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ORIGINAL ARTICLE

Comparison of Commonly Used Accident Analysis Techniques for Manufacturing Industries

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ABSTRACT
The adverse consequences of major accident events have led to development of accident analysis techniques to investigate thoroughly the accidents. However, each technique has its own advantages and shortcomings, which make it very difficult to find a single technique being capable of analyzing all types of accidents. Therefore, the comparison of accident analysis techniques would help finding out their capabilities in different circumstances to choose the most one. In this research, the techniques CBA and AABF were compared with Tripod β in order to determine the superior technique for analysis of major accidents in manufacturing industries. At first step, the comparison criteria were developed using Delphi Method. Afterwards, the relative importance of each criterion was qualitatively determined and the qualitative values were then converted to the quantitative values applying Fuzzy triangular numbers. Finally, the TOPSIS was used to prioritize the techniques in terms of the preset criteria. The results of the study showed that Tripod β is superior to the CBA and AABF. It is highly recommended to compare all available accident analysis techniques based on proper criteria in order to select the best one whereas improper choice of accident analysis techniques may lead to misguided results.

KEYWORDS: *Accident, Safety, Manufacturing, TOPSIS*

INTRODUCTION
Work-related injuries disrupt economic activities in workplaces; consequently, they are closely associated with economic losses [1]. The economic aspects of occupational safety include both causes and consequences. In other words, occupational losses would affect employees and employers, companies, governments, and the world as a whole. As an example, every year about 5500 people are killed in workplace accidents across the European Union [2]. Approximately 150 million working days are lost each year due to occupational accidents [3]. Eurostat has estimated that work-related accidents incurred costs of 55 billion euro's in 15 EU Member States in 2000. This estimate corresponds to 0.64% of the GDP of about 8500 billion euro's for EU15 [4].

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These total economic costs of occupational deaths and injuries were rose to $142.2 billion and a total of 120 million lost days due to occupational injuries in 2004 [5]. Occupational fatal injury rates are 3–4 times greater in developing countries compared to developed countries and they are mainly unintentional [6]. Approximately 14100 occupational injuries occur each year in Iran [7]. Therefore, occupational accidents impose huge costs on individuals, companies and societies, which is why they must be systematically investigated and by identifying their root causes the reoccurrence of them, must be prevented.

The purpose of accident investigation is to look for the unsafe behaviors and conditions that led to the final, adverse consequences [8]. The output of the accident investigation is usually a description of one or more chains of interacting causes. Understanding the reasons for incident occurrence is important for safety experts. Different methods have been developed to achieve such a goal. During the recent years, various methods with their own different strengths and weaknesses have been designed and developed to improve the effectiveness of accident analysis procedure. However, it has always been a controversial debate, which accident analysis technique is of higher priority for a specific industry. Similarly, the selection of proper method, according to scientific models and criteria is considered so important that inaccurate and inappropriate information could mislead the analyst.

Currently, different industries use a variety of techniques for accident analysis at different circumstances; some of them are briefly described as follows:

- ***Fault trees:*** A fault tree is one of the most commonly used technique for assessing safety, reliability, and accidents. Having a deductive approach, it begins by assigning the top event, in the case of accident analysis accident is considered as the top event, after that the events that directly led to the top event is determined. This process continues deductively until basic events are determined. AND/OR gate are used for indicating the relationship between various types of events. Minimal cut sets that determined using fault tree graph are used to select the best way to prevent similar accidents [9].
- ***STEP (Sequential Timed Events Plotting):*** Using this technique accident is graphically shown as a multi-linear event sequence. This technique has a simple worksheet with two axes; the vertical axis represents the actors of accident and horizontal axis represents time. Actor may be a front line worker, a maintenance person, a supervisor, and so on. It also can be a control system, a detector system, and so on. After completing the worksheet, the actions taken by each actor at any time that led to accident can be observed and assessed, and based on these data the preventive measures are inferred [10].
- ***STAMP (Systems-Theoretic Accident Model and Processes):*** A new and comprehensive technique developed by Nancy Leveson from Massachusetts Institute of Technology (MIT), this technique outlines that an accident necessarily is not a result of component failure, whereas it can also occur due to inadequate coordination between system components. The technique has a systemic view on accident based on systems theory concepts [11].
- ***Petri Net:*** The technique was firstly used for modeling of Programmable Logic Controllers (PLC) and manufacturing systems, but its applications have been extended in many fields including accident analysis. The graph of Petri Net, as the heart of technique, is composed of a set of nodes and arcs. Nodes itself are divided in two groups; places and transitions that are depicted using cycles and rectangles, respectively. There are two types of transition; enabling and firing. Arcs also used to connect places and transitions with each other. The technique is specifically suitable for investigating concurrent events or activities resulting in accidents [12].
- ***Change Based Analysis (CBA):*** The Change Based Analysis is a method of analyzing incidents looking for planned or unplanned changes that led to an undesired outcome. By definition, the change is "something that disturbs the balance of a system operating as planned" [13]. There are too many sources of deviations affecting system operation of which changes are the most important ones. Accidents will be analyzed by investigators through the difference between what has already occurred and the actual sequence of events using Change Based Analysis. It identifies specific differences between the situation of no-accident and the accident scenario. The accident causes is determined through evaluation of these differences [14].
- ***AAEB (Accident Analysis and Barrier Function):*** The Accident Analysis and Barrier Function (AAEB) Technique is a method for analysis of accidents resulted from a series of interactions between human and technical systems. Using the flow chart of the technique, both human and technical systems can be simultaneously assessed during accident analysis. This flow chart is composed of two parallel columns with blank boxes, one for the human systems and another for the technical systems [14].
- ***Tripod-β:*** The core model of the Tripod β tree describes the incident mechanism in relation to hazards, targets and events in terms of cause-effect relationships. What make up the basic building block are a hazard, target and event. A hazard is the cause of harm, which can change the state, and the target is what is damaged or changed, while the event is a happening consisting of hazard and target results in an accident or near miss. Harm is the undesirable change of the state [15].

According to the above-mentioned issues and by considering the decisive role of a proper accident investigation tool in promoting safety condition of workplaces, the purpose of this study is to compare and select the most suitable technique for manufacturing industries.

MATERIALS AND METHODS

The present study was performed in Mavadsazan Company, Tehran, Iran. The MAPNA Group consists of several companies that are active in the fields of equipment manufacturing, project implementation, operation and services. According to the instruction presented by the group, the member companies are allowed to use one the techniques Tripod-β, AAEB and CBA for accident analysis in different circumstances.

The TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) is a multi-criteria decision analysis [16]. The ideal solution so-called positive ideal solution is an alternative to maximize the benefit criteria/attributes and to minimize the cost criteria/attributes while the negative ideal solution known as anti-ideal solution maximizes the cost criteria/attributes and minimizes the benefit criteria/ attributes.

The main advantages of TOPSIS are could be summarized in the followings:

- It involves qualitative and quantitative criteria simultaneously.
- A significant number of criteria are involved in the selection process.
- It can be performed with acceptable speed.
- It is possible to change the input data in order to investigate the system response against the imposed changes.

The output can quantitatively express the priorities. It is clear that the quantitative priorities would be accepted by the manager more easily.

This descriptive, analytical study was carried out in Mavadsazan Company in Iran. The first step was to select the appropriate criteria for comparison of commonly used accident analysis techniques. The comparison criteria were selected based on the viewpoints of the Delphi panelists, literature reviews as well as preliminary requirements and expectations of the analyzing accidents techniques. The listed criteria mainly emphasize on descriptive requirements [5], revealing requirements [5], consequential requirements [5], validation requirements [5], practical requirements [17], accident sequences [17], safety barriers [18], analysis levels [15], accident model [17], being primary/secondary [17], analytical approaches [15], training needs [15], being realistic [18], being definitive [18], satisfying [8], being comprehensive [8], disciplining [8], being consistent and direct [8], functionality [18], non-causal [18], visibility [18], encouragement [18], independence [18], initiatives [18], discovery [18], competence [18], standards [8] enforcement[18].

It is worth noting that Delphi panelists were comprised from 49 specialists in the field of health, safety and environmental working in Iranian manufacturing industries.

The output of this phase was to identify 19 criteria to compare the techniques. At next step, the determined criteria were sent out to the Delphi panelists to be scored and short-listed through pair wise comparisons.

For this purpose, a questionnaire was designed and completed by the panelists who were elected through the following characteristics:

1. Literacy: M.Sc. and Ph.D.
2. Relevant work experience: at least ten years
3. Area of interest: safety, Health, Safety and Environment (HSE) management, industrial engineering, occupational hygiene.

Totally, 29 out of 42 questionnaires were filled out completely. At the end of this step, the following six criteria were selected by the experts:

- What is the implementation cost of the method? (Cost of implementation/CI)
- How long does it take to implement the method? (Time of implementation/TI)
- The training needs to use the method. (Training needs for implementation/TN)
- Does the method have the capability of being quantified? (Capability of being quantified/CQ)
- Does the method have the capability of depicting the event sequence? (Graphical description of the event sequence/GD) The level of the analysis (LA).

The accident analysis techniques are often able to determine the causes of the events at the following four levels [19]:

1. The work and technological system.
2. The staff level.
3. The management level.
4. The company level.

Finally, the obtained results were used to determine the relative importance of each criterion in the form of a matrix. The qualitative scoring scales ranging as high, medium, low or yes/no were applied to rank the criteria of the related matrix. Using triangular fuzzy numbers method, the qualitative data were initially converted to the quantitative values in order to being pre-processed. Then, for each qualitative option, the values of m, α, and β were determined at three different response levels as follows:

High= (1, 0.4, 0)
Medium= (0.5, 0.3, 0.3)
Low= (0, 0, 0.4)

Replacing qualitative options with the values of m, α, and β in the formula, the quantitative values of each option were calculated as follows [20]:

$$\mu_T(x) = \frac{m+\beta}{2(1+\beta)} + \frac{m}{2(1+\alpha)}$$

High=0.857
Medium=0.5
Low=0.143

The method of triangular fuzzy numbers was used to quantify the qualitative values as the input data of the model.

Afterwards, the techniques were prioritized using TOPSIS. At first step, the normal decision-making matrix was calculated (Equation 1).

Equ. 1:

$$\mathbf{n_{ij}} = \frac{\mathbf{x_{ij}}}{\sqrt{\sum_{i=1}^{m} \mathbf{x_{ij}^2}}}, \qquad \mathbf{i = 1, \dots, m}, \qquad \mathbf{j = 1, \dots, n}$$

In the second step, the weighted decision making matrix was computed:

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Equ 2:

$$\mathbf{v_{ij} = w_j n_{ij}}, \qquad \mathbf{i = 1, \dots, m}, \qquad \mathbf{j = 1, \dots, n}$$

In the third step, the positive and negative ideal solutions were determined:

Equ. 3

$$A^+ = \{v_1^+, \dots, v_n^+\} = \{(max_j v_{ij} | i \in I), (min_j v_{ij} | i \in J)\}$$

$$\mathbf{A^- = \{v_1^-, \dots, v_n^-\} = \{(\min_j v_{ij} | i \in I), (\max_j v_{ij} | i \in J)\}}$$

In the fourth step, the separation criteria were calculated using n-dimensional Euclidean distance:

【 d】↓i↑↓ = {∑↓(j = 1)↑n≣(v↓ij − v↓j↑ −)↑2 }↑(1/2), i = 1, …, m

$$d_i^+ = \left\{ \sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2 \right\}^{\frac{1}{2}}, \qquad i = \mathbf{1}, \dots, m$$

In the fifth step, the relative closeness to the ideal solution was calculated according to the Equation 5.

$$\mathbf{R_i} = \frac{\mathbf{d_i^-}}{(\mathbf{d_i^+ + d_i^-})}, \mathbf{i = 1, \dots, m}$$

RESULTS

As suggested in Table 1, the "Analysis Level" and "Training Requirements" account for the highest and lowest relative importance, respectively.

Table 1. The relative importance of the comparison criteria

Criterion	**Quantified value**
Cost of implementation (CI)	0.59
Time of implementation (TI)	0.62
Training needs for implementation (TN)	0.59
Capability of being quantified (CQ)	0.64
Graphical description of the event sequence (GD)	0.71
Levels of analysis (LA)	0.82

As mentioned earlier, the obtained results were used to determine the relative importance of each criterion in the form of a matrix. Depending on the criteria, a triple (high, medium, low) or the binary (Yes/No) qualitative scoring scales were used for rating (Table 2).

Table 2. The qualitative ranking matrix of the techniques based on the predetermined criteria

Criteria / **Technique**	**CI**	**TI**	**TN**	**CQ**	**GD**	**LA**
CBA	Medium [21]	Medium [21]	Low [14]	Medium [12, 22]	No [14]	High [14]
AAEB	Medium [5]	Medium [5]	High [8, 14]	Low [12, 22]	No [14]	Medium [14]
Tripod - β	Medium [21]	Medium [21]	High [14]	Medium [12, 22]	Yes [14]	High [14]

The method of triangular fuzzy numbers was used to quantify the qualitative values in order to use as input data in the model (Table 3).

Table 3. The qualitative values of the comparison techniques based on the predetermined criteria

Criteria / **Technique**	**CI**	**TI**	**TN**	**CQ**	**GD**	**LA**
CBA	0.5	0.5	0.2	0.5	0.0	0.8
AAEB	0.5	0.5	0.8	0.1	0.0	0.5
Tripod - β	0.5	0.5	0.9	0.5	1	0.9

In order to prioritizing the techniques by TOPSIS, the normal decision-making matrix was calculated (Table 4).

Table 4. Normal decision-making matrix

Criteria / **Technique**	**CI**	**TI**	**TN**	**CQ**	**GD**	**LA**
CBA	0.29	0.28	0.09	0.35	0	0.46
AAEB	0.29	0.28	0.52	0.10	0	0.27
Tripod - β	0.29	0.28	0.52	0.35	0.71	0.46

The following results were obtained by calculating the weighted decision-making matrix (Table 5).

Table 5. Weighted decision-making matrix

Criteria / **Technique**	**CI**	**TI**	**TN**	**CQ**	**GD**	**LA**
CBA	0.18	0.19	0.05	0.26	0	0.41
AAEB	0.18	0.19	0.29	0.07	0	0.24
Tripod - β	0.18	0.19	0.29	0.26	0.47	0.41

The results of positive and negative ideal solution analysis are shown in Table 6. It should be mentioned that the lower numerical values of "Implementation cost", "Implementation duration" and "training needs" would lead into a more positive ideal solution. On the contrary, the higher numerical value of the criteria "Quantification capability", "Graphical presentation of event` sequence (graphical presentation capability), and "analysis levels" (analysis scope) will result in a positive alternative.

Criteria / Ideal solution	CI	TI	TN	CQ	GD	LA
Positive	0.05	0.19	0.05	0.44	0.47	0.41
Negative	0.30	0.32	0.29	0.07	0	0.07

Table 6. The positive and negative ideal solutions

Table 7 shows the results of criteria prioritization using n-dimensional Euclidean distance.

Table 7. The prioritized criteria using Euclidean distance

d-	d+	Euclidean distance / Technique
0.41	0.56	CBA
0.29	0.67	AAEB
0.58	0.41	Tripod - β

The results of the relative closeness to the ideal solution are presented in Table 8.

Table 8. Prioritization of techniques

Technique	R	Precedence
CBA	0.43	2
AAEB	0.31	3
Tripod - β	0.54	1

DISCUSSION

The accident analysis techniques should provide managers with appropriate inputs towards selecting appropriate corrective actions. However, it is hard to find a single technique, which is capable enough to consider all types of causes [9]. Accordingly, the selection of the most appropriate accident analysis technique and identification of incident causes could be resulted in saving the limited resources of organizations. In the present study, three commonly used accident analysis techniques were compared to select the superior one. In a similar study, 14 techniques including Tripod-β and CBA were compared with each other [14]. Besides, Kontogiannis et al. [12] compared the techniques of Petri Nets, Fault trees Analysis and STEP. Three other techniques of STAMP, HFACS and Accimap were also compared by Salmon et al. [23]. The advantages and drawbacks of the techniques STEP and FRAM were specified by Herrera and Woltjer through accident analysis [10].

In the present study, six criteria were selected to compare commonly used accident analysis techniques in order to identify the superior one. Depending on analysis situation, researchers in various studies have used other criteria for comparing and choosing the most appropriate techniques. As such, Sklet used 8 criteria including training needs and analysis level to compare accident analysis methods [14]. Kontogiannis et al. [12] compared accident analysis techniques using 12 criteria including multiple levels of representation and event sequence.

In this research, the obtained results indicated that CBA and Tripod-β techniques are superior to the AAEB in terms of analysis scope. In other words, the CBA and Tripod-β techniques can identify more root causes than the AAEB technique. The obtained results revealed that the scope of the AAEB methods is limited to the Levels 1 (the work and technological system) and 2 (the staff level) while the scope of the CBA and Tripod-β methods cover Levels 1 to 4. This is in contradiction with the results reported by Sklet which the scope of the CBA technique covers levels 1 and 2 and the AAEB and Tripod-β techniques are limited to the levels 1-3 and 1-4, respectively [14].

The second characteristic studied was the capability of graphical presentation of the event sequence. The method Tripod-β provides a graphical illustration of the whole accident scenario. The Tripod-β demonstrates graphically the accident analysis components including target (e.g., worker), hazard (e.g., hot pipe work) and event (e.g., workers' burning) in addition to the failed defenses caused by active failures, preconditions and latent failures (BRF) ("event trios"). This is similar to the findings of Sklet [14] and Mohammad Fam et al. [17]. However, the CBA and AAEB techniques lack this capability.

The training requirement was the third criterion selected in this research for evaluation of the accident analysis techniques. The techniques Tripod-β and AAEB were categorized as "expensive" and "cheap" classes in terms of training needs, respectively. From the point of view of Sklet, the Tripod-β technique requires a specialist while a novice could be just enough to run the AAEB technique [14].

In terms of the capability of being quantified, the CBA and Tripod-β techniques have higher capability than the AAEB method. Counting the number of superficial causes, prerequisites and hidden causes involved in the occurrence of an accident could lead into the quantified expression of the contribution of each cause. The quantification capability of the Tripod-β technique was also confirmed by Mohammad Fam et al [10]. The studied techniques were found the same in terms of running time and cost.

In conclusion, the final findings of this research revealed the following priority order Tripod-β< CBA< and AAEB. Therefore, the Tripod-β was proposed as the most suitable technique of accident analysis at Mavadsazan Company.

CONCLUSION

Given the number of accident analysis techniques as well as their strengths and weaknesses, it is highly recommended to compare all available techniques based on proper criteria in order to select the best one whereas inappropriate selection of accident analysis techniques may lead to misguided results.

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