.

shows a branching of the tree (from left right). Titles of the branches are in the right column of the table. Identifier codes are written in the cells on the left side and references to the pages in the manual [4], where generic questions of MORT may be found, are adjacent to the titles. Condition is linked to the tree by a horizontal line and assumed risk events are denoted by R3 and R4 in the titles. The table does not contain definitions of logical relations.

Table 2 illustrates the main rules of the transformation but does not represent its final result. A few more modifications of the MORT diagram, which are described below, were performed during its transformation into the final table:

(1) The subtree SB4 is not included in the final table since it is supposed that the analyst will use some form of causal chart to remind the existence of further episodes.
(2) Identifier codes of "c" level in the SD5 subtree were corrected. The codes c8 and c9 are duplicated in the original diagram [6]. Numbering of "c" codes up to c16 (instead of original c14) is introduced in the final table to remove this duplicity.
(3) All transfers of the original diagram were removed during the transformation. This step made the table substantially longer but it prevents the problems caused by returns during the passage through the MORT diagram in the established sequence. Relevant subtrees replaced almost all triangular transfers. Transfers to SC2-a1 represent the only triangular transfers that were exempted from this rule. These transfers (denoted by underlining arrows in the diagram) were removed without any replacements from branches SC2-a2, SC2-a3, and SC2-a4. This means that during the root cause identification, despite what of the branches SC2-a1, SC2-a2, SC2-a3, and SC2-a4 is selected to be problematic (red), the subsequent analysis has to be always performed in the branch SC2-a1.

Table 2
MORT diagram subtree SB2 transformed into a sequential table

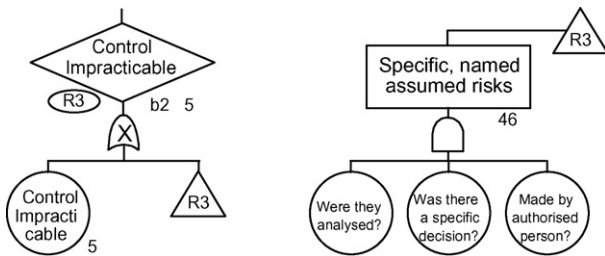|					
SB2				5	Vulnerable People Or Objects
	SB2-a1			5	Non-functional
		SB2-b1		5	Control LTA
		SB2-b2		5	R3 Control Impracticable
	SB2-a2			6	Functional
			condition		Barriers LTA
		SB2-b3		6	Control of Exposure LTA
		SB2-b4		6	Evasive Action LTA
			SB2-c1	6	Means of Evasion LTA
			SB2-c2	6	R4 Evasion Impracticable

Fig. 4. Branch SB2-b2 interpreted as a "XOR" combination of an event and a transfer to "Assumed Risks".

Transfers that were hidden inside the assumed risk branches (denoted by small ellipses with letter R and number inside) had to be unfolded before the relevant trees could replace them. The left part of Fig. 4 shows that each of the branches was interpreted as an event and a transfer to the "Assumed Risks" branch interrelated by the exclusive OR. The transfer itself was interpreted according to description on page 46 of manual [4] and is shown in the right part of Fig. 4. Table 3 illustrates the result of an assumed risk branch transformation.

An unfolding of all the transfers in the diagram results in a renumbering of assumed risks in the sequential table. There are assumed risks R1 to R51 in the table instead of maximum R12 in the original diagram. After the transfers to the Assumed Risks had been unfolded, the branch Assumed Risk was not necessary in the MORT diagram. It only indicates whether any

of the assumed risks was found to contribute to the root causes during the MORT analysis.

7. MORT diagram transformation into a software tool

Difficulties with the printed copy of MORT diagram gave rise to an idea that a virtual diagram in the memory of a personal computer should replace the printed diagram. The idea led to the transformation of the root cause identification using the MORT diagram in a process supported by a software tool. The MORT diagram and the manual [4] were transformed into a tool named MORT WorkSheet which was created in the environment of the Microsoft Excel® program. The MORT WorkSheet allows the removal of the drawbacks of the MORT analysis described earlier.

MORT WorkSheet consists of six sheets. The first is called MORT Sheet. The MORT diagram was transformed in the form of a sequential table and was included in the MORT Sheet. Its rows were numbered and references to pages of manual [4] were replaced by quotations of the manual that were included in comments. Fig. 5 introduces the appearance of the MORT Sheet. The figure shows heading of the MORT Sheet, sequential MORT table in the left and central parts, an example quotation of the manual in the open comment in row No. 36, and four columns, which are placed in the right part of the sheet, right to the column of branch titles. The heading and the last-named four columns were included in the sheet in order to enable and support performance of the MORT analysis. The four columns

Table 3
Unfolded branch SB2-b2 in the sequential table

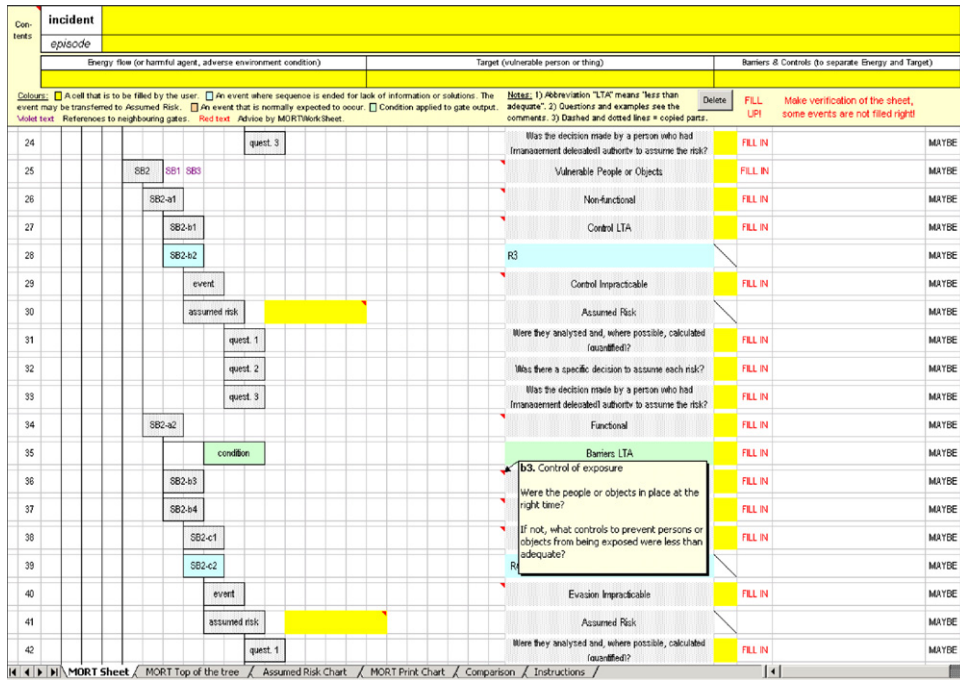|					
SB2-b2				R3	
	event			5	Control Impracticable
	assumed risks	name of the risks		46	
		question1			Were they analysed and, where possible, calculated (quantified)?
		question2			Was there a specific decision to assume each risk?
		question3			Was the decision made by a person who had (management delegated) authority to assume the risk?

Fig. 5. Subtree SB2 in the MORT WorkSheet.

help the user to make equivalent actions to coloring the diagram according to Table 1, so we will call them the coloring columns.

We noticed that the visible descriptions of logical relations were removed during the transformation of the diagram into the table. But the logical relations between branches represent an essential property of the diagram and therefore they were included in the MORT Sheet. The way in which the relations are included reflects the way in which they act. If a branch in the diagram has a certain logical value, then possible combinations of logical values of subordinate branches are limited by the nature of relation under the superior branch. Similarly, the given logical values of subordinate branches limit the possible logical value of superior branch.

The formulas describing both types of limitations were developed for all sorts of logical relations that are present in the MORT diagram. Specifically, the formulas were developed for logical OR (the most frequent relationship), logical AND (two occurrences at top of the diagram), logical OR with condition,

a specific combination of logical XOR and AND (that occur at assumed risks events, see Fig. 4), and for the top of SC2 branch (where a special approach to the elimination of transfers was applied). Complete descriptions of the developed formulas are presented in work [7].

Downward limitations are exploited in the MORT Sheet to accelerate coloring the diagram. Upward limitations help to make echo checks of coloring. The developed formulas were included in hidden columns to project the relationships described in the MORT diagram into behavior of coloring columns. This feature transformed the diagram into a software tool.

8. Support of the MORT analysis by the MORT WorkSheet

As it is shown in Fig. 5, MORT WorkSheet consists of six sheets. The first of them (MORT Sheet) was created to support the main part of the root cause identification procedure (step 2
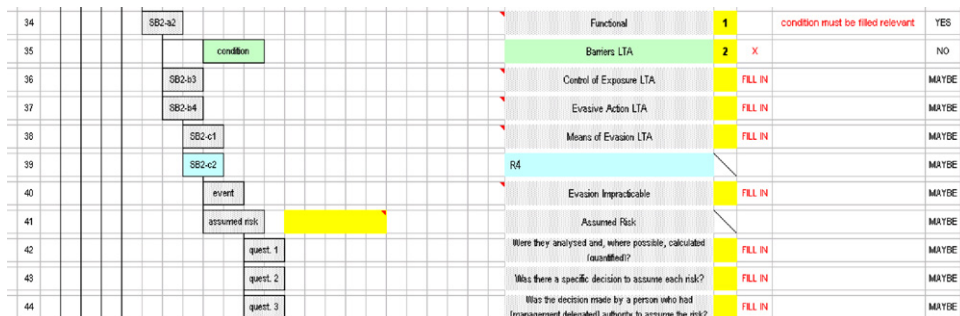

Fig. 6. Incorrectly filled condition under SB2-a2 gate.

Fig. 7. Incorrectly filled events SB2-b3 and SB2-b4 under SB2-a2 gate.

Fig. 8. Incorrectly filled events under the assumed risk gate SB2-c2.

in Table 1). The second, third and fourth sheets (MORT Top of the tree, Assumed Risk Chart, MORT Print Chart) help the analyst to inspect, present and output results of the identification. The fifth sheet (Comparison) was included to support archiving, retrieving and comparison of results; and the sixth sheet (Instructions) provides the analyst with basic information about the tool and its usage.

8.1. MORT Sheet

The MORT Sheet represents a form where only the selected cells (yellow cells in the original tool) are allowed to be filled. The MORT analysis is realized by filling the MORT Sheet form. The analyst commences his/her work in the heading of the MORT Sheet. After filling in cells of the heading, the step 2.1 from Table 1 is completed. The analyst then enters the sequential table and starts to assess relevancy of its individual rows. Each row represents one branch of the MORT diagram and the rows

Table 4
Coloring columns in the MORT Sheet

Coloring columns			
Yellow column	Hint column	Instruction column	Result column

are arranged in the established sequence according to the step 2.2 in Table 1. In accordance with step 2.3, each of the rows has to be assessed.

Making the assessment of the branch relevance the analyst exploits the content of the row, primarily of its coloring columns, which provide him/her with an online guidance. There are four coloring columns. The first of them is composed mostly of the cells allowed to be filled so we call it yellow column. The second coloring column is called hint column, the third one is instruction column and the fourth one is result column see Table 4. As one can see in Fig. 5, at the start of the analysis the yellow column is empty, the hint column contains only "FILL IN"

Fig. 9. Correctly filled subtree SB2-a2.

incident Fire in the sieving room

episode V: Fire of the sieving machine room
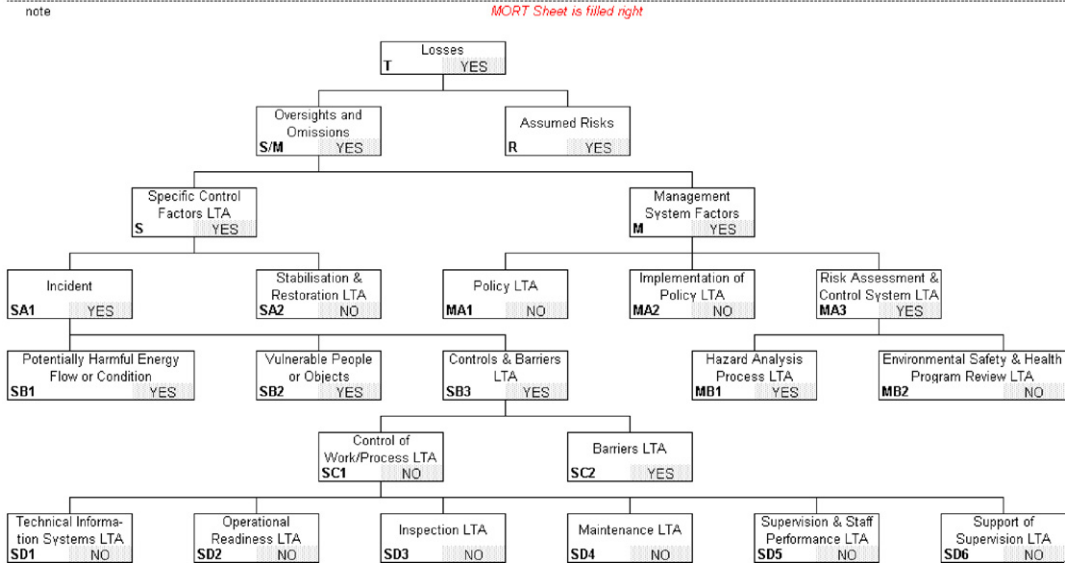
note *MORT Sheet is filled right*

Fig. 10. MORT Top of the tree for episode V of the incident example.

hints, the instruction column is empty (except the instruction in its heading) and the result column contains only "MAYBE" results.

If the hint column of the row contains the hint "X", the yellow column of the row is not required to be filled.

If the row contains the hint "FILL IN" in its hint column, the analyst has to ask the relevant questions of MORT according to step 2.3.1 in Table 1 and to color its yellow column according to step 2.3.2. A comment adjacent to the title of a branch may be used as detailed and accessible help for step

		incident	Fire in the sieving room													
		episode	*V: Fire of the sieving machine room*													
		Energy flow (or harmful agent, adverse environment condition)					fire of powder in the room									
		Target (vulnerable person or thing)					sieving machine room									
		Barriers & Controls (to separate Energy and Target)					effective shower extinguishing system									
	Sort to select Root Cause Paths							*MORT Sheet is filled right*								
1	T									YES	Losses	straty
2	S/M									YES	Oversights & Omissions	prehliadnutie & vynechanie (opomenutie)
3		S								YES	Specific Control Factors LTA	špecifické faktory riadenia
4			SA1							YES	Incident	nehoda
5				SB1						YES	Potentially Harmful Energy Flow or Condition	potenciálne škodlivý tok energie alebo pot. škodl. podmienky
6					SB1-a1					YES	Non-functional Energy Flow	tok energie nie je súčasťou systému
8						SB1-b2				YES	R1	R1
10							assumed risk	the control is impracticable		YES	Assumed Risk	prijaté riziko
25				SB2						YES	Vulnerable People or Objects	zraniteľné osoby alebo objekty
34					SB2-a2					YES	Functional	osoby alebo objekty sú súčasťou systému
35						condition				YES	Barriers LTA	podmienka: bariéry nedostatočné
36					SB2-b3					YES	Control of Exposure LTA	riadenie expozície osôb/objektov nedostačuje
45				SB3						YES	Controls & Barriers LTA	riadiace prvky & bariéry nedostatočné
554					SC2					YES	Barriers LTA	bariéry nedostatočné
556						SC2-a2				YES	Between	bariéry medzi zdrojom a cieľom
559							SC2/a4-b1			YES	R33	R33
561							assumed risk	a barrier is not possible		YES	Assumed Risk	prijaté riziko
1000		M								YES	Management System Factors LTA	faktory systému manažmentu nedostatočné
1028			MA3							YES	Risk Assessment & Control System LTA	systémové hodnotenie a riadenie rizika nedostatočné
1029				MB1						YES	Hazard Analysis Process LTA	proces analýzy zdrojov rizika nedostatočný
1030					MB1-a1					YES	Concepts & Requirements LTA	poňatie a požiadavky analýzy zdrojov rizika nedostatočné
1079					MB1-b5					YES	Specification of Requirements LTA	špecifikácia požiadaviek nedostatočná

|◄ ◄ ► ►|\ MORT Sheet / MORT Top of the tree / Assumed Risk Chart \ **MORT Print Chart** / Comparison / Instructions / |◄|

Fig. 11. MORT Print Chart for episode V of the incident example after sorting.

	incident	Fire in the sieving room								
	episode	*III: Blast of ether vapour in the pit of elevators*								
	Energy flow (or harmful agent, adverse environment condition)		combusted dust outlet or spark in the pit of elevators							
	Target (vulnerable person or thing)		flammable vapour in the pit of elevators							Result of
	Barriers & Controls (to separate Energy and Target)		exhaustion of vapour from the pit							comparison
									Delete	Exists a
			MORT Sheet is filled right					RC (E1)	RC (E2)	common min. RC.
7	S-SA1-SB1-a1-b1			YES	Control LTA		riadenie toku energie nedostačuje	1	1	TRUE
9	S-SA1-SB1-a1-b2-ev1			NO	Control Impracticable		riadenie toku energie je nepraktické	0	0	FALSE
10	S-SA1-SB1-a1-b2-AR1			NO	Assumed Risk		prijaté riziko	0	0	FALSE
16	S-SA1-SB1-a2-b3			NO	Control of Use LTA		použitie riadenia toku nedostačuje	0	0	FALSE
18	S-SA1-SB1-a2-b4-c1			NO	Control LTA		riadenie toku energie nedostačuje	0	0	FALSE
20	S-SA1-SB1-a2-b4-c2-ev2			NO	Control Impracticable		riadenie toku energie je nepraktické	0	0	FALSE
21	S-SA1-SB1-a2-b4-c2-AR2			NO	Assumed Risk		prijaté riziko	0	0	FALSE
27	S-SA1-SB2-a1-b1			NO	Control LTA		riadenie osôb alebo objektov nedostačuje	0	0	FALSE
29	S-SA1-SB2-a1-b2-ev3			NO	Control Impracticable		riadenie osôb alebo objektov nepraktické	0	0	FALSE
30	S-SA1-SB2-a1-b2-AR3			NO	Assumed Risk		prijaté riziko	0	0	FALSE
36	S-SA1-SB2-a2-b3			YES	Control of Exposure LTA		riadenie expozície osôb/objektov nedostačuje	1	1	TRUE
38	S-SA1-SB2-a2-b4-c1			NO	Means of Evasion LTA		prostriedky úniku osôb/objektov nedostatočné	0	0	FALSE
40	S-SA1-SB2-a2-b4-c2-ev4			NO	Evasion Impracticable		únik osôb/objektov nepraktický	0	0	FALSE
41	S-SA1-SB2-a2-b4-c2-AR4			NO	Assumed Risk		prijaté riziko	0	0	FALSE

Fig. 12. Comparison sheet shows similarity of episodes III and IV of the incident example.

2.3.1. Customary color-code was modified for the MORT Sheet purposes. Red color means "yes" or "branch is relevant" and is expressed by writing number 1 in the yellow column. Green color (no/branch is not relevant) is expressed by number 2 and blue color (maybe/relevancy of the branch will be assessed later) by number 3.

As soon as the yellow column of the row is filled, hidden formulas of the MORT Sheet make evaluation of its content and project its results into coloring columns of the row and neighboring rows. As a part of this evaluation, the built-in downward limitations are exploited to identify the lower rows of the MORT Sheet that are not required to be filled. The hint "X" is written in their hint column. This automatic action helps to accelerate coloring the diagram. Built-in upward limitations are exploited to make echo checks of coloring. If a mistake is found, a message is shown in the instruction column of relevant rows.

Overall status of the analysis is described in the headings of the hint and instruction columns. Writings "FILL UP!" and "Make verification of the sheet, some events are not filled right!" are shown in the headings if the built-in tests conclude that the analysis is not completed. It means either that some of MORT Sheet rows are not and have to be completed (at least one "FILL IN" stays in the hint column) or that review of the blue parts is necessary (at least one "2" stays in the yellow column) or that some mistakes were found by the echo checks (at least one message in the instruction column). Writings "OK" and "MORT Sheet is filled right" are shown in the headings after all the above deficiencies are removed i.e. after step 2.4.2 from Table 1 is completed. At this moment, the result column contains only "YES" or "NO" results. "YES" cells of the result column represent the red part of colored MORT diagram mentioned in step 3 of Table 1. MORT analysis of an episode is completed; and the built-in tests in hidden formulas helped to control its consistency and completeness.

The next four figures illustrate the way in which the MORT Sheet is filled and how the built-in tests help the analyst. A possible filling procedure of SB2-a2 branch is shown. Fig. 6 shows that if the SB2-a2 gate is marked as relevant, the condition must be marked as relevant, too. Fig. 7 shows that if the SB2-a2 gate is relevant, then at least one of the subordinate gates is required to be relevant. Fig. 8 shows that both the event and all three questions under the assumed risk gate SB2-c2 cannot be filled as relevant simultaneously. Correctly colored branch SB2-a2 is shown in Fig. 9.

Hypertext references were created at many branches in the MORT Sheet in order to ease movement in the long table representation of the MORT diagram. E.g., two hypertext references to branches SB1 and SB3 are visible in Fig. 5 in two cells at the branch SB2. The analyst may display target branch title moving the cursor above the hypertext reference cell. Clicking at the hypertext reference cell will move the analyst to the target branch row in the MORT Sheet.

The delete button in the heading of the yellow column serves to prepare the MORT Sheet for a new start of the analysis. If the Delete button is pushed, all the yellow cells below the heading of the MORT Sheet are deleted.

8.2. Other sheets

The second sheet of the MORT WorkSheet shows only the top of the MORT tree structure —namely, the branches which are identified by codes consisting of a maximum of two capital letters and one figure. The sheet is called "MORT Top of the tree" and presents an overview of an actual status of a tree coloring during the root cause identification process. Colors of the branches are transferred automatically from the MORT Sheet and they are expressed using the identical convention (red = YES, green = NO, blue = MAYBE). Fig. 10 shows the appearance of the sheet after completion of the analysis of episode V in the incident example.

The third sheet is called "Assumed Risk Chart" and it is a simple table summarizing actual status of assumed risk branches in the MORT tree during the MORT analysis.

Table 5
Investigation summary for the episodes of the incident example

Basic MORT factors	Root causes by MORT	Modified recommendations (after the MORT analysis)	Original recommendations
I. Skidding of the belt of elevator 1			
Energy flow	Control of use LTA	Try to use a spring to stretch the belt	
Target	Control of exposure LTA		
Controls & barriers	Barrier failed	Regular checks	
	Codes and manuals LTA	Improve maintenance procedures for the belt of elevator	
Management	Standards and directives LTA		
	Arrangement LTA	Replace manual setting by an automatic stretching (use a spring)	
II. Initiation of the dust outlet in the pit of elevators			
Energy flow	Control LTA		Require moistening before start of repair, include moistening into repair procedures, equip repairman with humidifier
Target	Control of exposure LTA	Exclude presence of dry powder, use wet cleaning	
Controls & barriers	Task assignment LTA	Require moistening before start of repair, include moistening into repair procedures, equip repairman with humidifier	
	Did not provide		
Management	Guidance and directives LTA		
	Standards and directives LTA		
III. Blast of the ether vapor in the pit of elevators			
Energy flow	Control LTA		Assure exhaustion of ether vapors from bottom of the pit and minimize volume of the pit of elevators
Target	Control of exposure LTA	Assure exhaustion of ether vapors from bottom of the pit and minimize volume of the pit of elevators	
Controls & barriers	Barrier was not provided		
	Policy LTA		
Management	Arrangement LTA	Eliminate interconnections of equipment, separate the pits of elevators	
IV. Transfer of fire to powder in the funnel of 2nd sieving machine elevator and to powder at the sieving machine 1			
Energy flow	Control LTA		Locate only one sieving machine in the room
Target	Control of exposure LTA	Eliminate all combustible chemicals from the room during maintenance, locate only one sieving machine in the room	
Controls & barriers	Barrier was not provided		
	Task assignment LTA	Include elimination of powder from the room during maintenance in the task procedures, create simple list of actions that are necessary for safe work	
	Task procedures did not agree with situation		
Management	Policy LTA	Eliminate all combustible chemicals from the room during maintenance	
	Internal standards LTA		
V. Fire of the sieving machine room			
Energy flow	Control impracticable (R1)	Minimize the amount of combustible chemicals in the room (one sieving machine in the room, minimize the allowed load of the room)	
Target	Control of exposure LTA		
Controls & barriers	Barrier is not possible (R33)		
Management	Local codes & byelaws LTA		

The fourth sheet is called "MORT Print Chart". It reproduces the list of colored MORT tree branches and enables their sorting according to their color. Pushing the button "Sort to select Root Cause Paths" in the heading of the sheet rearranges the list of tree branches so that the red (=YES) branches occupy front positions. Fig. 11 shows the top of the resulting list for episode V in the incident example. In accordance with step 3 of Table 1, the sheet enables

the presentation (printing) of the resultant root causes of the episode.

Step 3 of Table 1 provides a definition of incident root causes in the MORT analysis. As it is visible from structure of the MORT tree (see Fig. 10) even for an individual episode description of root causes represents a logical combination of the lowest level branches (basic events). The following relation describes a set of all the possible root causes P:

$$P = [(SB1 \cap SB2 \cap SB3) \cup SA2] \cap M$$

where SB1 represents the set of basic events of the subtree "Potentially Harmful Energy Flow or Condition", SB2 represents the set of basic events of the subtree "Vulnerable People or Objects", etc.

A $p \in P$ is called the minimum root cause, if no $q \in P$ exists, that $q \neq \emptyset$ and $q \subset p$. The minimum root causes represent unifications of either four, or two basic events from the MORT tree. In the first case, just one basic event is from the SA2 subtree and just one is from the M subtree. In the second case there is just one basic event from the subtree SB1, one from the subtree SB2, one from SB3 and just one from the M subtree. As a result of root cause identification for an episode E, we determine a specific $RC(E) \in P$. Each resultant root causes may be written as a finite unification of minimum root causes: $RC(E) \Leftrightarrow p1 \cup p2 \cup \ldots \cup pN$.

A practical way of describing episode root causes is based on the result column from the MORT Sheet, which represents a chain of logical values YES/NO. Since this chain contains many excessive values that do not belong to basic events it is reduced to the chain of logical values of MORT tree basic events. After the reduction, resulting root causes of the analyzed episode are represented by the $RC(E1)$ column in the fifth sheet of the MORT WorkSheet tool —Comparison sheet. Fig. 12 shows the top of the $RC(E1)$ chain for the episode III of the incident example.

A description of the episode root causes by the chain of logical values is suitable for archiving and retrieving. Moreover, it is also useful when a possible recurrence of root causes in different episodes is investigated. In this case two episodes have to be compared. Root causes of the episode $E1$ recur in the episode $E2$, if at least one minimum root cause p exists, that is contained in both $RC(E1)$, and $RC(E2)$: $p \in RC(E1) \cap RC(E2)$.

Relevant testing is performed in the Comparison sheet. Root cause chain of the episode $E2$ has to be copied to the $RC(E2)$ column (yellow color) and the result of comparison is shown in the adjacent column. Fig. 12 shows that root causes of the episode III recurs in the episode IV of the incident example.

The sixth sheet of the MORT WorkSheet is called "Instructions". It contains basic information about the purpose of the tool and explains how to use it.

9. Comparison of MORT-supported and conventional investigations

Causal factor charting of the incident example led to an identification of five causal factors equal to episodes (Fig. 2). The MORT WorkSheet was then applied to each of the episodes. Resultant root cause identification is summarized in the first

and second columns of Table 5. Original corrective recommendations that were assigned to individual episodes are included in the last column of the table. Subsequently, we attempted to modify the recommendations in order to respond to all the root causes identified by the MORT analysis. A brief summary of the results of the modification is in the third column of the table. Eventually, Table 5 summarizes the results of modification of one old conventional incident investigation by using systematic incident analysis techniques.

We can state that the summarizing tables of all the studied incidents provided similar results. Table 5 represents a typical picture that we received after the modification of old conventional incident investigation had been performed. We found that each of the old investigation reports covered a majority of causal factors of the incident and identified greater part of its root causes. On the other hand, the supplementary application of systematic techniques always revealed some causal factors and root causes that were not covered by the original investigation. Consequently, for each of the incidents the modified set of recommendations represented an expansion of the old set.

Table 5 illustrates these results. It shows two causal factors that were not analyzed in the original investigation and a few new recommendations. The modified investigation is visibly more concentrated on managerial and procedural factors contributing to the incident. Most importantly: the better coverage of causal factors and root causes does not result from new information or from the higher experience of analysts. It results exclusively from the application of tools that improve analysis effectiveness.

10. Conclusions

The preceding comparison confirmed what is well known from the guidelines [2]: Process incident investigations should follow formal logical methodologies. We showed that combined application of causal charting and the root cause identification using the MORT diagram improves the effectiveness of investigation. However, the main intention of our article was to introduce the new software tool MORT WorkSheet, which makes the application of the above-mentioned technique comfortable. As it is shown in the article, MORT WorkSheet represents a spreadsheet application that contains everything that the analyst needs during the root cause identification. The task was reduced to filling an electronic form. MORT WorkSheets provides the analyst with essential advantages in comparison with the application of MORT diagram printed copy. The analyst's work is supported by online guidance, detailed and easily accessible help, and by functions that check its correctness. MORT WorkSheet provides detailed, specific, and well-documented results and facilitates their archiving, retrieval and comparison. With the MORT WorkSheet the MORT analysis is performed in a manner that corresponds with the contemporary standards of office work.

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