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Integration of Human and Organizational Factors with Quantitative Risk Assessment based on Accident Investigation

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Abstract

This paper presents a statistical analysis of past accidents that occurred between 1988 and 2012 reported to the European Commission's Major Accident Reporting System (eMARS) focusing on Human and Organizational Factors (HOF). The main purpose of this work is to quantify the HOF integrated with conventional risk assessment approaches and to provide future guidelines to relevant standards and current best practices.

The accident analysis results are further used to quantify the HOF assessment based on the probabilistic Rasch model. A new approach, Method for Error Deduction and Incident Analysis (MEDIA) is proposed which can be used with Quantitative Risk Assessment (QRA) studies for chemical process industry.

Keywords: Human and organizational factor, accident investigation, chemical process industry, quantitative risk assessment, HAZID identification.

1 Introduction

The human and organizational factors (HOF) have a very important role to maintain the integrity of operations and equipments in chemical process industry. Nivolianitou et al. (2006) have concluded after performing an accident investigation of major accidents reported to European major accident reporting system (MARS/eMARS) that, 40% of the major accidents have an immediate cause related to human factors. Furthermore, Bello and Colombari (1980) also highlighted after performing a survey that at least 40% of total abnormal events during industrial activities are caused by the human factors. OGP (2010) also strengthen the notion of HOF by claiming that human factor aspects during normal and maintenance operations account for around 30% of loss of containment (LOC) events.

1.1 Overview of Human Reliability Methods

It has been reported by Alvarenga et al. (2014) that human reliability analysis (HRA) in general lacks a human reliability database. While, Lees' (2012) has pointed out that large number of human error data points are collected from nuclear industry.

A number of human reliability methods already existed, some of these methods are reported in Table I.

Table I: Review of some of the existing human factor methods

Method	**Domain**	**Qualitative/ Quantitative**	**References**
Predictive Human Error Analysis (PHEA)	Chemical	Qualitative	Embrey (1992), Baber and Stanton (1996)
Tecnica Emiprica Stima Errori Operatori (TESEO)	Chemical	Quantitative	Bello and Colombari (1980)
System for Predictive Error Analysis and Reduction (SPEAR)	Chemical	Qualitative	CCPS (1994), sited in Lees' and Stanton et al. (2005)
Techniques for Human Error Rate Prediction (THERP)	Nuclear	Quantitative	Swain and Guttmann (1983)
Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H)	Nuclear	Quantitative	Gertman et al. (2005)
Human Error Analysis and Reduction Technique (HEART)	Nuclear	Quantitative	Williams (1986)

The PHEA method has adopted the error classification against the behavioural taxonomy. While, TESEO was developed to quantify the reliability of control room operator based on five parameters. The SPEAR method uses the error classification initially developed in PHEA but also includes the affect of performance shaping factors (PSF). The THERP was the first systematic approach for HRA which can quantify HRA by using an event tree structure, which can also provide the dependency among tasks and the affect of PSF. The SPAR-H method provides the nominal human probability for "operational" and "diagnostic" tasks that are $1\times10^{-}3$ and $1\times10^{-}2$, respectively. The SPAR-H method provides both +ve and -ve affect of PSF on human reliability. However, the use of scale and PSF levels in SPAR-H lacks the justification and validation as also pointed out by Laumann and Rasmussen (2015), who have tried to adjust the SPAR-H PSF levels for chemical industry based on expert's opinion. The HEART by Williams (1986) quantifies the human reliability for nine different generic tasks and considers the affect of error producing conditions (EPCs) by applying the relevant multipliers.

In this work, emphasis was done to perform the HOF assessment integrated with major risk assessment/management techniques in order to improve the overall plant's safety and to make the risk management procedure more efficient and cost effective. Therefore, some of the risk assessment/management techniques are briefly highlighted in the following section.

1.2 Major Risk Assessment/ Management Techniques

There are number of techniques that are widely used in chemical process industry to evaluate and manage risk during any phase of a project's life time. Some of these techniques are highlighted in Table II with associated standards or guidelines.

Table II: Review of risk assessment/ management techniques

Method	Qualitative/ Quantitative	Relevant Standards/ Engineering Guidelines
Hazard Identification (HAZID)	Qualitative	ISO 17776 (2000)
Hazard and Operability (HAZOP) study	Qualitative	IEC 31010 (2009), IEC 61882 (2001)
Quantitative Risk Assessemnt (QRA)	Quantitative	CCPS (2000), Purple-Book (2005), Perry and Green (1997)
Safety Integrity Level (SIL) assessment	Semi-qualitative	IEC 61511 (2003)
Layer of Protection Analysis (LOPA) (also called barrier analysis)	Quantitative	IEC 31010 (2009)

The HAZID is a technique for the identification of all significant hazards associated with a particular activity under consideration, ISO (2000). The International standard ISO (2000) provides checklists to identify the potential hazards. The table C. 8 in the standard provides checklists for hazard identification during operations, which can be modified based on current work. The HAZOP study uses guidewords to identify the possible deviations from operations. A QRA is a methodology for determining the risk of the use, handling, transport and storage of dangerous substances. (Purple Book, 2005). The results from a QRA are provided in the form of a safety report to demonstrate if calculated risk from an establishment is in acceptable zone. The procedures to determine whether a safety report has to be made are provided in the EU Directive (Directive 2012/18/EU) as also mentioned in the Purple Book (2005). The SIL assessment defines the level of integrity required by a safety instrumented function (SIF) to prevent/mitigate the hazardous event. While, during the LOPA analysis it can be determined if there are sufficient measures to prevent or mitigate a risk. However, the main use of LOPA is to provide the specification of independent protection layers (IPLs) and SIL (SIL levels) for instrumented systems as describes in standard IEC 61511 and also mentioned in standard IEC 31010. A LOPA study can also be used to allocate risk reduction resources effectively by analysing the risk reduction (IEC 31010). A LOPA can help to identify the most critical layers to spend further resources and time (IEC 31010). The Figure 1 depicts the safety layers concept which is normally used for risk reduction in chemical process industry.

1.3 Integration of Human and Organizational Factors

A number of attempts have been made in the past to integrate the HOF aspects with the risk assessment techniques. For example, Øien (2001) has provided the organizational risk influence model (ORIM) to estimate the impact of organizational factors on the risk as compliment to QRA studies. Barrier and operational risk analysis of hydrocarbons release (BORA-Release) method was developed to calculate the establishment's specific conditions of technical, human, operational and organizational influencing factors and their impact on the barrier's performance that are established to prevent the hydrocarbon release as illustrated by Aven et al. (2006). The ω-factor approach has been developed by Mosleh et al (1997) to quantify the affect of sub-organizational attributes on equipment's reliability and on operator's performance. This model has used the concept of inherent failure characteristics and characteristics induced by organizational factors for both equipment and operator. The I-Risk approach quantify the affect of the management/organizational factors to QRA risk calculations by performing an audit. The organizational factors are assessed according to provided weights and ratings as proposed by Papazogloua et al. (2003).

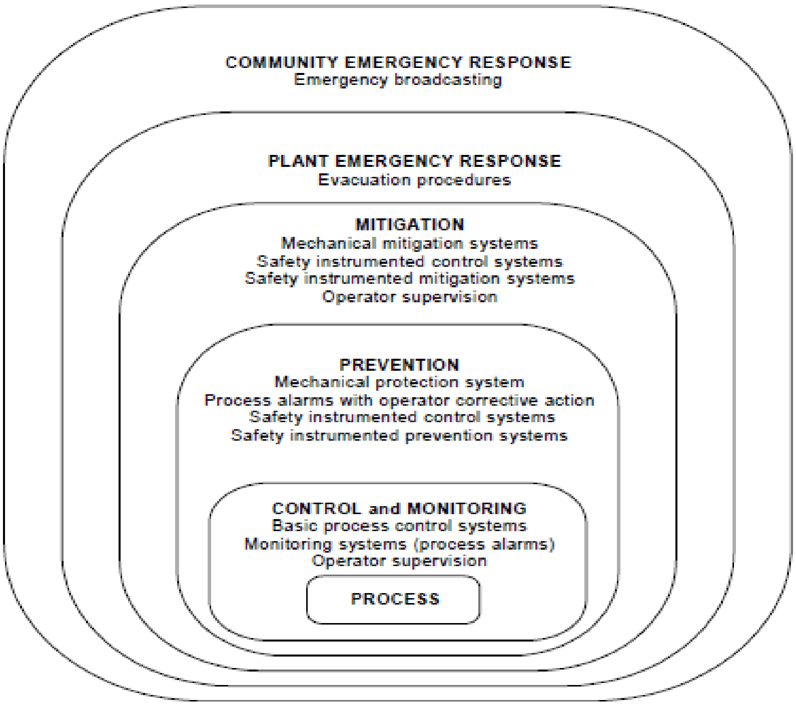

Figure 1. Risk reduction method, adapted from IEC 61511-3 (2003) p. 10

In another attempt to integrate the HOF, Schönbeck et al. (2010) has proposed a new approach to adjust the design values of safety integrity levels by considering the operational affect of the HOF, which can adversely impact the design risk reduction expressed as safety integrity levels. In this work, Schönbeck et al. (2010) has identified eight safety influencing factors with a potential to influence the performance of safety instrumented functions. Therefore, by providing weights and rating to these factors operational SIL can be obtained from design SIL.

In order to provide an integration of HOF with current risk assessment techniques, it has been decided to learn from past accidents, that can also provide the necessary data required to quantify a HOF analysis.

1.4 Learning from Past Accidents

The past accidents can be used to learn lessons retrospectively and to apply the lessons learned in a prospective manner. The International standard also illustrates to use the historical data and to predict the probability of occurrence of a failure in the future (IEC 31010:2009).

During this work, historical data from the European Commission's major accident reporting system (eMARS) has been analysed for past accidents occurring from 1988 to 2012. The purpose of eMARS is to facilitate the exchange of lessons learned from accidents and near misses involving dangerous substances to improve the chemical accident prevention and mitigation of potential consequences (eMARS, 2014). It is obligatory for the European Union (EU) Member States to report major accidents to eMARS if the threshold of an event meets the criteria established in annex VI of the Seveso III Directive (Directive 2012/18/EU). Prior to Seveso III Directive, same practice was followed due to preceding Directives. The criteria to notify an accident is based on discharge amount of a dangerous substance listed in annex I of the Directive for lower and upper-tier establishments and also based on the consequences as a result of an accident.

2 Accident Analysis

The causal factors to accidents have been identified based on a subjective judgment. However, in order to ensure the consistency throughout the analysis, taxonomies for human and organizational factors were developed as illustrated in Table III. The main rationale behind the selection of these taxonomies are:

1. Taxonomies should be quantifiable based on information present in eMARS accident reports.
2. Taxonomies should cover as much as possible all failures attributes as observed during the preliminary analysis of accidents.

The human factor behavioural/action taxonomy is slighted modified compared to PHEA taxonomy to cover different types of human/ operators actions. While, organizational factor taxonomy is modified from the taxonomy proposed by Øien (2001) to include the main organizational influencing factors.

The accidents have been analysed according to modified Swiss cheese models which can provide a distinction according to initiating cause (i.e. technical or human) to an accident and subsequent diagnostic/preventive layers (i.e. technical or human). The Swiss cheese mode was proposed by James Reason, which among others can be found in Reason (2008). During the preliminary analysis of accidents, it has been observed that accidents occurred frequently due to the absence or malfunctioning of a subsequent diagnostic/preventive layer. Therefore, modified Swiss cheese models are considered in this work to get a better understanding of accident's evolution in time. Further information about accident models and use of modified Swiss cheese models can be found in Ahmad and Pontiggia (2015).

Table III: Taxonomies and considered parameters

Human factor taxonomy	Organizational factor taxonomy	Equipment involved	Type of hazard
1. Monitoring equipment from field (M) 2. Monitoring/ operating equipments from control room (A) 3. Communication (C) 4. Manual tasks on-field (F) 5. Reporting (R)	1. Training (T_O) 2. Design (D_O) 3. Procedures (P_O) 4. Management (M_O) 5. Safety culture (S_O)	1. Pipework 2. Vessel 3. In-line equipment	1. Flammable 2. Toxic 3. Both

2.1 Results of Accident Analysis

An accident analysis has been performed for accidents occurred from 1988 to 2012 across seven industry types that typically are considered under the umbrella of chemical process industry as shown in Figure 2. A total 438 accidents have been analysed of which 197 accidents involved human or organizational characteristics during the accident.

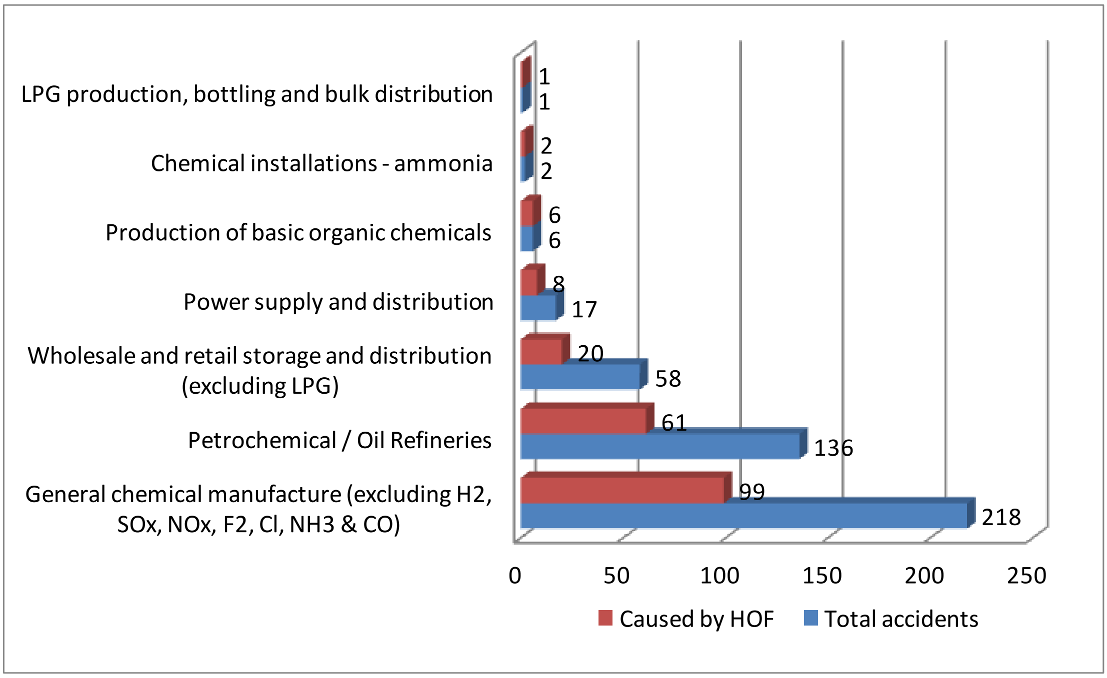

Figure 2. Total accidents versus accidents caused by HOF (1988-2012)

In order to compare the trend of total accidents and accidents caused by HOF. The time period 1988-2010 was divided into two halves as shown in Figure 3. The %age of accidents caused by HOF has increased from 43% to 47% during the period 2000-2012. While, a decrease trend of total number of accidents was observed in the second half. The decreased trend of accidents could be due to the improved design and control of plants, which also adds more complexity to the operations. The added complexity can possibilily explain the increased trend of accidents due to HOF.

During this analysis, it was observed that contractor's operations are very critical and about 15% of total accidents were occurred when contractors were responsible for certain type of operations, mainly during maintenance activities. The accidents were also observed according to plant's operating condition when accident actually occurred or when an abnormality was induced into the system as identified in post-accident investigations.

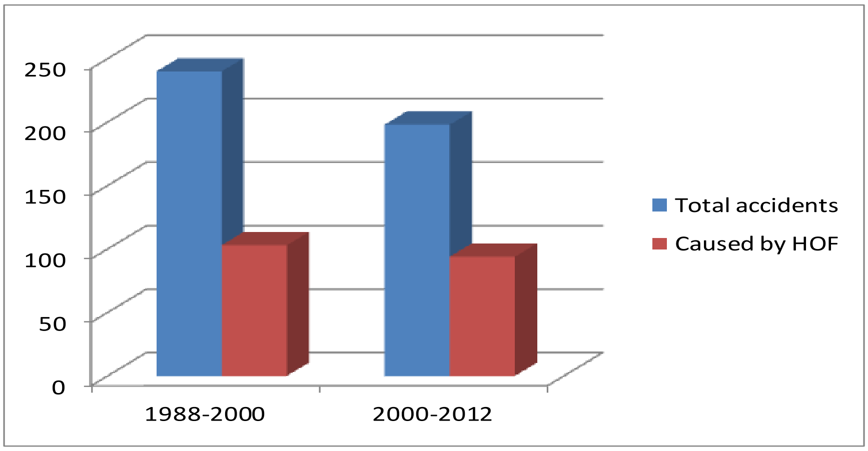

Figure 3. Comparison of total accidents and caused by HOF

The Figure 4 shows the distribution of accidents in plant's different operational stages and when among other causes contractor's operation was also a cause to the accident.

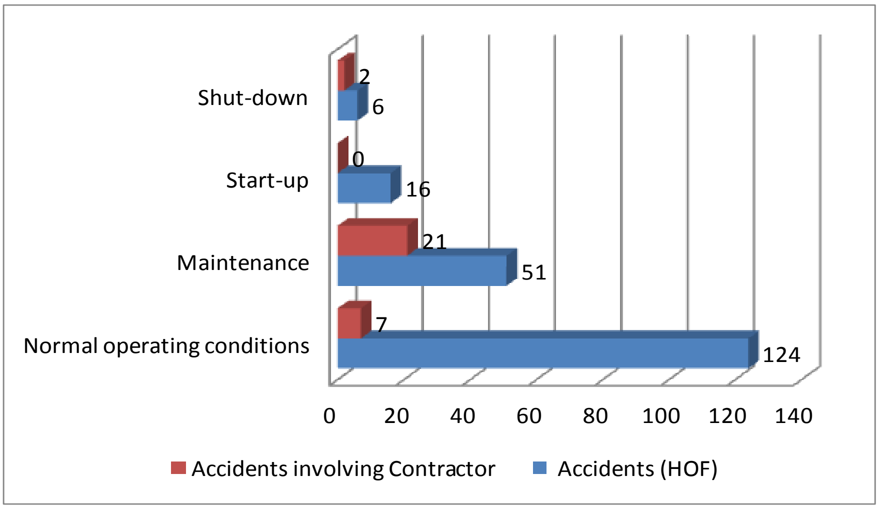

Figure 4. Accidents involving contractor in plant's different operational stages

The Figure 5 illustrates the type of equipment involved during the accident and corresponding initiating cause to an accident. The use of modified Swiss cheese models can help to structure the initiating causes into three main classes. The three main classes have been identified as follows:

1. Human
2. Technical
3. Technical + human

Only those technical caused accidents are considered in which organizational attributes were present.

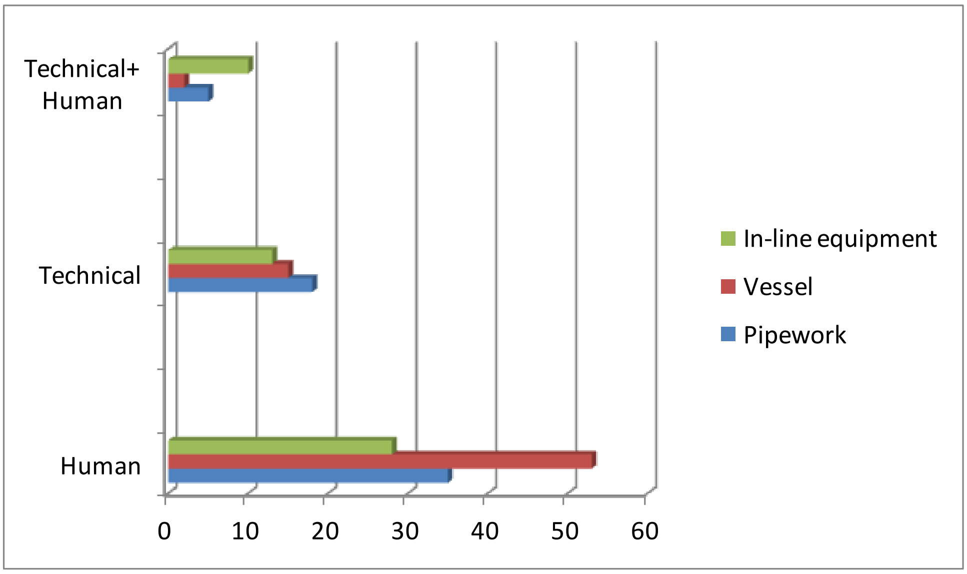

Figure 5. Comparison of initiating causes and type of equipment

In Figure 5, 8% of the analysed accidents did not provide enough information to identify the initiating causes to an accident or those accidents exhibit more complex situation. Therefore, those accidents are excluded from this comparison. Similarly, 3% of analysed accident did not provide information about the involved equipments or the observed accident situation is too complex to identify the main involved equipment. However, “vessel” equipment is involved in most of the accidents irrelevant of initiating cause to the accident (i.e. 40%). These operations mainly involved human activities related to cleaning/maintenance of vessels and mostly carried out by the contractors.

2.2 Affect of Organizational Factors

The organizational factors which are reported in Table III have been observed for their influence on operator’s actions. If it is assumed, that situation during an accident is comparable to situation during normal operations with respect to organizational influence on human/ operator actions. In this case analysed accidents can provide estimates of the average comparative influence of organizational factors on human actions. However, it is reasonably possible that for some accidents more than one organizational factor are involved, therefore Table IV shows the normalized affect of different organizational factors on human/operator action types.

Table IV: Influencing affect of organizational factors on different action types

	Type of layer	**PSFs** / **Failures***	**Organizational factors****				
			Training	Design	Procedures	Management	Safety culture
Main contributing factors	Operational layer	Technical	0.11	0.25	0.24	0.38	-
		M	0.25	0.42	0.25	-	-
		A	0.14	0.29	0.29	0.29	-
		C	0.44	0.11	0.44	-	-
		F	0.21	0.20	0.37	0.18	-
		R	-	-	-	1	-
	Diagnostic or preventive layer	Technical	0.13	0.50	0.13	0.25	-
		M	0.30	0.10	0.30	0.10	0.20
		A	0.30	0.10	0.50	0.10	-
		F	0.29	-	0.57	0.14	-

* Taxonomy from Table III. ** Only those values are reported with influencing affect ≥ 10%.

Therefore, aforementioned table can provide the influencing affect of different organizational factor on different failure types (i.e. action types). Since human taxonomy is behavioural/action based taxonomy so by assuming that organizational influencing can vary among different action types, Table IV can provide weights of organizational factors on the human actions. A set of checklists have been developed during the accident analysis by identify the specific causes for each factor. The checklists have helped to remain consistent throughout the analysis and can also provide the future guidelines to avoid recurrences of same causes by analysing them prospectively.

3 Quantification of Human Error Probability - Probabilistic Rasch Model

Quantification of human error probabilities (HEPs) from past accidents require some further assumptions due to lack of available data and validation of available data. This challenge has also been identified by Sträter (2000) who has tried to obtain the HEP from the observed frequencies against the THERP database. Furthermore, Sträter (2000) argued that operational data is always reported by a certain threshold as shown by eq. (1). Therefore, only limited frequencies can be obtained from operational experience or from past accidents. In present work, the reporting thresholds are indicated by Seveso Directive (Directive 2012/18/EU).

$$\mathrm{h}(\text{erroneous action of type i} \mid \text{event above certain reporting threshold}) \tag{1}$$

The Figure 6 illustrates the observed error frequencies against different actions types. The total number of observed instances were 172, when there was some kind of human (i.e. operator) error caused the accident.

In order to compare the obtained frequencies from accidents to existing database (e.g. THERP), Sträter (2000) argued that THERP database from Swain and Guttmann (1983) provides mostly values for rule-based behaviour or associated errors. Therefore, one can assume that for all actions, one would have to get roughly identical basic totalities of requirements. Since, rule-based behaviour idea is more connected to acquaintance of operator to an action of type i (i.e. frequency of use). Moreover, after comparing the assumptions of standard logarithmic distribution (used for THERP values) with the practical operational experience, Sträter (2000) has justified to compare the observed frequencies with THERP.

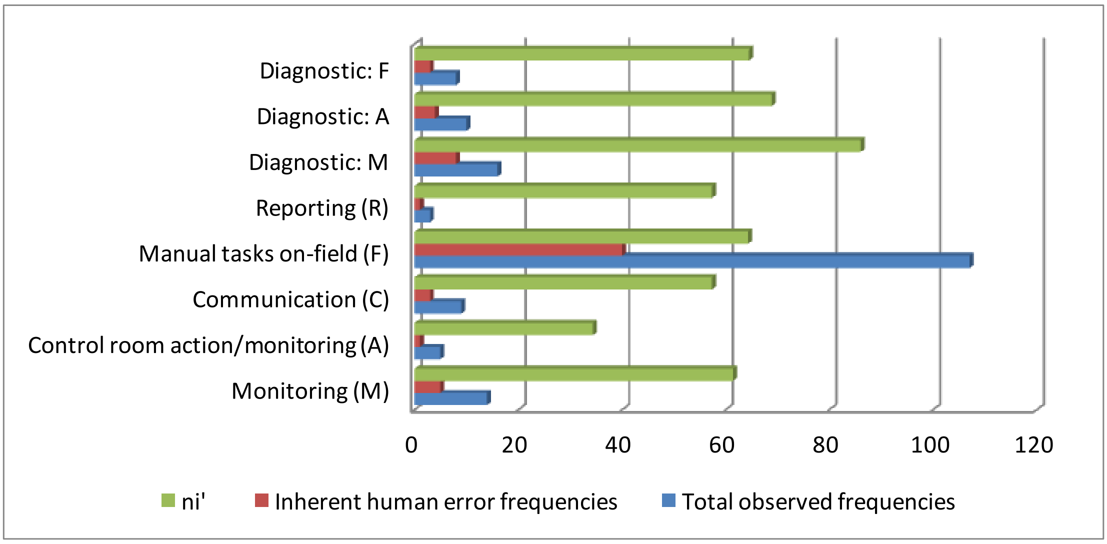

Figure 6. Absolute and relative frequencies against different action types

The concept of inherent human error and error caused by organizational factors has been used in this work as also used in ω-factor approach Mosleh et al. (1997). The relative frequencies for an action type (i.e. n'_i) is calculated according to eq. (2).

$$n'_i = \left(\frac{M}{m_i}\right) \times n_i \tag{2}$$

Whereas:

M Total number of observed accidents
m_i Number of accidents corresponding to i^{th} action type (i.e. observed frequencies)
n_i Number of accidents with inherent human failures corresponding to i^{th} action type

In order to make the numerical adjustments to observed frequencies, calibration of frequencies was proposed by Sträter (2000) and probabilistic model according to Rasch has provided the maximum numerical agreement within THERP uncertainty bounds.

The Rasch model assumes that observed values and true values of a property are interrelated via a item characteristic curve (monotonously rising function) Rasch, (1960). Since, Rasch model has been already modified and used by Sträter (2000).

Therefore, in this work it has been decided to use the Rasch model to obtain the nominal HEPs from observed frequencies as done in the CAHR, Sträter (2000).

3.1 The Rasch Model

The modified Rasch model proposed by Sträter (2000) is provided by eq. (3)

$$P_{\text{Failure of Type i}} = \frac{e^{C_{\text{Failure of type i}}}}{1+e^{C_{\text{Failure of type i}}}} = \frac{e^{D_i}}{1+e^{D_i}} = \frac{e^{\left[\frac{n'i\,-\,\mu}{s_n}\right]}}{1+e^{e^{\left[\frac{n'i\,-\,\mu}{s_n}\right]}}} \qquad (3)$$

Whereas:

n'_i Relative frequency of i^{th} action type

μ Mean value

s_n Deviation, determined by iterations (condition which provides the maximum agreement with the THERP values). ($S_n \approx 5.41$)

Hence, by using the least square method and to verify if maximum predicted values from the Rasch model are within the uncertainty bounds of THERP values, HEPs are obtained for each action type.

The Figure 7 shows the THERP values for each action type and the predicted values by Rasch model on logarithmic and normal scale against the relative frequency axis.

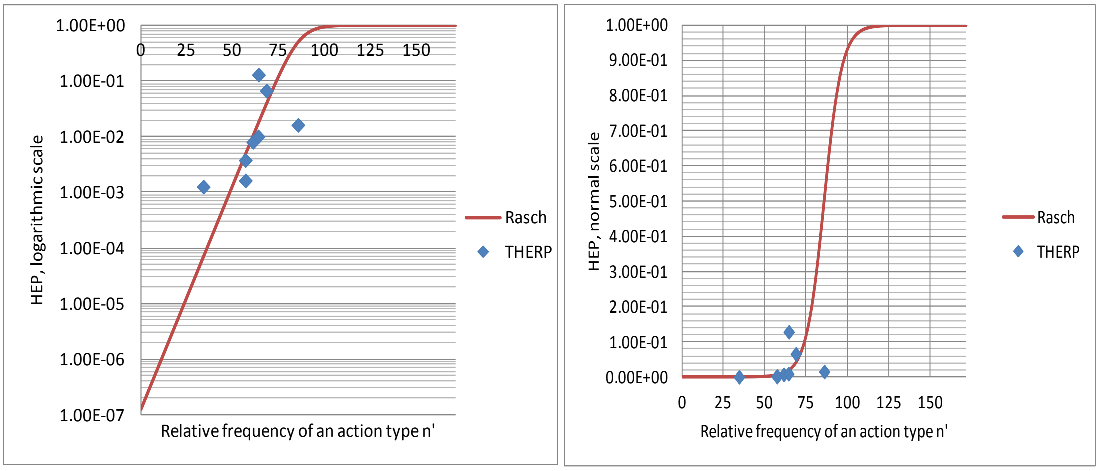

Figure 7. Rasch model prediction against THERP values

The Figure 8 illustrates a comparison of HEPs from THERP and the obtained HEPs from accident analysis for each action type. It can be observed that manual on-field operations (F) have an increased HEP compare to other action/error types, this is due to the fact that manual on-field operational errors have been observed in a higher frequency compare to other actions types. On the other hand, inherent control room actions (A) errors have been observed in fewer numbers, therefore HEP against this action type shows a decreased trend. This can also be explained by the division between industry domains (i.e. nuclear and chemical process), since THERP database was developed mainly for nuclear industry and accident analysis in this scope of work has been performed in chemical process industry. Therefore, it can also be express that this analysis makes numerical adjustments to THERP HEPs against the observed failure events from chemical process industry.

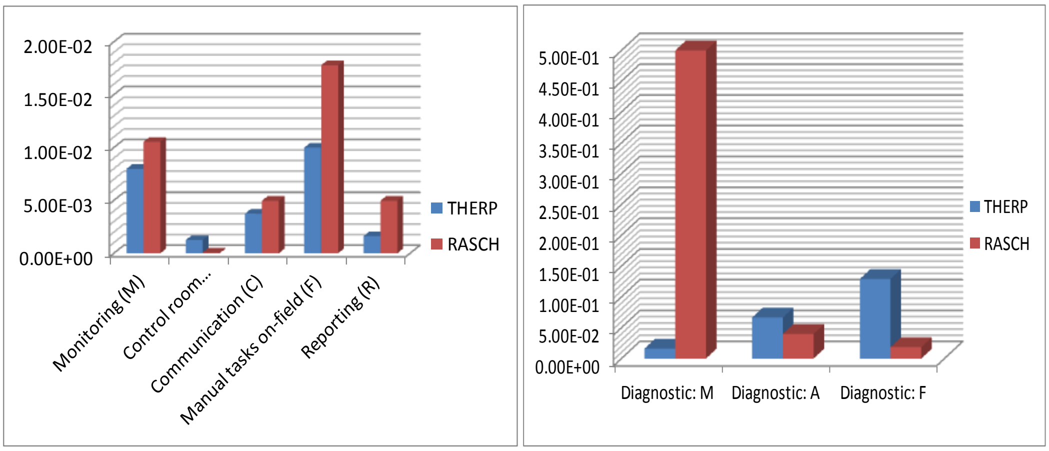

Figure 8. Comparison of predicted HEPs of Rasch model and THERP HEPs (operational & diagnostic layer)

4 New Methodology: Method for Error Deduction and Incident Analysis (MEDIA)

The Figure 9 illustrates the framework of new proposed method, method for error deduction and incident analysis (MEDIA). In MEDIA, all the organizational PSF can be rated on a likert scale by an analyst using the provided checklists by analysing the extent to which the considered attributes are embedded in a specific plant. An example of these checklists has been provided in Ahmad et al. (2015). The combined affect of PSF for an action type can be calculated by using eq. (4).

$$\mathrm{PSF}_{\mathrm{combined}} = \sum_{n=1}^{i=5} (\omega_n . r_n) \tag{4}$$

Whereas:

ω_n Weight of nth PSF, from (Table IV)

r_n Rating of nth PSF

The critical human interventions can be identified from process and instrumentation diagrams (P&IDs), HAZOP output and other relevant studies. A separate set of checklists has been developed for each of the human action types. The obtained nominal HEPs from the Rasch model have been changed to HEPs by using the SPAR-H method according to eq. (5) as mentioned in Gertman et al. (2005, p.56).

$$\mathrm{HEP} = \frac{\mathrm{NHEP} \cdot \mathrm{PSF}_{\mathrm{combined}}}{\mathrm{NHEP} \cdot (\mathrm{PSF}_{\mathrm{combined}} - 1) + 1} \tag{5}$$

The criticality of an action failure is considered by using the concept of safety layers. It has been observed that whenever failure of an action corresponds to a higher safety layer the consequences of failure are also severe, mainly due to possible absence of subsequent safety layers. For example, if monitoring of an alarm fails for an event and event has analysed to be credible during risk assessment, there should be subsequent safety layer (e.g. double alarms, SIFs etc). Assuming that subsequence layers will work (when required), these layers have potential to bring system back under safe conditions.

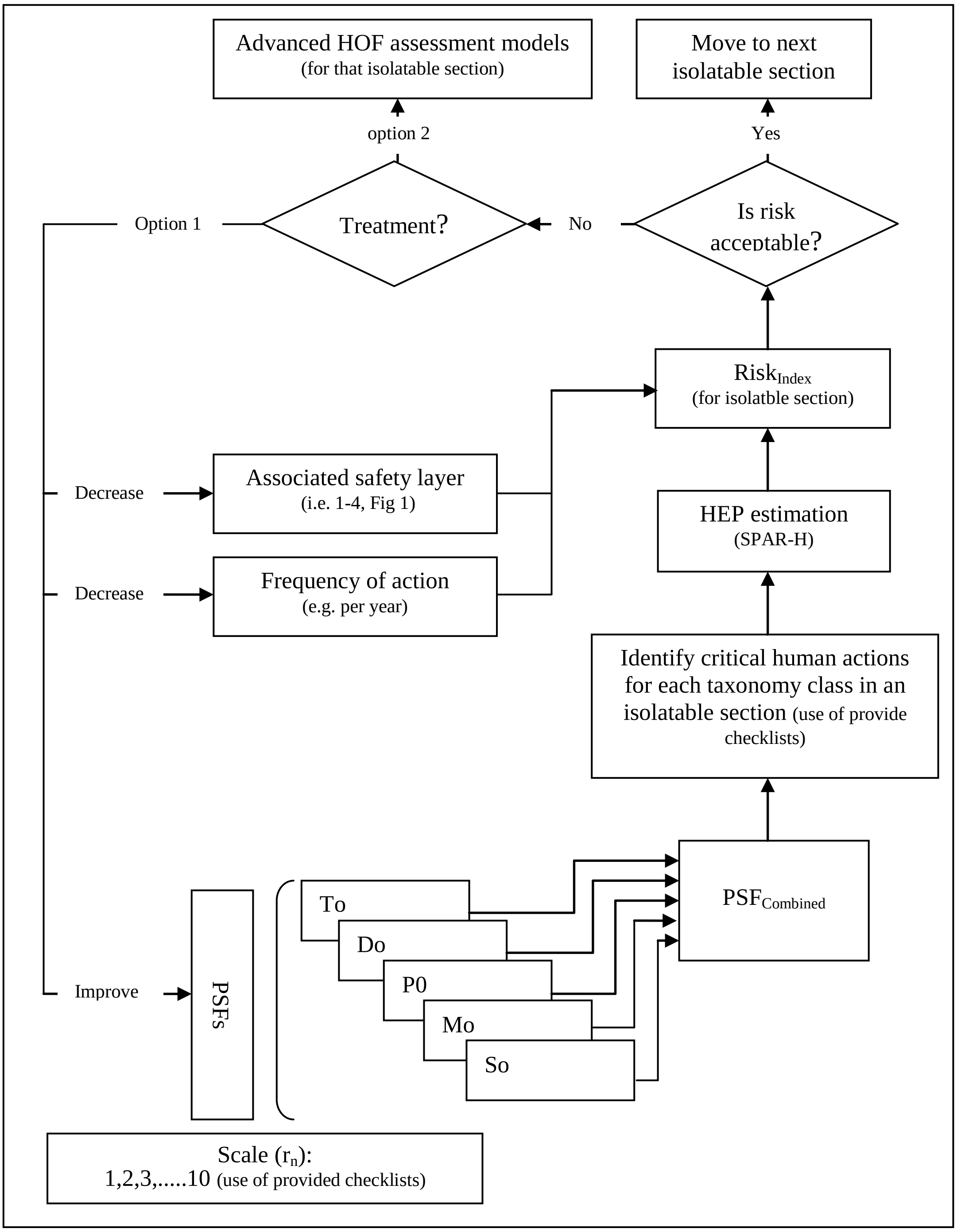

Figure 9. Framework of method for error deduction and incident analysis (MEDIA)

On the other hand, if a human failure occurs in a higher safety layers (e.g. maintenance of PSVs or proof testing of SISs) and not detected in-time. In this case, due to possible absence of subsequent layers, human failure can lead to much severe consequences.

Meanwhile, frequency of human interventions for a specific time period is also considered as shown in Figure 9. The obtained risk index for a specific isolable section can reduce by improving the PSF quality, by decreasing the frequency of operations or by decreasing the associated safety layer. The associated safety layer can also be decrease by providing an addition manual supervision. It has been observed that lack of supervision especially during contractor's operations was one of the main causes of accidents.

5 Discussion

The past accidents can provide the required data for quantification of human factors and to provide estimates of organizational influence on operations. However, estimates are based on certain assumptions. But, giving the fact of inadequacy of existing data and its validation to quantify the HOF especially in chemical process industry, this work can provide estimates of HOF quantification. These estimates can also be used in other calculation methods (e.g. FTA, etc).

The new proposed methodology (i.e. MEDIA) can provide an indication about the critical sections in a plant with respect to HOF, where more resources and times should be spend. Since checklists are based on past accident events, therefore considered attributes can provide more relevant aspects to be improved in order to improve the overall plant situation. However, MEDIA cannot account for the internal human PSF and time stress, therefore based on initial indication further analyse can be followed by using more advanced human reliability and cognitive methods. Alternatively, the checklists can also be used during the HAZID analysis according to the guidelines provided by ISO (2000). A case study of MEDIA is being carried out for a gas treatment plant. An immediate validation of HOF data is difficult to carry out through operational experience. However, the obtained HEPs are comparable with already existed HF data.

The future work can be focused to provide rating of organizational attributes by using key performance indicators (KPIs). The aspect of using KPIs is considered to be more practical than sheer ratings since most of the industries observe and maintain their KPIs database.

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