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Hazard Analysis and Risk Assessments for Industrial Processes Using FMEA and Bow-Tie Methodologies

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ABSTRACT

Several risk assessment techniques have been presented and investigated in previous research, focusing mainly on the failure mode and effect analysis (FMEA). FMEA can be employed to determine where failures can occur within industrial systems and to assess the impact of such failures. This research proposes a novel methodology for hazard analysis and risk assessments that integrates FMEA with the bow-tie model. The proposed method has been applied and evaluated in a real industrial process, illustrating the effectiveness of the proposed method. Specifically, the bow-tie diagram of the critical equipment in the adopted plant in the case study was built. Safety critical barriers are identified and each of these is assigned to industrial process with an individual responsible. The detection rating to the failure mode and the values of risk priority number (RPN) are calculated. The analysis shows the high values of RPN are 500 and 490 in this process. A global corrective actions are suggested to improve the RPN measure. Further managerial insights have been provided.

Keywords: Safety, FMEA, RPN, Bow-tie

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1. INTRODUCTION

For any industry processes to be successful, it has become essential to identify and analysis of the hazards types and sources, to assess the associated risks and to bring the risks to an acceptable level. The bow-tie model was applied to large scale industries, for the probabilistic assessment of risks of major industrial accidents. Many researches on FMEA have been carried out but still some applied research in the industrial processes field is required so, about explore the successful utilization of the FMEA technique in the area of manufacturing and design in large industrial process scale. Liu *et al*. (2011) discussed traditional FMEA Using fuzzy evidential reasoning approach and grey theory. A Novel approach for prioritization of failure modes in FMEA using multi criteria decision making techniques (MCDMT) is discussed by Maheswaran and Logan (Maheswaran and Logan, 2013).

Bow-tie diagram combines fault tree (FT) and event tree (ET) analyses to explore the primary causes and consequences of a critical event (Kahn *et al*., 2014). The bow-tie diagram has widely been used in risk analysis, reliability engineering and safety assessment presented by Aneziris *et al*. (2008). Bellamy *et al*. (2013) introduced an application of bow-tie in industrial practice, the “Storybuilder” method, to identify the dominant patterns of safety barrier failures, barrier task failures, and underlying management flaws. An evaluation of barrier performance can be achieved with this approach. An important and useful feature is that this barrier analysis helps to identify missing or ill-designed barriers that is a keyissue in risk assessment. Kurowicka *et al*. (2006) gives a detailed account of bow-tie diagram and the barrier functions associated with it. A semi-quantitative assessment of occupational risks using bow-tie representation is presented by Celeste and Cristina (2010). They presented and discussed a specific case study, in the shipyard's technological area of surface treatment and protection, to demonstrate the method's applicability and usefulness. Techniques to identify and evaluate risks in the process and to decide how to act on them in order to eliminate or reduce them to protect the population and the environment are often mistaken. Summarizing these two categories of techniques, they can distinguish the following general components (Catalin *et al*., 2013): (1) to identify risks: is the intrinsic presence, observation of what happens. Hazard and operability analysis (HAZOP) method is a method for identifying operational problems associated with the design, maintenance or operation of the safety system. It is an objective process to evaluate the different parts of a given system that provides a systematic and well-documented potential hazard and (2) risk assessment: their intrinsic presence, previous experience, codes of practice use the method hazard analysis (HAZAN) estimation method used to assess hazards to decide how to take action to eliminate or reduce the risk.

From all the above, it is apparent that bow-tie methodology represents a step forward in the current state of the art concerning the management of risks, including those associated with occupational safety. This is the context in which the authors equated the use of the qualitative bow-tie diagram in combination with a matrix approach, based on accident statistics of the activity under analysis. To demonstrate the proposed methodology for hazard and risk assessments analyses, this paper describes an application case in a large industrial scale, called Emisal company which located in Fayoum city, Egypt, whose main activity is to produce anhydrous Sodium Sulphate and Sodium Chloride refined salt), Magnesium sulphate Heptahydrate (Epsom salt), Sodium chloride Pure.

Hence, the main objective of this paper, though, is twofold: (1) to explore FMEA methodology for identifying potential failure modes for process, assess the risk associated with those failure modes and prioritize issues for corrective action and identify and carry out corrective actions to address the most serious concerns and (2) to as certain to what extent the bow-tie diagram would be successfully applied to occupational risks, in individual firms, by their own people.

3. METHODOLOGY

There are several techniques developed to perform the risk assessment to mitigate the suffering. FMEA is one of the most widely used risk assessment tool. Recently, FMEA has been adopted in wide spectrum of fields such as the chemical, aerospace, military, automobile, electrical, mechanical and large scale industries. The FMEA provides reliability and safety of a plant and helps to identify the potential process failures existing in a plant (Arun *et al*., 2013). Bow-tie model is one of the best tools developed for this communication. Barriers may be strong against a specific accident sequence and hence have smaller holes or weak which contribute to reduction of human error routes and which would permit larger holes (Celeste and Cristina, 2010).

3.1 Failure Mode and Effect Analysis (FMEA)

The basic FMEA process is presented in Figure 1. The FMEA process evaluates the overall impact of each and every component failure mode. The FMEA objective is to determine the effect on system reliability from component failures, but the technique can be extended to determine the effect on safety. FMEA input data includes detailed hardware/function design information. Design data may be in the form of the design concept, the operational concept, and major components planned for use in the system and major system functions. FMEA output information includes identification of failure modes in the system under analysis, evaluation of the failure effects, identification of hazards, and identification of system critical items in the form of a critical items list (AIAG, 2002).

Actually, the FMEA methodology is designed to identify potential failure modes for process, assess the risk associated with these failure modes and prioritize issues for corrective action and identify and carry out corrective actions to address the most serious concerns (Virtanen and Hagmark, 2007). In FMEA, failures are prioritized according to how serious their consequences are, how frequently they occur and how easily they can

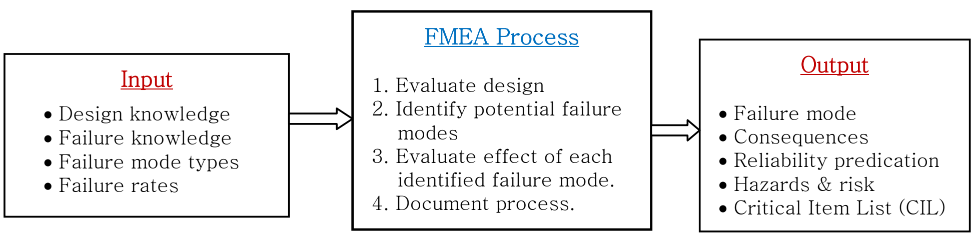


Figure 1. FMEA overview.

be detected. Ideally, FMEA begins during the earliest conceptual stages of design and continues throughout the life of the product or service. Results are used to identify high-vulnerability elements to guide resource deployment.

An FMEA can be done any time in the system. RPN is simply calculated by the following equation:

$$RPN = \text{Severity (S)} \times \text{Occurrence (O)} \times \text{Detection (D)} \quad (1)$$

The total RPN is calculated by adding all of the risk priority numbers. The small RPN is always better than the high RPN. It could be computed for the entire process and/or for the design process only. Once it is calculated, it is easy to determine the areas of greatest concern. There could be less severe failures, but which occur more often and are less detectable. These actions can include specific inspection, testing or quality procedures, redesign (such as selection of new components), adding more redundancy and limiting environmental stresses or operating range. Once the actions have been implemented in the design/process, the new RPN should be checked, to confirm the improvements (Janarthanan, 2013; Abdel-Aziz and Helal, 2012).

3.2 Bow-Tie Methodology

It is used for risk assessment, risk management and risk communication. This methodology is designed to give a better overview of the situation in which certain risks. In addition, bow-tie methodology helps people understand the relationship between the risks and organizational events. It is a graphical tool to illustrate an accident scenario, starting from accident causes and ending with its consequences. While centered on a critical event, bow-tie is composed of FT on the left-hand side identifying the possible events causing the critical event (or top event), and ET on the right-hand side showing the possible consequences of the critical event based on the failure or success of safety barriers (Zuijderduijn, 2000; Nicola *et al*., 2013). Figure 2 identifies the main threats on the left hand-side and demonstrates in a "bow-tie" shape how barriers prevent the escalation of the initial threats to one of several final outcomes. Safety critical barriers are identified and each of these is assigned to a business group with an individual responsible. Outline of bow-tie construction is introduced in Figure 3. Risk in bow-tie methodology is elaborated by the relationship between hazards, top events, threats and consequences (see Figure 4). Barriers are used to display what meas-

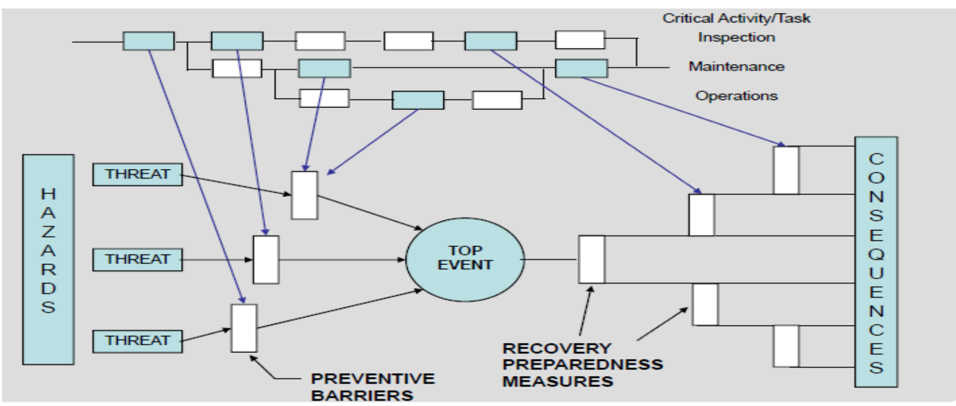


Figure 2. Bow-tie modeling.

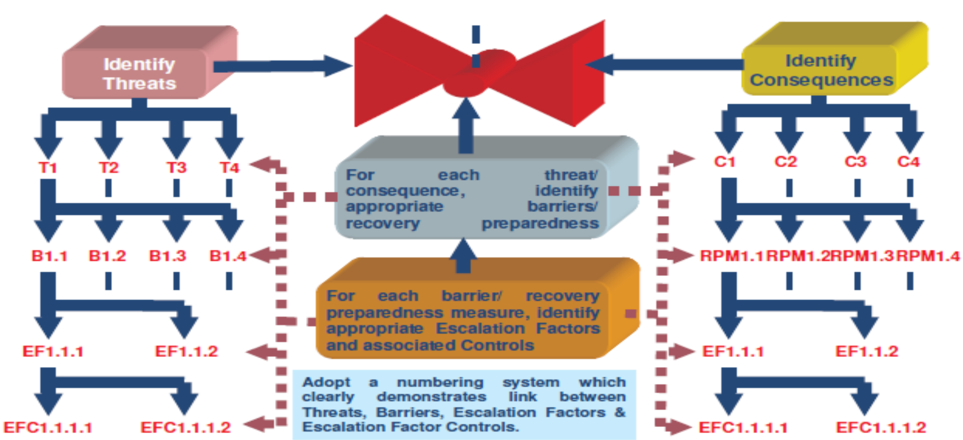


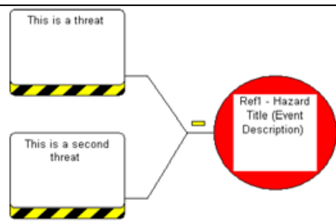
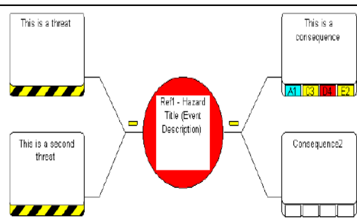
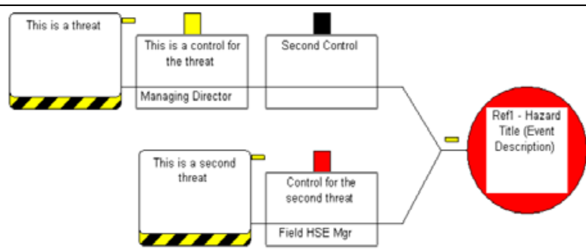
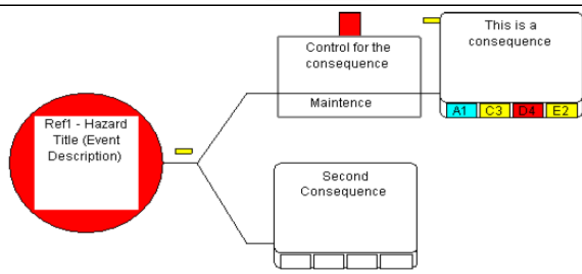
Figure 3. Bow-tie construction (Ramzan, 2006).

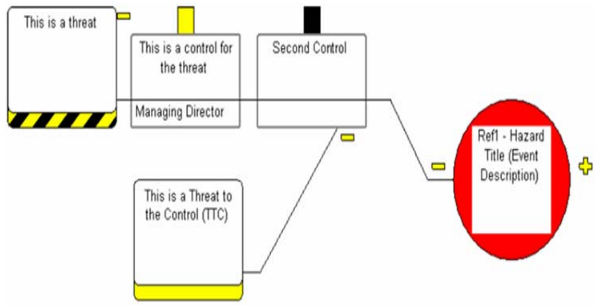
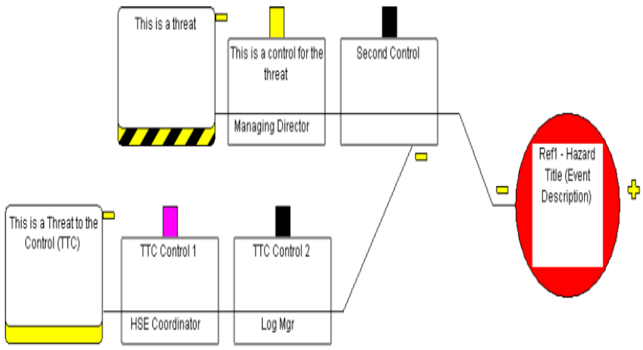
ures an organization has in place to control the risk. The process involves the systematic identification of hazards and effects, assessment of the associated risks and the specification of the control and recovery measures which must be in place and maintained in place. Bow-tie diagrams of industrial processes critical components will be

SEVERITY	CONSEQUENCES				LIKELIHOOD				
	People	Asset	Environment	Reputation	1 Very Unlikely	2 Unlikely	3 Possible	4 Likely	5 Very Likely
1	No/ Slight Injury	No/ Slight damage	No/ Slight effect	No/ Slight Impact	Low	Low	Low	Low	Low
2	Minor Injury	Minor damage	Minor effect	Limited Impact	Low	Low	Low	Medium	Medium
3	Major Injury	Local damage	Local effect	Major Impact	Low	Low	Medium	Medium	High
4	Fatality	Major damage	Major effect	Nat. Impact	Low	Medium	Medium	High	High
5	Multiple fatalities	Extensive damage	Massive effect	Internat. Impact	Medium	Medium	High	High	High

Figure 4. Risk assessment matrix.

Table 1. The bow-tie steps

Steps	Model
Step 1. Identify the bow-tie hazard	
Step 2. Assess the Threats	
Step 3. Assess the Consequences	
Step 4. Control	
Step 5. Recover	

Step 6. Identify threats to the controls	
Step 7. Identify the controls for the threats to the controls	

built using risk analysis software (bowtiexp-6.03). From bowtiexp-6.03 software, bow-tie steps are listed in Table 1.

4. CASE STUDY

In this paper, the FMEA and bow-tie methodology areapplied to a particular type of accident in the anhydrous Sodium Sulphate factory, The critical equipment in factoryconsists of (melter, boiler, crystallizer, thickener, evaporators, packing machines, centrifugal pump, plate heat exchanger and screw pumps). This equipment was selected based on analysis of historical data of the factory and interviews with key personnel involved in the safety, maintenance and operation.

5. RESULTS AND DISCUSSIONS

In this section, results and discussions of real case study analyses are presented. First, the results for hazard analysis through FMEA in case study are discussed. Second, the results associated to the risk analysis through the bow-tie diagram are carried out.

5.1 Hazard Analysis Through FMEA

There are nine subsystems identified, at which potential failure mode (FM) can occur, as shown in Table 2. In this table, FMEA punctuation form is presented. It shows the form of FMEA for S, O and D. The calculated RPN values and criticality for the failure modes are presented. There are several FM with high values of RPN. It can be observed that the values of RPN for packing and sewing machines are 500, 490 respectively. Packing machines are the highest criticality values of failure modes. In Figure 4 and Figure 5, comparison between current and new values of RPN for potential failure mode is presented. These figures show that the difference (Δd = RPN Current-RPN New) and difference percentage (Δd% = (Δd/RPN Current)×100) values of RPN for potential failure modes. It is found that there are improvements of these FM which reflect the reducing values of RPN for potential failure modes. Also, it is noticed that the value of RPN for packing machines decreases from 500 in the current conditions to 36 in the new conditions and value of RPN for sewing machine decreases from 490 in the current conditions to 48 in the new conditions. Based on these results, global corrective actions were suggested to improve the RPN.

5.2 Risk Analysis Through the Bow-Tie Diagram

As shown in Figure 7 to Figure 14, the main threats on the left hand-side and demonstrates in a "Bow-tie diagram" shape how barriers prevent the escalation of the initial threats to one of several final outcomes are introduced. As can be seen from these figures, safety critical barriers are identified and each of these is as-signed to industrial process with an individual responsible. Some shell sites use a feature called matrix of permitted operations which defines in matrix format what activities may or may not be done if the relevant barrier is not functional. This is a form of risk based operations, but it focuses on forbidden operations and it is understood the approach has not found favor in ope-rating sites as it is too restrictive on operations. Figure 9 shows bow-tie diagram of packing worker injury. The main

Table 2. FMEA Sheet for factory

Subsystem	FM	Risk Factors (or) Criteria						RPN Current	Corrective Actions Recommended	RPN New
		Potential Failure Effects	S	Potential Causes	O	Current Controls	D			
Heat exchanger	FM 1: Burst of pipe due to pipe blockage	factory trip	4	Deposits inside pipes	3	None	8	96	1. Maintenance and cleaning the heat Exchanger 2. Precaution signs.	24
	FM 2: Burning skin of operator	Burning and scalds to operator.	6	Bad insulation	5	Isolation	3	90	1. Isolation by guard rail. 2. Preventive maintenance. 3. Warning signs. 4. Wearing PPE at all time.	16
Continues and discontinues centrifugal	FM 3: Draw bodies	Cut and other injuries and may lead to death due to the high kinetic energy involved in centrifuge	6	Operator contact with rotating parts	4	None	5	120	1. Isolation by guard rail. 2. Warning signs. 3. Training of workers to increase awareness.	40
	FM 4: Mechanical failure.	Total destruction to the machine	8	- Over load - No preventive - maintenance	1	None	10	80	1. Preventive maintenance. 2. Wearing PPE at all time. 3. Following Operation manual correctly.	20
Pumps	FM 5: Mechanical failure (operational problem)	Pumps out of service	6	Increase sodium sulfate crystals concentrations	7	Preventive maintenance	4	168	No recommendation	8
	FM 6: Electricity supply fails		6	- Interruption in secondary electric line. - Diesel generator out of service.	7	Diesel generator stand by	5	210	Checking two electrical line and inspection generators continuously	6

Table 2. (Cont.)

Subsystem	FM	Risk Factors (or) Criteria						RPN Current	Corrective Actions Recommended	RPN New
		Potential Failure Effects	S	Potential Causes	O	Current Controls	D			
Belt conveyor transporting the salt from Dryer to storage	FM 7: Belt damage	Factorytrip.	7	Overload and speed indicator not operating	3	Overload and speed indicator	5	105	1. Training to operators 2. Following Operation manuals correctly 3. Regular preventive maintenance and inspection.	14
			7	Alignment sensor not operating	3	Alignment sensor	5	105		14
Sewing machine (close up the salt bag)	FM 8: Injury of the hand of the operator	Injury to worker	7	Operator not focused while performing the work.	7	None	10	490	Personnel protective equipment. Installing mechanical guard.	48
Evaporator	FM 9: Feed pumps trip	Evaporator fail to operate	7	Mechanical failure electricity fails	4	Using another energy source corrective maintenance	7	196	Use three source of energy applying preventive maintenance	30
	FM 10: No heating steam		8	Valve FCV 15 fails to open. Steam pipe defect. Valve FCV 158 fails to open.	3	Checking pipes and valves	8	192	Applying preventive maintenance of valve FCV 158 and pipeline	36
	FM 11: Increase steam pressure		9	Sensor TI144 fail to detect pressure increase steam flow	4	Checking sensor and valve	7	252	Inspection sensor continuously use pressure safety and relief valves	48
	FM 12: Increase steam temperature		8	Sensor PI115 fail to detect temperature increase steam flow	5	Checking sensor and valve	4	160	Inspection sensor continuously use pressure safety and relief valves	18
	FM 13: Flipping pump P1334A fail		7	Mechanical failure electricity fails	4	Using another energy source corrective maintenance	3	84	Use three source of energy applying preventive maintenance	6

Table 2. (Cont.)

Subsystem	FM	Potential Failure Effects	Risk Factors (or) Criteria					RPN Current	Corrective Actions Recommended	RPN New
			S	Potential Causes	O	Current Controls	D			
Boiler	FM 14: Drum safety valve	Boiler failure (operate-explosion)	7	- Valve defects - control fails	8	Inspection of safety valve	4	224	Valve preventive maintenance	8
	FM 15: Low level drum		7	Feed-water pump failure	7	Checking of pump	5	245	- Continuous checking of safety valve - Preventive maintenance of safety valve	20
	FM 16: Flame failure		6	Control failure	8	Corrective maintenance	4	192	Preventive maintenance	12
	FM 17: Excessive high superheated outlet temperature	- Boiler trip - Co-generation plant Trip - Sodium Sulphate factory Shutdown	6	Incorrect burner sequence	8	Temperature sensor checking	6	288	Checking temperature Use automatic interlock of temperature	27
			6	Too much fuel being fired	6	Temperature sensor checking	6	216	Fuel valve checking Use automatic interlock of safety valve	18
	FM 18: Low steam pressure		6	Low water	7	Checking water feed pump	7	294	Inspection and checking water feed pump	12
	FM 19: Low discharge pressure		4	Pump rotation incorrect	7	Checking / inspection of pump	6	168	Continuous checking of pump Preventive maintenance of pump	6
			4	Impeller damaged or loose on shaft	8	Checking and inspection of pump shaft	6	192	Continuous checking of pump Preventive maintenance of pump	18
Packing machines.	FM 20: Machine trapping worker hands while he is feeding the bags.	Injury to worker	5	Operator not focused while performing the work.	10	None	10	500	1. Personnel protective equipment. 2. Manual activation of machine clamps. 3. Training.	36
	FM 21: Back ach of the operator.		6	Worker lifting the salt bags the wrong way.	7		8	336	Personnel protective equipment.	36

Table 2. (Cont.)

Subsystem	FM	Risk Factors (or) Criteria						RPN Current	Corrective Actions Recommended	RPN New
		Potential Failure Effects	S	Potential Causes	O	Current Controls	D			
Crystallizer	FM 22: Cooling pump fails	Crystallizer fail to operate	7	Mechanical failure electricity fails	3	Using another energy source corrective maintenance	4	84	Use three source of energy applying preventive maintenance	27
	FM 23: Brine pump fails		8	Mechanical failure electricity fails	4	Using another energy source corrective maintenance	3	96	Use three source of energy applying preventive maintenance	45
	FM 24: No cooling in crystallizer shell		7	Feeding pumpstrip Defects in cooling material pipeline	4	Checking pipeline and pump	4	112	Inspection of pipeline and applying preventive maintenance in system pies	64
	FM 25: No brine in crystallizer		8	Pumps trip	3	Using another energy source corrective maintenance	3	72	Use three source of energy applying preventive maintenance	48
	FM2 6: Sensors (to detect temperature) trip		6	Sensor failure and not calibrated	4	Calibrating sensors	5	120	Inspection and calibrating sensors continuously applying preventive maintenance in sensor	60

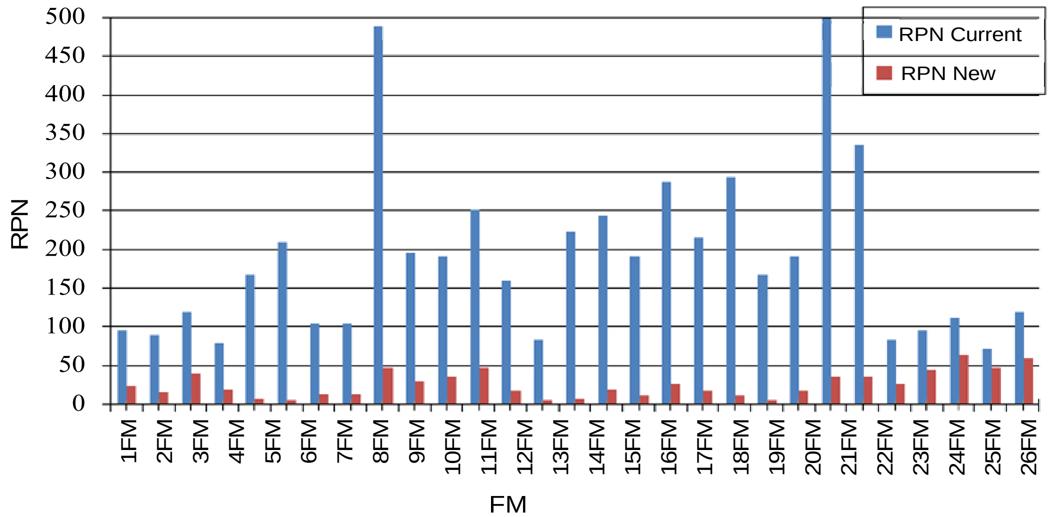


Figure 5. Comparison between current and new RPN values for FM.

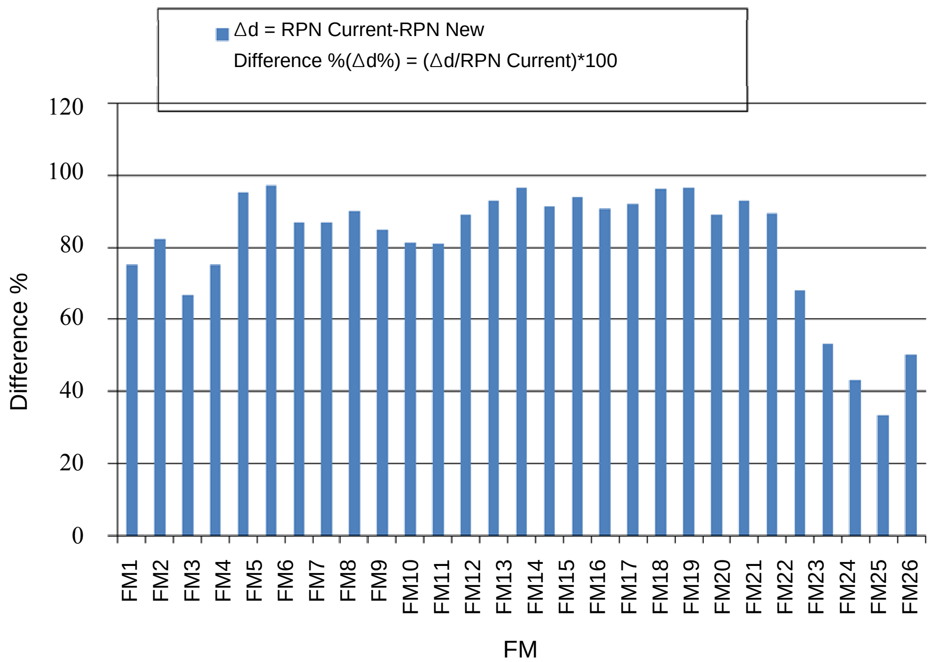


Figure 6. Shows the RPN difference for FM.

threats of the working injury are safety working montoring, install, and regular inspection.The main consequence of corrective action of packing worker injury is application of OSHA. Figure 11 shows bow-tie diagram of noise injury. In Figure 15, bow-tie risk assessment is plotted. As can be seen from this figure, risk categories in factory for people, asset, environment and reputation. From this figure, the values in red and brown are considered critical. The subsystem on each zone found to have RPN highest value were studied further to minimize the S, reduce the O of the failure mode, and improve the D. Based on these results, the main consequence of the corrective action should be applied in critical equipment for factory.

6. CONCLUSION

In this paper, bow-tie and FMEA methodologies are suggested to hazard analysis and risk assessments for the industrial processes. FMEA is a systematic tool for identifying the effects or consequences of FM and is used to eliminate or reduce the chance of failure. Bow-tie is considered as an approach that has both proactive and reactive elements and that systematically works through the hazard and its management. Moreover, bow-tie is particularly useful to represent the influence of safety systems on the progression of accident scenarios. Safety systems, either technical or organizational elements, are placed in two main branches of the diagram.

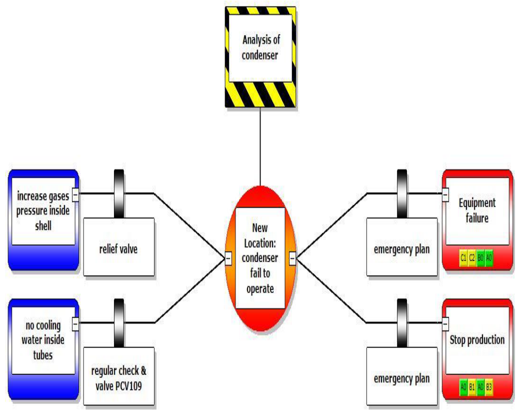


Figure 7. Bow-tie diagram of condenser.

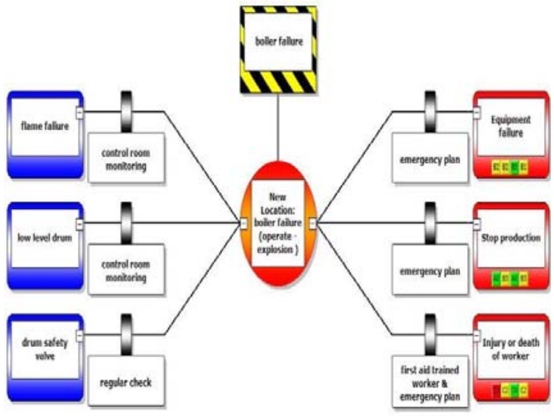


Figure 8. Bow-tie diagram of boiler.

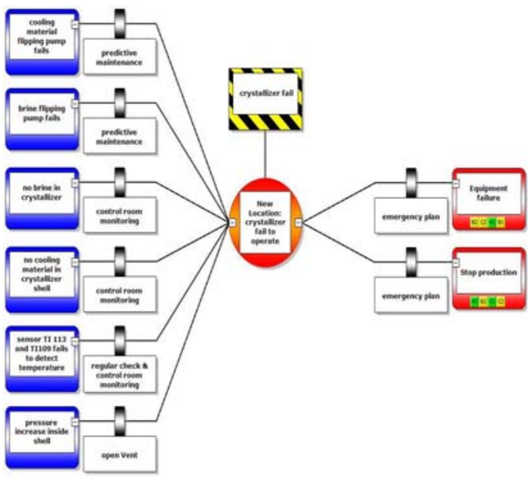


Figure 9. Bow-tie diagram of crystallizer.

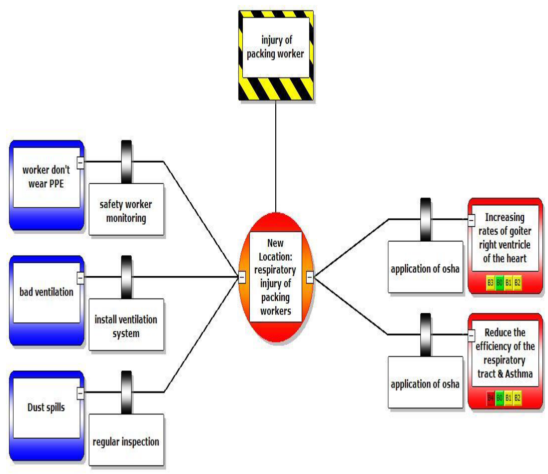


Figure 10. Bow-tie diagram of packing worker injury.

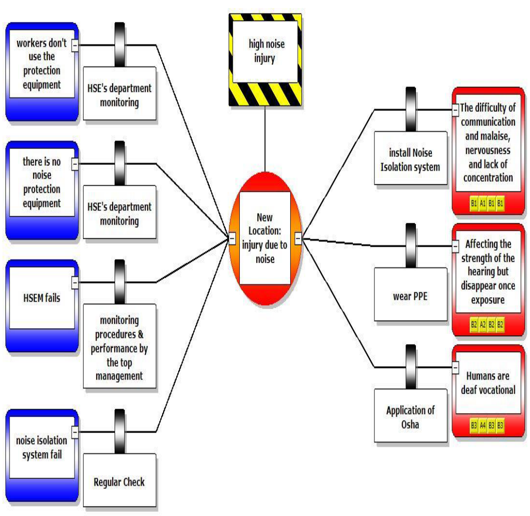


Figure 11. Bow-tie diagram of noise injury.

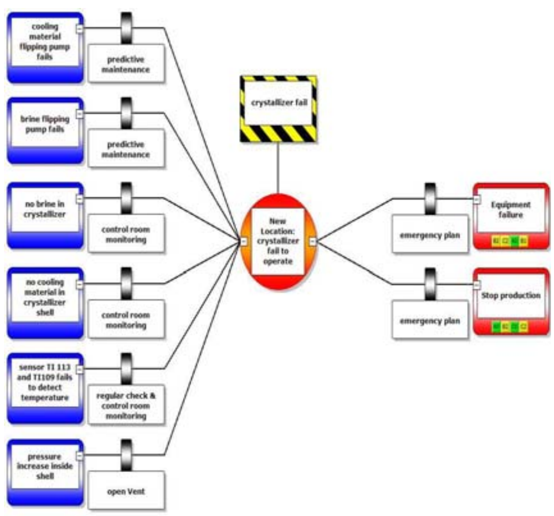


Figure 12. Bow-tie diagram of crystallizer damage.

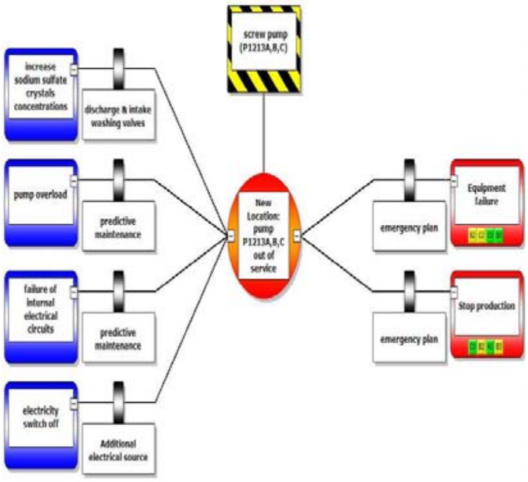


Figure 13. Bow-tie diagram of screw pump Failure.

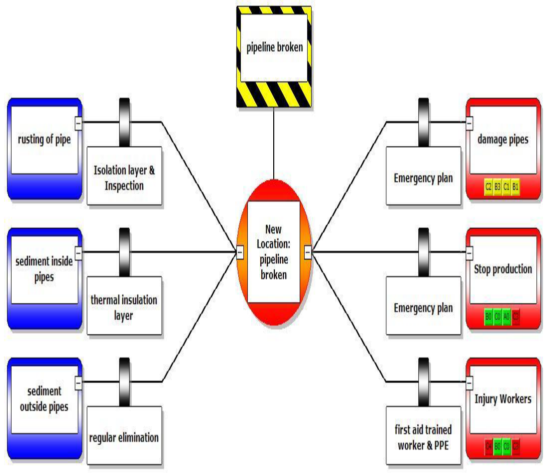


Figure 14. Bow-tie diagram of piping subsystem.

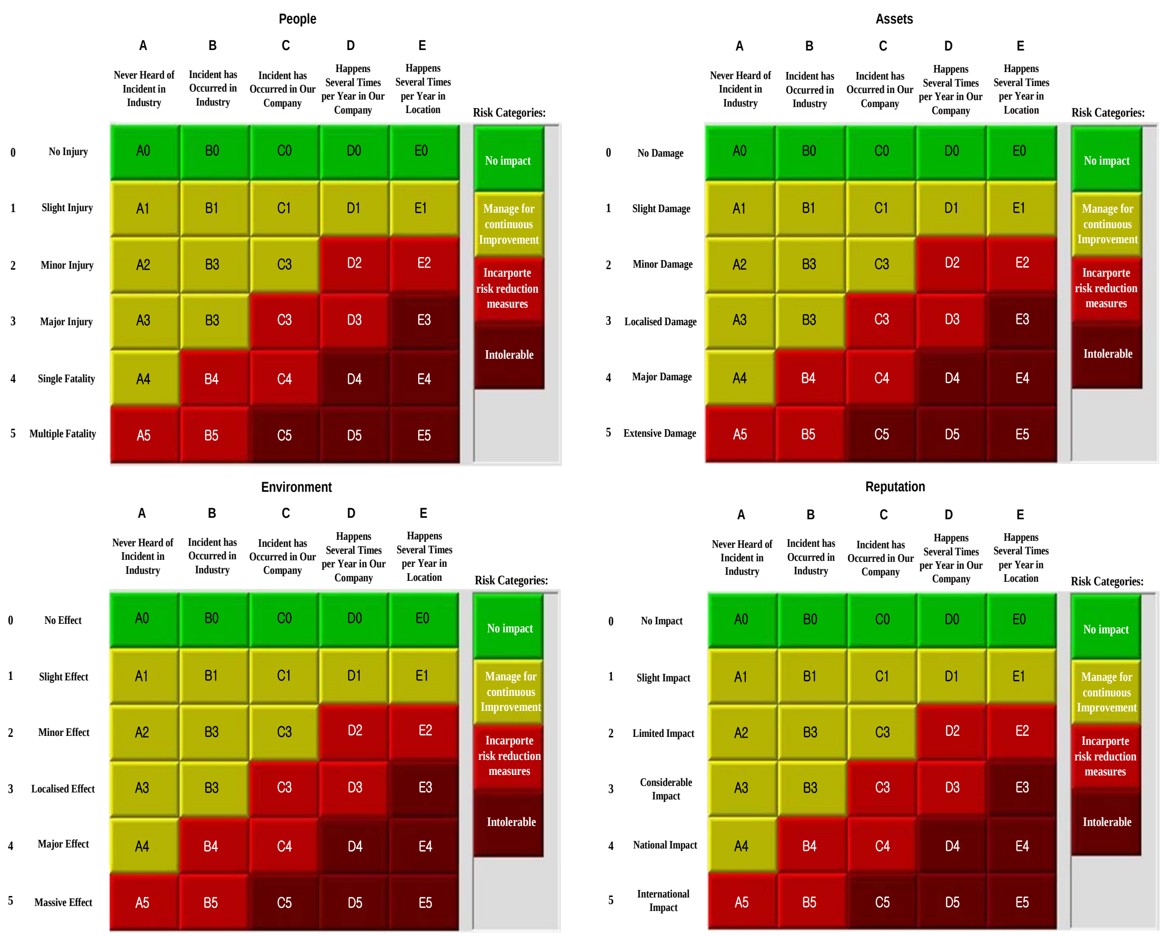


Figure 15. Bow-tie risk assessment.

Bow-tie model is essentially a probabilistic technique, but in time it has developed in different versions, depending on the system under analysis.

This paper has introduced a new methodology that integrates FMEA and bow-tie, presenting the proper way for application in process industry. This paper has thus described an application case in a large industrial scale, called Emisal company which located in Fayoum city, Egypt. As a result of this methodology, the detection rating to the failure mode, the values of RPN are calculated based on FMEA analysis. A set of corrective actions are suggested to improve the values of RPN. As a result of the subsequent bow-tie analysis, safety critical barriers are identified and each of these is assigned to industrial process with an individual responsible. The results show the effectiveness of the proposed methodology in process industry.

The current research can be further extended in future research work through various directions. The first direction can be the integration of the proposed methodology with other risk assessment techniques. Furthermore, the proposed method can be applied to other industrial and risk environments.

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