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A systematic approach towards accident analysis and prevention

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Abstract−A systematic approach towards accident analysis and prevention has been developed. It relies on system theory as an incident causation model, and adopts a hybrid model for identifying elements of the safety management system. PDCA (Plan-Do-Check-Act) process, commonly practiced in business for quality control, has been applied to defining components of the system. Using the experts' judgment, accident data and their reported causes are correlated to the defined components, with RBI (risk-based inspection) defined consequence scores as weighting factors. The application of this approach allows users such as governments and companies to identify and prioritize among causes of accidents and near-misses in the petrochemical industry. A case study using the accident data of Yeosu petrochemical complex from 1990 to 2004 has been applied to illustrate insights readily obtainable by using the developed analysis technique. The results suggest comprehensive identification and ranking of accident causes for effective prevention of accidents in the future.

Key words: Accident Analysis, Accident Prevention, PDCA, Petrochemical Industry, Quantitative Method

INTRODUCTION

1. General

Safety-related problems have been an issue for a long time in the chemical industry, not only in S. Korea but also in other parts of the world. The world has seen numerous accidents in chemical plants such as the explosion in Flixborough, England (1974) or leak of TCDD in Seveso, Italy (1976) whereby up to hundreds of lives have been injured or killed, with millions of dollars lost [1].

The potential and/or actual devastating consequences of accidents in the chemical industry naturally led to the research and development efforts towards a firm safety management system. According to the recent findings and achievements, the safety management system consists of numerous elements for which diverse criteria have been developed for identification, assessment and management of risks. Among the various models proposed, ones developed by OSHA (Occupational Safety and Health Administration) and CCPS (Center for Chemical Process Safety) are widely recognized [1]. They differ in a few of the elements included since OSHA focuses more on the regulative, and legislative aspects of the safety management system while CCPS puts emphasis on the administrative, industrial aspects of the system. The elements included in each model are summarized in Table 1.

The common elements between the OSHA and CCPS model include incident investigation. It refers to the systematic efforts towards consistent examination and learning from near misses and major consequence accidents [2]. It serves as a useful method for identifying common aspects regarding the causes that triggered or contributed to such unfortunate events [3]. Furthermore, the results of analysis data such as the pattern classification among different types of accidents can help focus the safety efforts. It also enables the recognition of the leading indicators for impending accidents. In sum, an incident investigation, when properly done, is essential for understanding and preventing harmful consequences.

Despite its usefulness, the incident investigation has not yet received proper attention, especially in the field of accident analysis, at least domestically. Although new techniques and methodologies have been continuously developed in other fields of safety management such as SIL (Safety Integrity Level) in risk assessment, insignificant changes have been made in the way accidents are analyzed in practice. Many companies still rely on the simple, statistical analysis technique (described in detail in 3.1) for recognizing patterns and trends in their accident data. According to the experience of the authors, these were the same tools prevalently practiced in companies when we visited them in 2003. As a result, not enough lessons are learned from accident data, and it is not hard to see similar kinds of accidents happening continually even within a single company.

This paper proposes a systematic approach towards accident analysis and prevention that incorporates the PDCA (Plan-Do-Check-Act) process commonly practiced in improving business into identifying causes of accidents in the chemical industry. In addition, a quantitative, probabilistic method is employed in prioritization of identified causes. The proposed way of analyzing accident data provides insights for effective prevention of accidents at both company and government level.

2. Theoretical Background

As CCPS recognizes, to be effective an investigation must apply an approach which is based on basic incident causation theories and use tested data analysis techniques [2]. Indeed, numerous theoretical concepts and associated models have been developed to explain how and why accidents happen. They provide the ground upon which experts investigate, analyze and recommend preventive actions a-

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Table 1. List of the safety management elements defined by OSHA, and CCPS

Models	Unshared elements	Shared Elements
OSHA	Employee participation, process safety information, process hazard analysis, operating procedures, contractors, pre-startup review, mechanical integrity, hot work permit, emergency planning and response, compliance audits, trade secrets	management of change, training, incident investigation
CCPS	Accountability objective and goals, process knowledge & documentation, capital project review & design procedures, process risk management, process & equipment integrity, human factors, standards/codes & laws, audits and corrective actions, enhancement of process safety knowledge	

Table 2. Commonly used accident indexes and their pros and cons

Name	Description of the index	Advantages	Disadvantages
FAR	$\frac{\text{Number of fatalities}\times 10^8}{\text{Total hours worked in a period}}$	Allows a comprehensive analysis over a long period of time.	Does not contain info on injuries and is insensitive to changes in accident type.
FR	$\frac{\text{Number of accidents}}{\text{Total hours worked}}\times\frac{10^6}{\text{yr}}$	Accurately measures the number of accidents in a given period of time.	Does not distinguish accidents in terms of the severity of consequences.
SR	$\frac{\text{Number of lost work hours}}{\text{Total hours worked}}\times\frac{10^6}{\text{yr}}$	Accurately reflects the severity of accidents in a given period of time.	Cannot distinguish between many minor accidents and few major ones.
FSI	$\sqrt{\text{FR}\times\text{SR}}$	Accurately reflects both the frequency and severity of accidents in a given period.	Becomes inaccurate if annual working hours of FR and SR are not equal.

gainst accidents. Among the several theories introduced so far, the following three are widely accepted: domino theory of causation, system theory, and hazard-barrier-target theory. In brief terms, the domino theory views accidents as a consequence of errors starting in one or more of the five dominoes-ancestry and social environment, fault or person, unsafe act, unsafe condition, and injury; on the other hand, system theory acknowledges as many causes of an accident as there are system components; lastly, according to hazard-barrier-Target-theory, there are hazards for which barriers are prepared to manage them but that accidents happen due to simultaneous exposure of flaws in all barriers [2]. Among the three, the approach this study proposes is based on the system theory, which is also known as the *multiple-cause theory*. It is chosen since it recognizes accidents as "an abnormal effect or result of the technological or management system," which coincides with the way we classify accident causes. In addition, it also enables the development of models of complex engineering systems and management structures that can be utilized in generating preventive actions.

3. Various Accident Analysis Techniques

There are several techniques based on which accident data can be analyzed. Some focus on calculating indexes like FR (frequency rate of injury) that statistically measures the safety performance and/or patterns in the workplace, while others attempt to use frequency measures in discovering trends in terms of place, time, type, and other factors of accidents [4,5]. Recently, more techniques have been developed towards identifying the most frequent and/or important causes of accidents. The three kinds are explained with exemplary techniques in the following paragraphs.

3-1. Simple Statistical Analysis Technique

It is the technique commonly used by most companies and government agencies in S. Korea. Accordingly, the number of accidents is counted for a specific period of time (usually 1 year) in terms place, time, type, etc. For example, KOSHA presented the number of accidents of each type in its annual accident report as one of the analysis results: It revealed that out of 23 types, "turn over" (when people fall down on a flat surface due to causes such as slipping, or over speed) and "fall" (when people fall from architecture, buildings, machines, scaffolding etc.) have been the most frequent, with 18,527 and 14,027 cases each that together made up about 37.5% of all accidents in the country's workplace during 2008 [6]. Information obtained by this simple, statistical analysis technique is advantageous in that trends and patterns can be easily observed; however, it cannot explain what have been the root causes of accidents, or what can be done to prevent them in the future.

3-2. Accidents Rate Indexing Techniques

Various indexes have been developed to compare the safety status of workplaces and countries. Some of the most commonly used ones are summarized in Table 2 [4].

3-3. Other Techniques

Several attempts on identifying the most important causes from the accident data can be found in the literature. They are not restricted to accidents in chemical plants and employ a variety of causation models like the Swiss cheese theory in the case of analytical HFACS (Human Factors Analysis and Classification System) for investigating shipping accidents, or the sequential model for the method developed by Jacobbson et al. [7]. Various (mathematical) tools such as FAHP (fuzzy analytic hierarchy process) and a Buckley solution algorithm or CART (classification and regression trees) method have been applied for ranking of the causes. However, none of them uses system theory, and few incorporate the viewpoint of the system management [8].

PROPOSED ANALYSIS TECHNIQUE

1. Modeling and Assumptions for Identification of Causes

As stated in the previous section, the proposed technique relies

Table 3. Safety management system elements for the Hybrid model

Category	Elements	Remark
Software	Management commitment, Hazard identification and risk analysis, Operating procedures, Contractor management, Education/training, Management of change, Information management, Emergency planning, Incident investigation, Site entry and work permits	Elements can be modified according to the specific situation and needs of the user
Hardware	Facilities/equipments, Electricity/utilities, Hazardous materials, Storage/transportation	

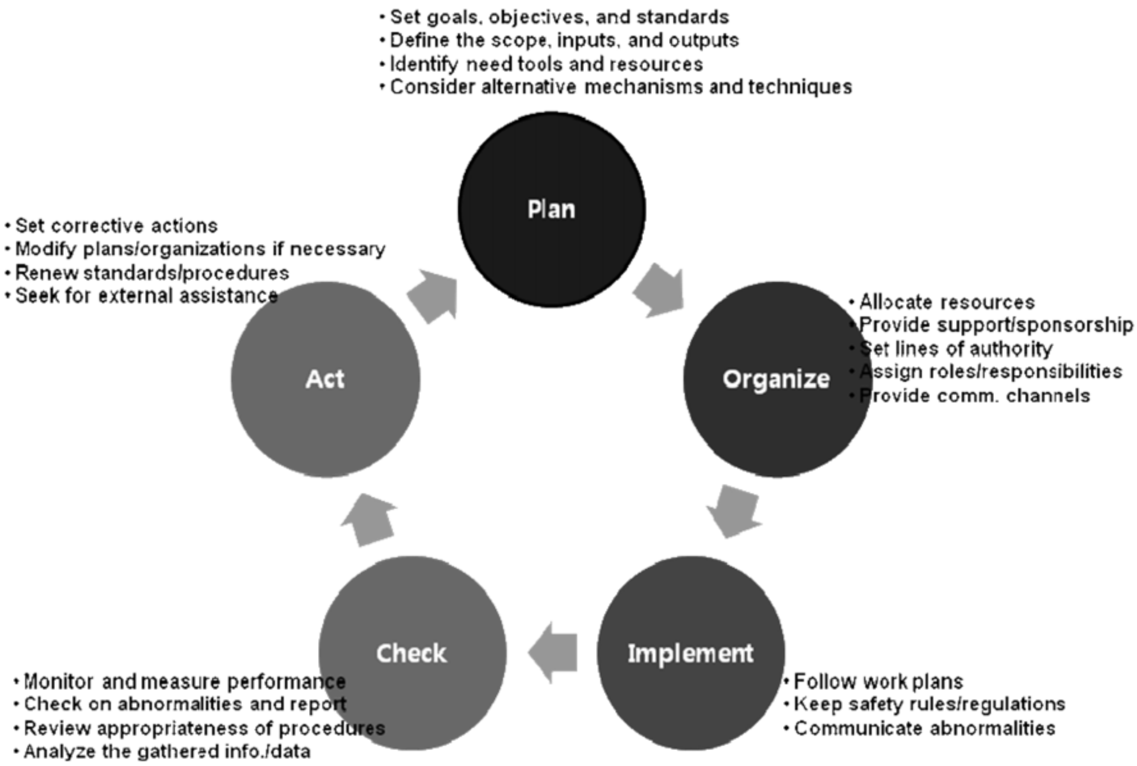


Fig. 1. The modified PDCA process for a safety management system.

on system theory as an incident causation model. Accordingly, the safety management system elements need to be defined in order to correlate with reported causes of accidents. In defining the elements, we developed a hybrid model that incorporates elements from three existing models-OSHA PSM (process safety management), CCPS PSM, and KPIA (Korean Petrochemical Industry Association) PSM [1]. KPIA PSM is the model for safety management system in which 12 elements, either software or hardware, have been classified by KPIA. They are the same elements evaluated during the safety auditing of companies. Elements were extracted based on their fitness, applicability to the PDCA process as well as coverage in explaining causes of past accident data. As a result, it consists of a total of 14 elements as listed in Table 3.

For each element, sub-categorization follows with respect to the PDCA process. In business, PDCA has long been commonly applied as a self-sustaining, continuous mechanism for quality control [9]. It consists of four steps for assuring the quality of goods produced and services provided; for the safety management system, we propose to modify the steps slightly into the following five: plan, organize, implement, check, and act. The modified version distinguishes differences between planning and organizing for more accurate identification of accident causes. The functions of each step are explained in Fig. 1 [1,9].

The functions in Fig. 1 provide the basis against which experts' judgment can be employed in correlating the reported accident causes with culpable components of the safety management system. For example, if one of the reports in the accident report highlights "carelessness of the employee" and "inappropriate installation of the damaged facilities" (which is actually the case for the accident in the BD Plant of Keum-Ho Petrochemical Corp. on the 19^{th} of May, 1986), the corresponding author correlates them to *implement of Operating procedures* and *plan of Facilities/equipment*, respectively. Here, at least two assumptions are made: the reported causes of accidents are correct, and the experts' judgment is valid. If the assumptions appear weak and/or unsatisfactory, they can be, at least in part, overcome by relying on a multiple number of accident investigators and experts for these tasks. Numerous methods have been developed for reliable application of experts' judgments, such as the use of fuzzy comparison ratios for quantification of HFACS implementation in analysis of shipping accidents [7].

2. Quantitative Prioritization of Causes

By applying the procedures previously described, a list of correlated culpable elements can be generated for each accident report. The collection of the lists over a defined period of time for a specific company, industrial complex, or country is then used into prioritizing the most important ones by a quantitative method. It takes into account both the seriousness of accidents to which components are correlated and the probabilistic rate of their appearances.

It is necessary to apply weighting factors that reflect the seriousness of accidents when prioritizing among the causes. Otherwise, wrong impressions can be made from the accident data analysis such that causes for accidents with high frequency, but minor consequences are given greater emphasis than for ones with devastating consequences and slightly lower frequency. To avoid such erroneous perceptions, ranking systems in many fields, from oil and gas, to steelworks and electricity generation have used the approach where the seriousness of consequences is also considered. This study adopted the consequence scoring system developed by M. Tweeddale for assigning weighting factors to individual accident cases [10]. It is based on a logarithmic scale and takes into account damages to both employees and physical properties in the manner described in Tables 4 and 5.

Using the weighting factors defined in the above, it now takes a three-step calculation for generating a list of culpable system components with weighted frequencies from the given accident data. In doing so, let C_i represent the accident case i during the given interval of time in which there are n number of cases. Then, C_{ji} is the correlated culpable component j of the accident case i. If, for example, there are m number of correlated components for the n number of accidents, a matrix **C** of m rows and n columns can be developed with C_{ji} as corresponding elements:

$$\mathbf{C} = \begin{matrix} C_{11} & C_{12} \dots C_{1n} \\ C_{21} & C_{22} \dots C_{2n} \\ : & : \dots : \\ : & : \dots : \\ C_{m1} & C_{m2} \dots C_{mn} \end{matrix} \quad (1)$$

For the weighting factor, two symbols are necessary: S_{1i} as the consequence score of case i in terms of injury or public health, and S_{2i} as the consequence score of case i in terms of the costs of consequential damage. Wi, the weighting factor for the accident case i, can be calculated as in the following:

$$W_i = 10 \wedge (S_{1i} + S_{2i}) \quad (2)$$

The collection of weighting factors W_i for n accident cases can be represented by a vector **W** of n rows. The multiplication between the matrix **C**, and the vector **W** can now give the resultant vector **R** of m rows whose elements make up the list of correlated culpable components with weighted frequencies:

$$\mathbf{R} = \mathbf{C} \otimes \mathbf{W} \quad (3)$$

With **R**, one can now understand which of the safety system management elements has been the most culpable for the n accidents during the given period of time. The priority order found in **R** can also be used in making managerial decisions on where to invest the most, or focus on for enhancing the safety management system.

CASE STUDY

1. Data and Results

An illustrative application of the proposed analysis technique to accident data of Yeosu petrochemical complex of S. Korea is presented. There are currently 86 companies enrolled in the complex, with a total 11,911 employees; the complex as a whole achieved net revenue of 26.35 billion dollars in the year 2007.

Originally, the accident data of Yeosu petrochemical complex consisted of 214 cases from the 1970 to 2004, summarized in Table 6 [11]. However, in this paper only 174 cases of 1990-2004 are used since reports for accidents from 1970 to 1989 are not descriptive enough to correlate the discovered causes with the safety management system components. All authors participated in the correlating tasks, and only the components agreed by all members were

Table 4. Consequence scores (logarithmic) for injury or public health

Description of effect	Score
10 fatalities or 100 serious permanent disabilities	6
1 fatality or 10 serious permanent disabilities, or 100 hospitalized	5
1 serious permanent disability, or 10 hospitalized, or 100 visits to medical practitioner, or large coverage in an early page of a national or major state newspaper, or equivalent coverage in other media	4
1 hospitalization, or 10 visits to medical practitioner, or 100 mildly injured or feeling unwell, or small coverage in national or major state newspaper, or leading story in a local newspaper	3
1 person visits a medical practitioner, or 10 people mildly injured or feeling unwell, or 100 complaints of related to injury or health	2
1 person mildly injured or feeling unwell, or 10 complaints related to injury or health	1

Table 5. Consequence scores (logarithmic) for the costs of consequential damage

Description of effect	Score
$10,000,000 repair cost of consequential damage or damage to assets or value of lost production	5
$1,000,000 repair cost of consequential damage or damage to assets or value of lost production	4
$100,000 repair cost of consequential damage or damage to assets or value of lost production	3
$10,000 repair cost of consequential damage or damage to assets or value of lost production	2
$1,000 repair cost of consequential damage or damage to assets or value of lost production	1

Table 6. Accident data of Yeosu petrochemical complex from 1970 to 2004

Period	Number of cases	Injury or public health				Damaged assets (thousand dollars)		
		Total	Death	Injury	Evacuation	Total	Movable	Immovable
1970s	7	9	9	-	-	9.6	9.6	-
1980s	33	559	31	2	526	63.3	51.6	11.7
1990s	122	310	32	117	161	6,049.7	2,296.0	3,753.7
2000s	52	2,331	29	52	2,250	1,365.3	316.8	1,048.5
Total	214	3,209	101	171	2,937	7,487.9	2,674.0	4,813.9

Table 7. Weighted frequencies by accident data in Yeosu complex

(a) during 1990-1999, and

	Plan	Organize	Implement	Check	Act	Rank
Management commitment	0	1010200	20010	3130	0	12
Hazard identification & risk analysis	100010	100000000	2323640	100010	10000	5
Operating procedures	101311110	210030	112741020	10410	10000110	1
Contractor management	0	100	100310	100	100000000	6
Education/training	110111020	11110	125320	11100	100101000	2
Management of change	0	0	10	0	0	14
Information mgmt.	120	0	100011100	10	0	7
Emergency planning	10010010	10001110	1110	0	100	8
Incident investigation	0	100	100110	1000	1000	13
Site entry & work permits	101000	1000	10012110	1000	0	9
Facilities/equipments	11122100	100030	12310	102238440	210	3
Electricity/utilities	1000000	0	200000	10110	0	11
Hazardous materials	0	0	100003020	2010	10000000	4
Storage/transportation	1000000	100000	100010	1001010	0	10
Rank	2	4	1	5	3	

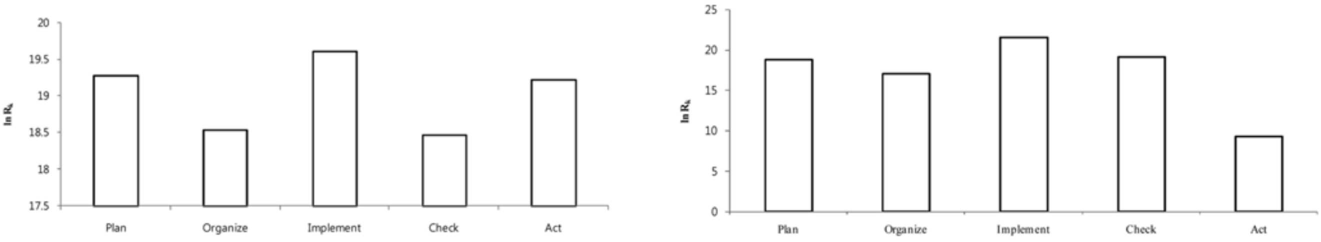
(b) 2000-2004

	Plan	Organize	Implement	Check	Act	Rank
Management commitment	0	0	101000	10000	0	12
Hazard identification & risk analysis	0	0	11121000	0	0	6
Operating procedures	21210000	1101110	100310020	100100100	0	4
Contractor management	1000000	0	2410000	10	0	8
Education/training	11101000	11000000	11020	0	0	5
Management of change	0	10000000	0	0	0	7
Information mgmt.	0	0	1011000000	0	0	2
Emergency planning	1000000	0	100	0	0	10
Incident investigation	0	0	20000	0	0	13
Site entry & work permits	100000100	0	102201000	101000000	0	3
Facilities/equipments	10	1000000	1020121010	10100	10000	1
Electricity/utilities	0	0	0	1000000	0	11
Hazardous materials	10000	10	110	0	0	14
Storage/transportation	10000	2000	1210000	0	0	9
Rank	4	2	1	3	5	

included in the classification and prioritization process. The results are presented in Table 7 and Figs. 2 and 3. They have been divided into two groups-one for accidents from 1990 to 1999 and the other covering cases from 2000 to 2004-so as to check any changes in the order of importance for culpable system components. It is done solely for this purpose with no other significant standards for dividing the periods; in practice, companies or government agencies are likely to compile accident data on a shorter time scale such as a year, and make comparisons on the annual basis.

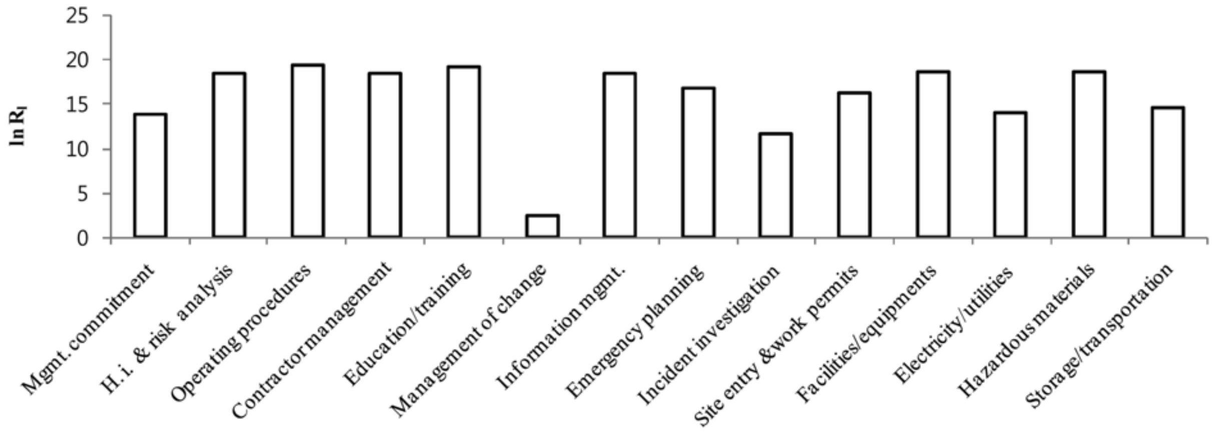
2. Discussion

Using the analysis results presented in Table 7 and Figs. 2 and 3, insights in the following areas can be obtained:

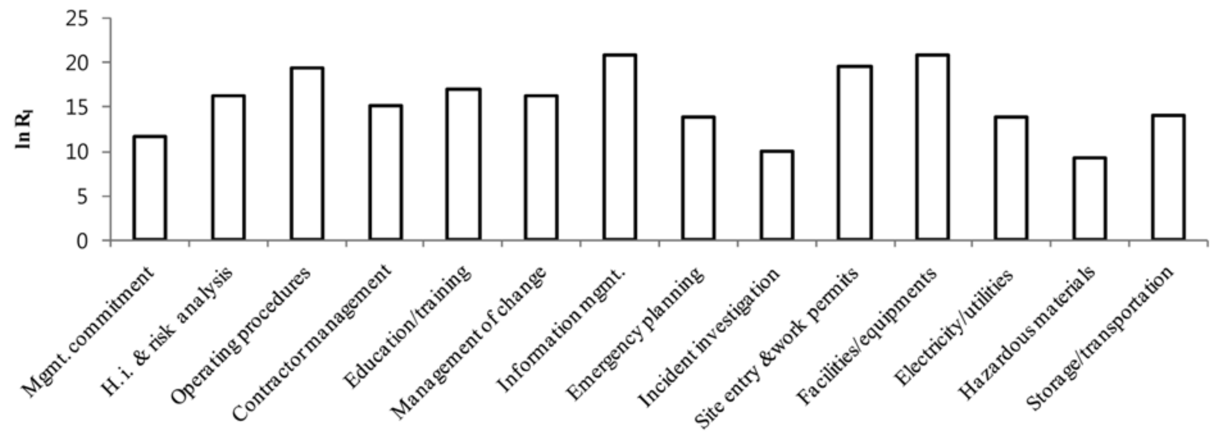


(a) Weighted frequencies for 5 steps in 1990-1999 (b) Weighted frequencies for 5 steps in 2000-2004

Fig. 2. Weighted frequencies for 5 steps of PDCA process by accident data in Yeosu complex.



(a) Weighted frequencies for 14 elements in 1990-1999



(b) Weighted frequencies for 14 elements in 2000-2004

Fig. 3. Weighted frequencies for 14 elements by accident data in Yeosu complex.

• Most vulnerable and thus should-be-improved elements and steps of the safety management system

• Relative contributions of each system component to the collection of accidents whose data have been analyzed under the proposed technique

• Individual effectiveness of efforts towards improving the safety performance of each system element and/or step (if more than two analysis results corresponding to different periods are available)

• Seriousness of accident consequences caused by mismanagement in the specific system component(s).

For example, from Table 7(a) and (b), it is clear that implementation of operating procedures and facilities/equipment has been the most responsible component of the safety management system for accidents in the complex during the 1990s and 2000s, respectively. In the 1990s, the implementation of operating procedures as the most culpable component indicates that following work plans, keeping safety rules/regulations, and/or communicating abnormalities have been the weakest area. As a matter of fact, not following the operating procedures has been the cause for most accidents (Fig. 2(a) and (b)), including the ones with worst consequences [4]. Accordingly, the priority issue for improving the safety management system of Yeosu petrochemical complex was and should have been making employees follow the established procedures. Meanwhile, from 2000 and on, the weakest part of the safety management system has been the implementation of facilities/equipment. In other words, following work plans, keeping safety rules/regulations, and/or communicating abnormalities when handling facilities/equipment have been the most responsible for accidents in the complex since 2000. In practice, examples of errors in this component include “use of inappropriate equipment”, “erroneous use of devices”, and “not changing the (eroded, fragile) parts of facilities.” Thus, the Yeosu petrochemical complex should have focused on more careful, timely handling of facilities/equipment from 2005 and on, according to the results obtained by the proposed analysis technique.

Like other techniques, the proposed systematic approach has strengths and weaknesses. The greatest strength of the proposed technique is that it assists managers of the safety management system in making decisions for enhancing the safety performance. With the ranking among the correlated culpable components, they can have a better understanding of what has been vulnerable in the organization’s safety management system. In addition, the alignment between definition of the system components and classification of categories for the best safety practice allows a systematic generation of suggestions for preventive actions. For example, the “operating procedures” that has been found as the weakest component of Yeosu petrochemical complex during 1990s (Fig. 3(a)), is also a category of the guidelines for the risk based process safety [12]. As a result, the guidelines for the best practice with respect to this component/category can be used in building preventive actions: “Deviations from procedures are addressed in a consistent manner, regardless of whether the deviations lead to a loss event or an improvement in the production process”; “periodically audit conformance to procedures”; “hold the organization accountable for consistently following procedures” and so on [12].

On the other hand, the proposed accident data analysis technique cannot be used in explaining the root causes that led to fallacies in the correlated components. From Table 7(a), for example, the technique illustrates that for the 1990s in the Yeosu petrochemical complex, not implementing the operating procedures was the most problematic, but does not explain why procedures were not followed. To understand reason(s) behind such a phenomenon, a different kind of effort is needed, but since it has been discovered that following the operating procedures is the most urgent issue, the top management now knows where to focus and what should be done. Another potential drawback of the technique lies in the definition of the components that make up the safety management system. If the definition of components is not continuously reviewed and updated, problems may arise such that accidents occur due to vulnerability in areas of undefined component(s); therefore, it is important that consistent efforts are given in defining what constitutes the safety management system.

CONCLUSION

This paper proposes an analysis technique whereby systematic identification and prioritization of causes are performed for accidents in the petrochemical industry. It can be adopted as a supplementary measure for analyzing accident data that can contribute in two aspects. First, it adds a perspective of the system management: other commonly practiced techniques are based on domino and/or hazard-barrier-target theory and do not recognize the existence or roles of system components as culpable for accidents. Moreover, rankings are seldom given that also take into account the seriousness of consequences in a quantitative manner as in the proposed technique.

The application of the proposed analysis technique for identifying and prioritizing the causes of accidents reveals that insightful information and lessons can be learned from accident data. The incorporation of the PDCA process into the identification of accident causes and use of the hybrid model for defining the safety management system allow a practical, systematic perspective on vulnerable components. In addition, the ranking of culpable components based on the weighted frequencies clearly shows the most blameworthy and thus necessary areas of improvement. As a result, an efficient plan which focuses on most urgent areas of the safety management system can be developed for improving the safety performance.

It is also possible to extend the database of accidents in the petrochemical industry based on the proposed analysis technique. The accident reports can include experts’ judgment on the correlated culpable components of the safety management system [13], as well as the root causes investigated. Once the database is successfully established, it can be used by other stakeholders of the petrochemical industry, including the government in setting the safety regulations.

NOMENCLATURE

C_i : case i from the collected accident data
C_{ji} : correlated culpable component j of the accident case i
C : matrix representation of the lists of correlated culpable components for the given accident data
S_{1i} : consequence score of case i in terms of injury or public health
S_{2i} : consequence score of case i in terms of the costs of consequential damage
R : vector representation of the list of correlated culpable components with weighted frequencies
W : vector representation of weighting factors Wi’s as elements

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