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Review Article

Accident Analysis Techniques in the Industries: A Review

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Abstract: Since the industrial revolutions, accidents have become more common and frequent in all the industries. To find out the causes of these accidents, plenty of techniques have been used until now. A review of the existing techniques of accident causation has been done in this study which highlights the strengths and weaknesses of all these techniques that have been used to find out the contributory factors of these incidents. In addition, the industries where these techniques have been used, have been identified and it is emphasized that these techniques should be applied in the textile industry in Pakistan which is the most accident prone industry in recent times. This study also leads to the realization that there is a need for newer techniques such as structural equation modelling that address the complex nature of accidents and deal with the interactions of contributory factors of accidents in large scale industries. It is also emphasized that the government should take the initiative of making an institution that gathers the accidents data so that the exact causes can be known and dealt with accordingly.

Keywords: Accident causation analyses, Systemic analysis, Sequential analysis, Human information models, Structural equation modelling, Manufacturing industries, Industrial safety.

1. INTRODUCTION

There have been plenty of disastrous accidents happening or happened worldwide such as Bhopal incident, Deep Horizon, Piper Alpha in which severe injuries and diseases occurred to gazillions, plenty of lives were lost, sensitive equipment was destroyed, there was an innumerable loss of property and the environmental damages, which changed the living style permanently. These life threatening incidents or accidents led to absenteeism, lack of skilled workers, adverse effects on the environment, which directly affected the industrialists, and indirectly to the GDP of developed as well as developing countries. Some of these accidents are caused due to a simple and/or single stimulus, however mostly are the results of a combination of errors made by human beings, arise by the equipment failure and those that are the consequences of poor environmental conditions altogether. As most accidents are caused by a series of failures and to find the reasons of such incidents is an uphill task, there have been and still are significant researches going on for accident causation and to bring the reasons behind such catastrophes to limelight.

2. LITERATURE REVIEW

Initially techniques such as what if and Checklist have been used but they have not been sufficient in explaining the scenarios of incidents and have therefore become redundant. To date, different accident analysis and risk analysis techniques are being used to identify different reasons of such calamities, to prevent such disastrous events from happening and to take precautionary measures before they actually happen and claim the precious lives of individuals. Each of these analysis methods has its merits and demerits, and is there to be further explored. These accident analysis methods have been classified into three groups which are systemic analysis, sequential analysis and human information models [1].

2.1. Systemic Analysis

Systemic analysis views accidents because of uncontrolled system interactions. It includes methods such as Failure mode and effects analysis (FMEA), Failure mode, effects and criticality analysis (FMECA), System Theoretic Accident Model and Processes (STAMP), System Theoretic

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Process Analysis (STPA), Causal analysis using systems theory (CAST), Hazard And Operability Analysis (HAZOP), Humans factor analysis and classification system (HFACS), Accimap, Functional resonance analysis method (FRAM), Layers of protection analysis (LOPA) and Swiss Cheese Model (SCM).

2.1.1. FMEA & FMECA

Failure mode and effects analysis (FMEA) procedure consists of a sequence of steps used to indicate all the probable failures in a process [2]. Failure modes, effect and criticality analysis (FMECA) is an extension of FMEA which includes criticality as well that is the mathematical estimation of severity and occurrence. FMECA has a pivotal role in reliability systems engineering which illustrates the potential of a system to perform at the given conditions for a fixed amount of time [3].

2.1.2. STAMP, STPA & CAST

System theoretic accident model and processes (STAMP) is a method in which the failures or accidents are investigated in the way that why the barriers placed cannot stop the occurrence of these accidents and why these barriers are not sufficient enough to ensure the safety of the entire system [4]. Two new methods System theoretic process analysis approach (STPA) and Causal analysis using systems theory (CAST) have been devised from STAMP in order to refine the existing accident analysis and the hazard analysis. System theoretic process analysis approach (STPA) is a hazard analysis approach that embodies the idea of STAMP method. Leveson who developed STPA is of the view that safety is of prime importance and accidents do not occur owing to the sequence of failures but by the poor indication and inappropriate recognition of safety related constraints in a system. These constraints may be human error, design error in equipment or organizational problems [5]. Causal analysis using systems theory (CAST) is also based on the STAMP approach which assesses the whole accident process in case of an accident and indicates the key causal factors. In addition, CAST also focuses on why the accidents occur in the first place which helps in prevention of accidents in future [6].

2.1.3. HAZOP & HFACS

Hazard and operability analysis (HAZOP) in the early days has been used to indicate the abnormalities in the proposed design. It is developed to spot the hazards and propose the safety measures to avoid these hazards especially in the process industries [7]. Human factor analysis and classification system (HFACS) is a human factor accident analysis initially proposed solely for the aviation industry. It embodies the idea of Reason's model which states that active failures are the result of latent failures. [8].

2.1.4. AcciMap & FRAM

AcciMap approach is an accident analysis approach that is used as means of modeling the socio-technical context to identify the combination of events and decisions that produce an accident. It differs from the traditional accident models in the way that it describes the different causal factors that lead to a failure event and their inter relationships in a graphical form. Such analysis with causal diagrams guide us to the patterns that lead to the occurrence of accidents from which one can judge what elements are necessary for safe operations [9]. Functional resonance analysis (FRAM) is a methodology used both for risk analysis and accident causation modeling. It has the capacity to entail the incidents that have already happened before and for that it is used as an accident analysis approach [10].

2.1.5. LOPA & SCM

Layers of protection analysis (LOPA) are a risk analysis approach developed to reduce risks in the process industries by evaluating the adequacy of the layers of protection. In a process plant the processes that are more risk prone are selected, each process is then related to the probable failures on the basis of a person's knowledge, experience and the database available [11]. Reason's model commonly known as Swiss Cheese Model (SCM) is a systemic approach which shows system's defenses diagrammatically in such a way that the pits in the slices exhibit the breakage of defenses. These slices look exactly like the Swiss cheese, hence the name. When the pits are in line in the slices, it leads to the occurrence of disasters and the inevitable accidents [12].

2.2. Sequential Analysis

Sequential analysis is the type of analysis which explains the accident as the outcome of a sequence of events in a proper order. Various methods such as Fault tree analysis (FTA), Event tree analysis (ETA),

Table 1. Applications of accident analysis techniques in different industries

No	Methods	Applications	References
1	FMEA	Space industry, Chemical industry, Thermal plant, Paper mill ,Nuclear industry, Oil and gas industry.	[2, 19-22]
2	FMECA	Aerospace industry, Railway industry, Aviation industry, Food industry, Electric power plant.	[3, 23-25]
3	STAMP	Oil and gas industry, Chemical industry, Nuclear industry, Aviation industry.	[4, 26]
4	STPA	Aviation industry, Chemical industry, Oil and gas industry, Defense industry, Automobile industry.	[5, 27-29]
5	CAST	Maritime industry.	[6]
6	HAZOP	Space industry, Oil and gas industry, Chemical industry.	[2, 30, 31]
7	HFACS	Aviation industry, Mining industry, Chemical industry,Railway industry.	[8, 32-34]
8	AcciMap	Chemical industry, Aerospace industry, Oil and gas industry, Maritime industry	[9, 35-37]
9	FRAM	Aviation industry, Construction industry, Chemical industry, Rail industry, Oil industry.	[10, 38, 39]
10	LOPA	Chemical industry,Oil and gas industry.	[40, 41]
11	SCM	Aviation industry,Chemical industry, Railway industry.	[12, 42, 43]
12	FTA	Chemical industry, Nuclear industry,Steel plant, Mining industry.	[13, 44-46]
13	ETA	Nuclear industry, Defense industry, Automobile industry, Chemical industry, Mining industry.	[14, 46, 47]
14	DEA	Oil industry, Chemical industry, Petrochemical industry.	[15, 48]
15	CA	Oil industry, Chemical industry, Electric power plant,Gas industry.	[16, 49-51]
16	CREAM	Electric industry, Maritime industry, Aviation industry.	[17, 52]
17	SPAR-H	Oil and gas industry, Petroleum industry, Nuclear industry, Chemical industry.	[18, 53-55]

and Domino effects analysis (DEA), Consequence analysis (CA) are included in this group.

2.2.1. FTA & ETA

Fault Tree Analysis (FTA) is a sequential methodology that has made its mark in the nuclear industry and is most often used as a tool for risk assessments and in the accident investigations. According to this methodology, an enabling event gives rise to a initiating event which has the capacity to cause an accident[13].Event tree analysis (ETA) is another sequential methodology which is said to be developed in 1974 during a safety assessment of a nuclear power plant. During this study, it was noticed by the WASH-1400 nuclear power plant team that with the help of fault tree analysis, risk analysis of the plant can be accomplished but the fault tree obtained would be very big and unmanageable. Therefore event tree analysis was introduced to present the table in much more viable form [14].

2.2.2. DEA & CA

Domino effect analysis (DEA) as the name suggests is the analysis of chain of events that lead to accidents or have the capability to cause an accident in the future. This kind of analysis is used to analyze such situations in which an explosion/fire/toxicity in one unit cause secondary and tertiary incidents in other units and the process continues [15]. Consequence analysis (CA) is a sequential analysis which assesses the consequences in case of an accident. It is a risk analysis methodology which determines the effects of a likely failure event on human, equipment and facility and tells about the possible consequences they may have to face [16].

2.3. Human Information Models

Human information models are the type of models, which explain accident as the cause of human errors, unsafe acts and unsafe conditions. They include methods such as Cognitive Reliability Error Analysis Method (CREAM) and Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H).

2.3.1. Cognitive Reliability Error Analysis Method

Cognitive Reliability Error Analysis Method (CREAM) is a human information model, which involves technical factors, factors of individuals and of the whole organizations. It is used as both an accident analysis and risk analysis technique in which actions of single actors are specifically addressed with the help of control modes. It can predict human error as well and can be used single handedly for accident investigations or can be collaborated with any other method for interactive systems[17].

2.3.2. Standardized Plant Analysis Risk-Human Reliability Analysis

Like CREAM, Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) is also a human reliability analysis method which has been initially developed in the nineties for nuclear power industry to determine the chances of human errors related to the workers' actions [18].

Table 2. Applications of accident analysis techniques in different industries

Methods	Strengths	Weaknesses	References
FMEA	-Indicates all the probable failures. -Supposes a failure mode and determines the worst case effects.	-Consequences are described mostly instinctively. -Unable to take complex failure modes into consideration.	[2, 56, 57]
FMECA	-Includes criticality which is the estimation of severity and occurrence. -Determines process reliability.	-An extensive knowledge of the issue under investigation is needed. -The implementation phase is difficult.	[3, 24, 25]
STAMP	-Investigates and assesses the minute things such as duties of the staff in addition to the large ones. -Mentions the causes of human performance and component failures.	-Cumbersome to use a STAMP model, takes a lot of effort and is unsuitable for a novice.	[4, 58]
STPA	-Is concerned with the safety constraints in a system. -Considers many of the systemic factors including the interactions.	-Analysis is too complex; a tool is needed for simplification. -The resulting tables are too large in size.	[5, 26, 27]
CAST	-Assesses the whole accident process in case of an accident and indicates the key causal factors. -Focuses on why the accidents occur in the first place.	-Detailed data about the system is needed which might not be available publically. -The recommendations based on CAST may also not be feasible or may take a long time to be implemented.	[6]
HAZOP	-It not only determines the hazards; it demonstrates the probability and consequence of an event. -Spots the hazards and proposes the safety measures to avoid these hazards.	-Depends solely on human knowledge and a whole team is required for a considerable long amount of time. -Does not include the interactions among various parts of the system.	[2, 7, 26, 59]
HFACS	-Takes into account all kind of errors. i.e. active as well as latent ones. -Multiple accident cases and scenarios can be easily entertained.	-Cannot be applied outside aviation industry satisfactorily. -The failure beyond the organization's premises such as government role cannot be incorporated.	[8, 60]
AcciMap	-Describes the different causal factors and their inter relationships in a graphical form. -Causal diagrams guide us to the patterns that lead to the occurrence of accidents.	-Training of AcciMaps and sufficient pertinent knowledge is essential in using this methodology. -The reliability can be challenged and also lacks taxonomical support.	[9, 58, 60]
FRAM	-Used both as a risk analysis tool and as an accident investigation tool. -Application is structurally easy.	-Demands vast knowledge about human factors and an extensive theoretical background with a big chunk of time to learn it in the beginning.	[58]
LOPA	-Includes all preventive and mitigative measures. -Includes its own calibration and contains the use of corporate criteria in a lucid way.	-Does not entail the common cause failures (CCF). -Takes considerable amount of time, requires a lot of resources and expertise of professionals.	[61]
SCM	-Considers the interactions between latent factors and the unsafe acts. -Shows system's defenses diagrammatically in such a way that the pits exhibit the breakage of defenses.	-Oversimplifies the causation analysis more than enough. -Is never aimed to be a detailed accident analysis model.	[12, 43, 60]
FTA	-Provides insights into the operation. -Enables the analyst to determine major contributors to TOP event frequency. -Takes different systems into consideration such as emergency systems, operations.	-Model is incomplete, only deals with the listed mechanisms. -There is a major uncertainty in the frequency of an event.	[44]
ETA	-Starts from one event and discovers the probabilities. -Used to quantify the chances of the end event in terms of different outcomes.	-Deals with only one starting event at one time. -A professional with practical knowledge and vast experience is required.	[62, 63]
DEA	-Analyzes chain of events that lead to accidents.	-Has a limited scope and only contains the clear causes of an accident.	[15]
CA	-Determines the effects of a likely failure event on human, equipment and facility and tells about the possible consequences they may have to face.	There is a great deal of uncertainty with many of these models. a potential error in terms of magnitude is anticipated in these consequence analyses.	[16, 44]
CREAM	-Involves technical factors, factors of individuals and of the whole organizations. -Addresses single actors as well and predicts human error.	-Lacks theoretical background and has limited ability to deal with the psychological factors.	[17, 64]
SPAR-H	-Determines the chances of human errors with performance factors.	-Prediction of human error probabilities may not be suitable.	[18, 55]

2.4. Structural Equation Modeling

Recently a statistical technique known as structural equation modeling has been used effectively in accident causation in order to identify and address the significant factors that contribute to the occurrence of these accidents. Structural equation modeling is a technique that hypothesizes how a construct/factor is defined by a set of variables and what is the link between constructs themselves [65] N and is preferred because of its ability to deal with complex theoretical models using multiple group models [66]. This technique has been effectively used to analyze 320 coal mines accidents in China which determined the lead causes that led to these minor and major accidents [67]. Since Pakistan is a developing country and is yet to implement zero accident vision, plenty of accidents occur in different industries yearly. Data of accidents has been collected online from February 2012 to April 2017. As it can be seen from the last five years' data, majority of accidents in Pakistan occurred in textile and garments industries therefore it is pertinent to use structural equation modeling in textile industry to know the reasons behind these accidents and to identify the primary and secondary causes that lead to them.

Table 3. Summry of injuries occured in industries

Sr #	Industry/City	Data of occurrence	Number of injuries	References
1	Medicine factory, Kharak	Feb 6th 2012	9 dead ,16 wounded	[68]
2	Gas Cylinder Company, Karachi	May 21st ,2012	1 dead,6 injured	[69]
3	Ali Enterprises Textile, Karachi	Sept 12th ,2012	289 people dead	[70]
4	Shoe factory, Lahore	Sept 11th ,2012	25 people dead,8 injured	[71]
5	Tissue paper and diaper factory, Karachi	Oct 5th ,2012	2 injured	[72]
6	Aslam Industry and Medical Gases, Rawalpindi	Jan 7th ,2013	3 dead,2 injured	[73]
7	Winboard factory, Faisalabad	Jan 9th ,2013	1 dead,5 injured	[74]
8	Layyah Sugar Mills, Layyah	Jan 13th ,2013	8 injured	[75]
9	Plastic factory , Lahore	Mar 30th ,2013	8 injured	[76]
10	Shoe making factory, Lahore	Apr 24th ,2013	No casualties	[77]
11	Thermopol factory, Lahore	Nov 15th ,2013	Valuable goods burned	[78]
12	Dawood exports, Faisalabad	Dec 26th ,2013	9 dead,8 injured	[79]
13	Fine Gas Company, Lahore	Mar 15th ,2014	4 dead,17 injured	[80]
14	Saad Garment factory, Karachi	May 15th ,2014	1 dead	[81]
15	Garments factory, Karachi	May 16th ,2014	1 dead	[82]
16	Garments factory SITE, Karachi	June 16th ,2014	No casualties	[83]
17	Garment factory Karachi	July 22nd , 2014	No casualties	[84]
18	KBI Textile Mills, Karachi	Dec 7th ,2014	No casualties	[85]
19	Food Factory, Karachi	Apr 13th ,2015	6 dead	[86]
20	Garment factory, SITE Karachi	May 4th ,2015	13 injured	[87]
21	Dye factory, Karachi	May 30th,2015	No casualties	[88]
22	Towel factory, SITE Karachi	July 23th ,2015	No casualties	[89]
23	Garment factory, Lahore	Sept 4th ,2015	4 dead,18 injured	[90]
24	Flour Mill, Gujranwala	Sept 5th ,2015	5 dead,30 injured	[91]

25	Garment factory, SITE Karachi	Sept 9th ,2015	1 dead	[92]
26	Plastic factory, Lahore	Nov 5th,2015	41 dead,103 injured	[93]
27	Steel Mill, Lahore	Nov 10th ,2015.	5 dead,3 injured	[94]
28	Arfan Steels, Lahore	Jan 5th ,2016	8 injured,	[95]
29	Plastic Factory, Gujranwala	Jan 6th ,2016	1 dead,30 injured	[96]
30	Daud Steel Mill, Swabi	Jan 8th ,2016	1 dead	[97]
31	Kashmir Sugar Mills, Jhang	Jan 19th,2016	8 dead,11 injured	[98]
32	Kims Biscuit factory, Hattar	Feb 25th ,2016	1 dead	[99]
33	Textile Factory, Karachi	Apr 4th , 2016	1 dead,4 injured	[100]
34	Plastic factory, Lahore	Apr 17th ,2016	No casualties,	[101]
35	Garment factory, Lahore	Apr 17th ,2016	No casualties	[101]
36	Plastic factory, Karachi	May 15th ,2016	5 dead	[102]
37	Fauji Cement, Fateh Jang	May 31st ,2016	No casualties,	[103]
38	Pharmaceutical factory, Karachi	June 24th,2016	No casualties	[104]
39	Paper Mill, Okara	July 1st ,2016	2 dead,3 injured	[105]
40	Cold Storage factory, Karachi	July 4th ,2016	6 dead,3 injured	[106]
41	Garments factory, Lahore	July 23rd ,2016	1 dead,4 injured	[107]
42	Cakes and Bakes Factory, Lahore	Sept 17th ,2016	3 dead,2 injured	[108]
43	Chemical factory, Karachi	Oct 4th ,2016	3 dead	[109]
44	Indigo Textile mills, Karachi	Oct 5th ,2016	3 dead,2 unconscious	[110]
45	Ciaton Engineering Company, Karachi	Oct 22nd ,2016	3 dead, 4 injured	[111]
46	SITE Textile factory, Karachi	Oct 25th ,2016	No casualties	[112]
47	Ashraf Garments, Lahore	Nov 11th ,2016	3 dead	[113]
48	Sugar mill, Rahim Yar Khan	Mar 18th ,2017	2 dead,2 injured	[114]
49	Shoe factory, Lahore	Apr 9th ,2017	No casualties	[115]
50	Cotton factory, Gujranwala	Apr 28th 2017	No casualties	[116]

3. CONCLUSION

This study is unique in the sense that a thorough review of existing accident causation techniques has been done and their strengths and weaknesses have been stated. The industries where these techniques have been applied worldwide have been pointed out and it is declared that for complex and integrated systems there is a need for newer techniques, which not only address the contributory factors but also address the interactions among these accident causation factors. Recently a statistical technique, structural equation modeling has been used in accident causation analysis in order to determine the causes and their interactions that lead to such catastrophes and it is emphasized that this technique should be used more in order to check it's feasibility and usage in accident causation[67].Keeping in view the recent statistics of accidents in industries in Pakistan, it is recommended that the textile industries specifically should be analyzed with the above mentioned techniques or more preferably with structural equation modeling to find the causes of the accidents in order to make the environment more stable and hazard free. Moreover, data has been gathered from the best available resource i.e. the online newspapers' archives and the online news. In some developed countries, there is a separate accident database and a separate institution for accident data, which files the data that contains the actual occupational accidents, their reasons, their causes and the damage that they caused and the lives they affected. In Pakistan there is no such institution so the data has been gathered using the sources of web, however it is a common practice in some developed countries as well to collect data of occupational accidents with the help of newspapers and TV channels such as BBC, Reuters, The Guardian, The Times of India and many more [117] . Accident data in biodiesel industries has also been gathered for a database with the help of documented sources such as the Herald, the Telegraph, CTV News [118], however it is essential to have an institution that logs the accidents data and the causes of these failures. In Pakistan there is no such institute currently therefore it is highly recommended for the government to make a separate organization that logs and documents all these details on daily basis.

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