Analysis of Management Actions, Human Behavior, and Process Reliability in Chemical Plants

PART I: Impact of Management Actions

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ABSTRACT

While management and engineering actions have a significant impact on process reliability, these factors have received too little attention in calculating plant risks. In this work, the focus is on understanding and modeling the influence of human behavior patterns on plant safety in two settings. The first, introduced in Part I, involves a framework to estimate the impacts of management and engineering decisions, process operator performance, and processing equipment operations on the failure state of chemical plants. As examples, the impacts of poor training, maintenance problems, operator inabilities, control system failures, and excessive feed quantities, on failure states are studied. The management and engineering team and the operators are found to have significant impacts on process reliability. While the theoretical framework introduced herein is illustrated using hypothetical plant data, it should provide a basis for more quantitative safety analyses. Attempts to obtain operating data in industrial plants for validation of the framework were unsuccessful due to confidentiality and liability issues associated with industrial data.

Keywords: Management actions, process reliability, human behavior

INTRODUCTION

Various factors are involved in the design and operation of chemical plants, as shown in Figure 1. These factors can have conflicting objectives in their conceptualization, implementation, and functionality. While profitability remains the key objective for shareholders and management in selecting optimal designs, other objectives like controllability and flexibility have been gaining importance [1-3]. Recently, the safety objective has received increasing emphasis as a consequence of serious accidents and potential terrorist threats [4]. To improve safety performance and better identify the weak links in plant operations, methods for plant-wide, dynamic risk assessment have been developed [5].

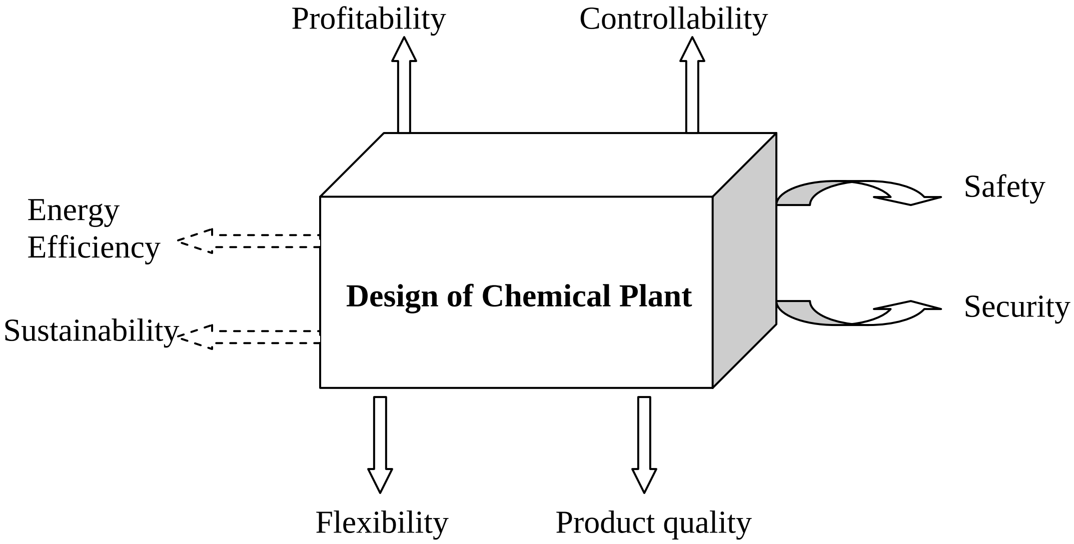


Figure 1: Design objectives for a chemical process

In the future, the contributions of other objectives such as energy efficiency, sustainability, and security, are expected to weigh more heavily when seeking optimal designs. Clearly, these issues complicate the multi-objective design optimization, with the resulting design dependent on the stakeholders and their biases. For example, the Department of Energy (DOE) would likely look for improved energy-efficiency in processes; the Department of Homeland Security (DHS), for processes that are easier to protect; and the shareholders and CEO, for designs with higher profitability. Given the difficulty in defining some of these objectives, their integration is even more complex – such as, when integrating the safety objective. The latter deserves a more quantitative accounting of the role of human behavior patterns, including those of managers and engineers, and process operators, as they interact with each other and the processing units in a chemical plant. These players often have different preferences, are influenced to different degrees by various factors, and consequently, may take different actions under similar circumstances.

The role of human behavior and decision-making in the design and operation of engineering systems, including those in the chemical, aviation, nuclear, health care, and construction industries, is crucial. Although the performance of the physical system, which has been the subject of several models and tools developed to date, directly impacts its potential failure, it is also important to recognize the role of human factors, management and engineering, and operator actions, which traditionally, have not been modeled quantitatively. This work focuses on human-human and human-hardware interactions and their impacts on the failure state.

The hierarchical structure of the operations in a business unit is designed to engage human interaction throughout. Managers, engineers, and process operators contribute to routine operations, occasionally resulting in adverse events in a plant, in spite of increasingly advanced technologies. Note that, at times, advanced technologies produce human-induced adverse events, especially when operators are not involved in tracking their performance step-by-step [6]. While quantitative analysis of these interactions is difficult, recent studies in the aviation and nuclear industries suggest the need for improved analyses in the chemical industry. In one study, human cognitive reliability models are introduced by Fang et al. [7] to obtain non-response probabilities for events as a function of the operator response time, regressed with Weibull and lognormal distributions. Note that such reliability methods have been applied more often in nuclear plants [8, 9].

Before new methods are introduced for the chemical industries, note that there have been significant *quantitative* analyses involving hardware reliability, but only *qualitative* analyses for human and management factors. Furthermore, relatively few human reliability assessments have been attempted in the chemical process industries (CPI), principally due to the difficulty in understanding human behavior [10]. One such attempt by Abu Khader [11] analyzed the impact of human behavior on process safety management in developing countries. However, a quantitative understanding of human behavior was difficult to obtain, as it is complicated by organizational factors and interaction levels within the working environment. In another study, a HORAAM (human and organizational reliability analysis in accident management) method was introduced to quantify human and organizational factors in accident management using decision trees [12]. Finally, Westfall Lake [13] discussed two strategies to prevent human error related to shift work in continuous chemical plants. These include: (i) the design of proper rest/work policies and guidelines at the management and engineering level to enhance 24-hour safety, and (ii) the adoption of appropriate measures at the operational level for preventing human errors.

To address the influence of management in process safety, Rosenthal et al. [14] discussed the role of process safety management systems (PSMSs) for prevention of low probability-high consequence (LP-HC) events. But they recognized that the lack of process-incident accident data often hinders the design of PSMSs that reduce LP-HC accidents. In one of the first promising attempts, Tuli and Apostolakis [15] extended root-cause analysis in industrial facilities from just human and/or hardware failures to include organizational factors. Several years later, Sorensen [16] used empirical evidence to emphasize that the safety culture, with its operational and management factors, influences operational safety more in chemical than in nuclear industries. Typical factors such as good organizational communications, good organizational learning, and the commitment of senior management to safety are identified, with the need to extend the list recognized.

In our work, new quantitative analyses are introduced in two areas of human decision-making in chemical plants. The first, discussed in Part I, involves the interactions of managers and engineers, with process operators, and with processing units, as they impact the failure state of the plant. Both direct and sequential interactions are studied. In the second, discussed in Part II, the conflicts and tradeoffs of management and engineering preferences with process operator preferences are modeled using game theory to select the complexity (scope, structure, depth of training, etc.) of a near-miss management system (NMMS) to be implemented. Given different favorable and unfavorable views, the benefits of selecting a NMMS that satisfies the preferences of both are emphasized. Note that, in both analyses, the management and engineering objectives are assumed to be similar, their actions being influenced by external and internal events in a like manner, and their interactions with, as well as impact on, operators occurring through similar mechanisms. Hence, they are represented by a lumped system variable that differs from the operators' variable.

These quantitative analyses are covered individually in Parts I and II, with conclusions presented at the end of each part.

IMPACT OF MANAGEMENT ACTIONS

The risk experienced by a system is defined as the probability of system failure multiplied by the extent of the impact (consequences) of each breakdown. While the failure probability is difficult to estimate alone, various factors add complications. For example, management actions play a critical role for many reasons, as shown in a model of the impact of management actions on system reliability developed by Murphy and Pate-Cornell [17] for the aviation industries. Adopting this nested model, a modified framework is introduced herein, shown schematically in Figure 2, for estimating the impacts of these factors on the failure probabilities of chemical plants. The inner-most oval represents the system failure state (FS). The surrounding ovals represent systems that influence the failure state, as well as influencing systems in adjacent internal ovals.

These are defined as the physical system (PS), which includes the processing equipment and safety systems; the operator system (OS), which includes the process operators; and the management and engineering system (MES), which involves the management and engineering team. Furthermore, the area of each oval qualitatively represents its impact on the failure state. As shown, while the MES and OS have been overlooked typically when estimating system failure probabilities, they contribute more than the PS to the system failure probability.

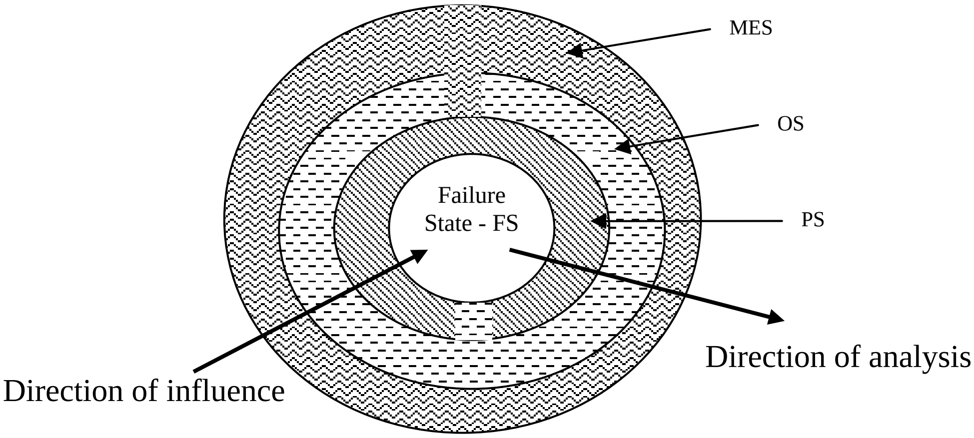


Figure 2: Hierarchical levels of system interactions in the operational stages

Figure 2 also shows that the direction of influence is from outside to inside ovals, and the direction of analysis, to be discussed, is from inside to outside ovals. The MES either directly impacts the OS or the PS. Furthermore, the OS either directly impacts the PS or the FS. Finally, the PS impacts just the FS.

Examples of the typical interactions, I, between the systems that lead to safety concerns are listed next:

(i) $I_{PS\text{-}FS}$: Interactions across the PS-FS interface include, but are not limited to, failure of the control systems, alarms, and valves.

(ii) $I_{OS\text{-}FS}$: Interactions across the OS-FS interface occur, for example, when an operator feeds excess reactants to the reactor or an operator forgets to open the cooling water valve. As a result of either case, the reactor temperature increases, possibly resulting in an explosion.

(iii) $I_{OS\text{-}PS}$: Interactions across the OS-PS interface occur, for example, when an operator fails to notice an abnormality, such as over-charge of a reactor due to being inattentive, not being informed (not paying attention to the operating instructions), or his/her inadequate skill level, possibly due to a lack of training.

(iv) $I_{MES\text{-}OS}$: Interactions across the MES-OS interface begin with the development of operating relationships and procedures, and are influenced by both management/ engineering and operator attitudes. Some of the causes for failure include poor training, long working hours, cutback of manpower, and lack of management leadership.

(v) $I_{MES\text{-}PS}$: Interactions across the MES-PS interface include the monitoring of maintenance capabilities, design problems, poor selection and management of contractors, and the type of NMMS.

Five types of scenarios that involve these interactions are considered leading to a possible system failure: (i) the MES affects the PS which then affects the FS (denoted as MES-PS-FS), (ii) the MES affects the OS which then affects the FS (denoted as MES-OS-FS), (iii) the OS affects the FS (denoted as OS-FS), (iv) the simultaneous occurrence of i and iii (denoted as MES-PS-FS$\cup$OS-FS), and (v) the MES affects the OS which affects the PS and eventually affects the FS (denoted as MES-OS-PS-FS).

To estimate the overall risk, attributes of the three systems, MES, OS, and PS, must be selected to characterize their states in potential accident scenarios. Note that two categories are defined for the PS, PS-E and PS-SS, to represent the equipment and safety systems. The following are typical attributes selected to demonstrate the analyses:

1. MES: ‘training’, ‘safety leadership’, and ‘incentive’ with values that characterize the management and engineering team views, for example, *less emphasized* and *more emphasized*. These give $8 = 2^3$ possible MES states.

2. OS: ‘experience’, ‘fatigue’, and ‘stress’ with values that characterize the operators, for example, *high* and *low*, giving eight possible OS states.

3. PS-E: ‘equipment quality’ and ‘equipment limitation’ with values, for example, *worn-out* or *new*, and *suitable* or *not suitable*, giving four possible PS-E states.

4. PS-SS: ‘control systems-alarms’ and ‘emergency relief systems’ (e.g., quench tanks) with values, for example, *advanced* or *bare minimum*, giving four possible PS-SS states.

Accident Probability Estimation

Given the potential scenarios, the systems involved, and their attributes, the probability of an accident is:

$$P(\text{Accident}) = \sum_q \sum_r \sum_s \sum_t P(q,r,s,t) P(\text{Accident} \mid q,r,s,t) \tag{1}$$

where $P(q, r, s, t)$ is the probability of a scenario involving states q (associated with the MES), r (associated with the OS), s (associated with the PS-E), and t (associated with the PS-SS). $P(\text{Accident}|q, r, s, t)$ is the conditional probability of an accident given a scenario involving states, q, r, s, and t, estimated using the execution model by Murphy and Pate-Cornell [17]:

$$P(\text{Accident} \mid q,r,s,t) = \int_{-\infty}^{\infty} f_{qrst}(z)\, p_{qrst}(z)\, dz \tag{2a}$$

$$f_{qrst}(z) = \left(\frac{2}{m^2}\right) z + \frac{2}{m} \tag{2b}$$

$$p_{qrst}(z) = k_1 e^{k_2 z} \tag{2c}$$

where f_{qrst} is the so-called *task-demand* distribution, m is proportional to the ease of operation, p_{qrst} is the so-called *ability* distribution, and k_1 and k_2 are parameters related to the ability of the operator. Here, k_1 represents the attributes having linear impact on the ability and k_2 represents those having exponential impact. For example, a shift in the value of a MES attribute is associated with k_2, while that of an OS attribute is associated with k_1.

A typical scenario is selected (so-called *base-case* scenario), for which values of m_b , $k_{1,b}$, and $k_{2,b}$ are assumed, as shown in Table 1. To obtain m, k_1, and k_2 for other scenarios, the multiplying factors (MF) associated with each of the states, q, r, s, and t, in Table 1 are also assumed. For a specific scenario, values of m, k_1, and k_2 are estimated by multiplying m_b , $k_{1,b}$, and $k_{2,b}$ by the appropriate multiplying factors. Note that the entries in Table 1 have been selected to provide a quantitative approximation of the ease of operation and the ability of the operators, given the actions of the management and engineering team. In an operating plant, these entries would be selected by persons responsible for risk analysis, who seek to represent the interactions of the management and engineering team with the operating team and the equipment and safety systems. To accomplish this, often surveys are conducted to monitor the safety culture of an operating plant. Readers should keep in mind that the values of the parameters in Table 1 are hypothetical. They need validation with industrial performance data.

Table 1 provides the coefficients for a total of 1,024 (8×8×4×4) possible scenarios, accounting for the MES, OS, PS-E, and PS-SS interactions and their attributes. To calculate the total accident probability, estimates are needed for the probability of each scenario and the conditional accident probability given the scenario. First, to estimate the probability of each scenario, the states of the MES, OS, PS-E, and PS-SS are assumed to be independent (a good first-order approximation). Consequently, the probabilities of the states are multiplied to estimate the probability of a scenario; that is, $p(q, r, s, t) = p(q)\times p(r)\times p(s)\times p(t)$, where typical state probabilities are tabulated in Table 1. Usually, these are assigned by people responsible for risk analysis at an operating plant. Note that these probabilities typically vary from company-to-company, and even plant-to-plant, depending upon management policies – with industry surveys assisting safety personnel in assigning these estimates.

Next, having computed values of m, k_1, and k_2 for each scenario, using Table 1 and Eqs. (2a)-(2c), the conditional accident probability of each scenario is estimated. Then, the total accident probability is computed using Eq. (1).

RESULTS

Having obtained the total accident probability, P(Accident), the impacts of different groups of scenarios on the overall accident probability are estimated. First, scenarios having the worst-case states of the MES, OS, PS-E, and PS-SS are identified. These are $q = 8$ ($\mathrm{T_{LE}}$, $\mathrm{I_{LE}}$, $\mathrm{S_{LE}}$), $r = 8$ ($\mathrm{E_L}$, $\mathrm{F_H}$, $\mathrm{S_H}$), $s = 4$ ($\mathrm{EQ_W}$, $\mathrm{EL_{NSU}}$), and $t = 4$ ($\mathrm{CS\text{-}A_{BM}}$, $\mathrm{ERS_{BM}}$), where, for example, $\mathrm{T_{LE}}$ is the *less emphasized* ‘training’ attribute, $\mathrm{F_H}$ is the *high* ‘fatigue’ attribute, and $\mathrm{CS\text{-}A_{BM}}$ is the *bare minimum* ‘control systems-alarms’ attribute, as defined in Table 1. Note that, as expected, a system is in its worst-case state when all of its attributes are in the worst case. Then, the probabilities of scenarios having one or more of the worst-case states for the MES, OS, PS-E, and PS-SS are summed and divided by the total accident probability to give 39.16%, an estimate of their impact. That is, for the scenarios selected above and the coefficients in Table 1, when an accident takes place, at least one worst case state is predicted to be involved in 39.16% of the scenarios.

Next, the probabilities of scenarios having just one of the worst-case states, from among the MES, OS, PS-E, and PS-SS, are summed and divided by the total accident probability. The impact of scenarios having the: (1) $q = 8$ state of the MES is 26.9%, (2) $r = 8$ state of the OS is 25.2%, (3) $s = 4$ state of the PS-E is 16.5%, and (4) $t = 4$ state of the PS-SS is 19.2%. Clearly, worst-case behavior patterns for the MES and OS have higher impacts than those of the PS-E and PS-SS. However, their impacts are less than the combined impact of the PS-E and PS-SS.

In summary, based upon the data in Table 1, as expected, the MES and OS roles in the safety and reliability of chemical plants are significant. The data can be adjusted to place more or less emphasis on their roles, which often have not been emphasized adequately in safety analyses. Furthermore, identification of the key factors that contribute to the risk should lead to improved risk management strategies. Note that while scenarios with multiple worst-case states have low probabilities, their conditional accident probabilities are high, giving high contributions to the overall accident probability, typical of low probability-high consequence (LP-HC) events.

Having estimated the impacts of scenarios with multiple worst-case states, the impacts of each attribute of the MES, OS, PS-E, and PS-SS on the overall accident probability are computed. Initially, impacts are estimated for scenarios having less desirable values of their attributes. For the ‘training’ attribute of the MES, with *less emphasized* (LE) values, these include scenarios, q = 5, 6, 7, and 8; for the ‘safety leadership’ attribute, scenarios q = 2, 4, 6, and 8; and for the ‘incentive’ attribute, q = 3, 4, 7, and 8. Then, the impacts of the attributes having LE values are computed:

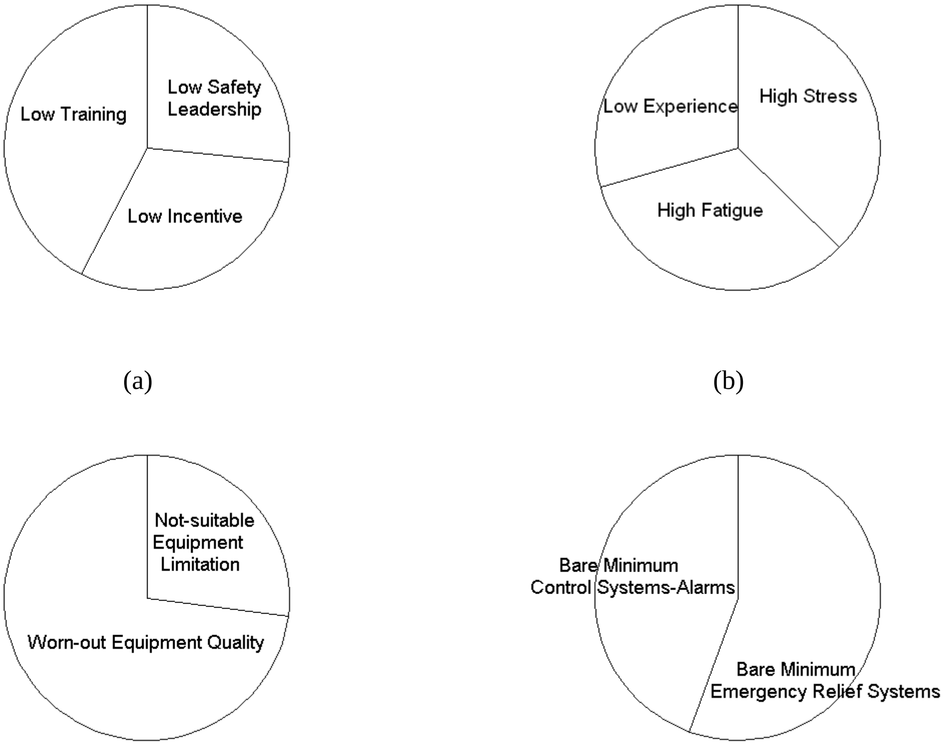
$$\text{Impact}_{\text{T}_{\text{LE}}} = \frac{P(\text{Accident})_{\text{T}_{\text{LE}}}}{P(\text{Accident})_{\text{T}_{\text{LE}}} + P(\text{Accident})_{\text{S}_{\text{LE}}} + P(\text{Accident})_{\text{I}_{\text{LE}}}} \tag{3a}$$

$$\text{Impact}_{\text{S}_{\text{LE}}} = \frac{P(\text{Accident})_{\text{S}_{\text{LE}}}}{P(\text{Accident})_{\text{T}_{\text{LE}}} + P(\text{Accident})_{\text{S}_{\text{LE}}} + P(\text{Accident})_{\text{I}_{\text{LE}}}} \tag{3b}$$

$$\text{Impact}_{\text{I}_{\text{LE}}} = \frac{P(\text{Accident})_{\text{I}_{\text{LE}}}}{P(\text{Accident})_{\text{T}_{\text{LE}}} + P(\text{Accident})_{\text{S}_{\text{LE}}} + P(\text{Accident})_{\text{I}_{\text{LE}}}} \tag{3c}$$

Finally, the relative impacts are displayed in pie charts, as shown in Figure 3a. Here, the impact of less management and engineering orientation toward operator training is greater than that toward plant safety and provision of incentives for the operators.

Similar calculations are carried out for the attributes of the OS, PS-E and PS-SS. For the OS, the impacts of *low* ‘experience’, *high* ‘fatigue’, and *high* ‘stress’ are shown in Figure 3b; for the PS-E, those of *worn-out* ‘equipment quality’ and *not-suitable* ‘equipment limitation’ in Figure 3c; and, for the PS-SS, those of *bare minimum* ‘control system-alarms’ and *bare minimum* ‘emergency relief systems’ in Figure 3d. For the OS, *low* ‘experience’, *high* ‘fatigue’, and *high* ‘stress’ have similar impacts. For the PS-E, the impact of *worn-out* ‘equipment quality’ far exceeds that of *not-suitable* ‘equipment limitation'. Finally, for the PS-SS, the impact of the *bare minimum* 'emergency relief system' is slightly higher than that for the *bare minimum* 'control systems-alarms'.



(a) (b) (c) (d)

Figure 3: Relative impact of attributes: (a) MES, (b) OS, (c) PS-E, and (d) PS-SS

Note that these estimates often vary from company-to-company and plant-to-plant, often due principally to the policies and decisions of the management and engineering team. Also, the scope of the plant has an impact, with high-volume, sophisticated, continuous processes differing significantly from multi-purpose batch operations. This quantitative analysis helps to identify the attributes that most influence the reliability of the systems. Furthermore, it highlights loop holes and those systems that can most improve the safety performance of an organization. As the analysis proceeds, more detailed attributes can help to improve its resolution. Although the attributes selected for the MES, OS, PS-E, and PS-SS herein are believed to be satisfactory for a preliminary analysis, a more complete list of attributes could be desirable. However, as attributes are added, care must be taken to avoid diminishing returns.

CONCLUSIONS

A quantitative model of human behavior in the chemical process industries has been presented. It has been applied to a reasonable, but limited number of scenarios, yielding several conclusions. The following are some of the conclusions, comments on the methodology, and recommendations for future studies:

1. The management and engineering team and the operators have significant impacts on the process reliability: 26.9% and 25.2% of worst-case states are affected by MES and OS actions (or the lack thereof), respectively.
2. The relative impacts of the attributes of the management and engineering team, the operators, and the physical system on the overall accident probability have been estimated.
3. Both sensitivity analysis and validation of these models are essential.
4. The results are obtained for a set of conditions assumed for a hypothetical company. They may differ for other conditions and companies based on their safety cultures and practices.

NOMENCLATURE

Acronyms

A	Advanced

BM	Bare minimum
CEO	Chief executive officer
CPI	Chemical process industries
DHS	Department of Homeland Security
DOE	Department of Energy
FS	Failure state
H	High
HORAAM	Human and organizational reliability analysis in accident management
$I_{MES\text{-}OS}$	Interactions across the MES-OS interface
$I_{MES\text{-}PS}$	Interactions across the MES-PS interface
$I_{OS\text{-}FS}$	Interactions across the OS-FS interface
$I_{OS\text{-}PS}$	Interactions across the OS-PS interface
$I_{PS\text{-}FS}$	Interactions across the PS-FS interface
L	Low
LE	Less emphasized
LP-HC	Low probability high consequence
MES	Management and engineering system
MF	Multiplying factors
ME	More emphasized
N	New
NMMS	Near-miss management system
NSU	Not suitable

OS	Operator system
PS	Physical system
PS-E	Physical system equipment
PSMS	Process safety management systems
PS-SS	Physical system safety system
SU	Suitable
W	Worn-out

Notation

CS-A_{A}	having advanced ‘control systems and alarms’
CS-A_{BM}	having bare minimum ‘control systems and alarms’
E_{H}	operator having high ‘experience’
E_{L}	operator having low ‘experience’
EL_{SU}	physical system having suitable ‘equipment limitation’
EL_{NSU}	physical system having non-suitable ‘equipment limitation’
EQ_{N}	physical system having new ‘equipment quality’
EQ_{W}	physical system having worn-out ‘equipment quality’
ERS_{A}	having advanced ‘emergency relief system’
ERS_{BM}	having bare minimum ‘emergency relief system’
f_{qrst}	*task-demand* distribution
F_{H}	operator having high ‘fatigue’
F_{L}	operator having low ‘fatigue’
I_{LE}	management and engineering team having less emphasis towards ‘incentive’

I_{ME}	management and engineering team having more emphasis towards ‘incentive’
$\mathrm{Impact}_{\mathrm{I}_{\mathrm{LE}}}$	impact of low orientation towards ‘incentive’
$\mathrm{Impact}_{\mathrm{S}_{\mathrm{LE}}}$	impact of low orientation towards ‘safety’
$\mathrm{Impact}_{\mathrm{T}_{\mathrm{LE}}}$	impact of low orientation towards ‘training’
k_1 and k_2	parameters of ability distribution, Eq. (2c)
$k_{1,\mathrm{b}}$ and $k_{2,\mathrm{b}}$	base-case scenario values for parameters of ability distribution
m	parameter of task demand distribution, Eq. (2b)
m_{b}	base-case scenario value of m
p_{qrst}	*ability* distribution
$P(\mathrm{Accident})$	probability of accident
$P(\mathrm{Accident}\mid q, r, s, t)$	conditional probability of an accident given a scenario involving states q, r, s, t
$P(\mathrm{Accident})_{\mathrm{I}_{\mathrm{LE}}}$	probability of accident due to low orientation towards ‘incentive’
$P(\mathrm{Accident})_{\mathrm{S}_{\mathrm{LE}}}$	probability of accident due to low orientation towards ‘safety’
$P(\mathrm{Accident})_{\mathrm{T}_{\mathrm{LE}}}$	probability of accident due to low orientation towards ‘training’
$P(q)$	probability of having state q for MES
$P(r)$	probability of having state r for MES
$P(s)$	probability of having state s for MES
$P(t)$	probability of having state t for MES
$P(q, r, s, t)$	probability of a scenario involving states q, r, s, t
S_{H}	operator having high ‘stress’

S_{L}	operator having low ‘stress’
S_{LE}	low emphasis of management and engineering team towards ‘safety leadership’
S_{ME}	more emphasis of management and engineering team towards ‘safety leadership’
T_{LE}	low emphasis of management and engineering team towards ‘training’
T_{ME}	more emphasis of management and engineering team towards ‘training’
z	variable used in estimating the probability of accident using *task-demand* and *ability* distributions

Counter

q	counter for states of MES
r	counter for states of OS
s	counter for states of PS-E
t	counter for states of PS-SS

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Table 1: Accident probability estimation data: (i) Multiplying factors (MF) of m, k_1, k_2 for attributes of MES, OS, PS-E, PS-SS, (ii) scenario probabilities for the states of MES, OS, PS-E, PS-SS

Category type	States	MF-m	MF-k_1	MF-k_2	Probability
MES $q = 1$	‘Training’ (T_{ME}), ‘Safety leadership’ (S_{ME}), ‘Incentive’ (I_{ME})	×1	×1	×1	$\boldsymbol{p(q)}$ 0.2
$q = 2$	T_{ME}, S_{LE}, I_{ME}	×1	×1	×4	0.1
$q = 3$	T_{ME}, S_{ME}, I_{LE}	×1	×2	×1	0.1
$q = 4$	T_{ME}, S_{LE}, I_{LE}	×1	×2	×4	0.1
$q = 5$	T_{LE}, S_{ME}, I_{ME}	×1	×4	×1	0.2
$q = 6$	T_{LE}, S_{LE}, I_{ME}	×1	×4	×4	0.1
$q = 7$	T_{LE}, S_{ME}, I_{LE}	×1	×8	×1	0.1
$q = 8$	T_{LE}, S_{LE}, I_{LE}	×1	×8	×4	0.1
OS $r = 1$	‘Experience’ (E_H), ‘Fatigue’ (F_L), ‘Stress’(S_L)	×1	×1	×1	$\boldsymbol{p(r)}$ 0.2
$r = 2$	E_H, F_L, S_H	×1	×3	×1	0.1
$r = 3$	E_H, F_H, S_L	×1	×2	×1	0.1
$r = 4$	E_H, F_H, S_H	×1	×6	×1	0.1
$r = 5$	E_L, F_L, S_L	×1	×1	×2	0.2
$r = 6$	E_L, F_L, S_H	×1	×3	×2	0.1
$r = 7$	E_L, F_H, S_L	×1	×2	×2	0.1
$r = 8$	E_L, F_H, S_H	×1	×6	×2	0.1
PS-E $s = 1$	‘Equipment quality’ (EQ_N), ‘Equipment limitation’ (EL_{SU})	×1	×1	×1	$\boldsymbol{p(s)}$ 0.4
$s = 2$	EQ_N, EL_{NSU}	×1	×1	×2	0.1
$s = 3$	EQ_W, EL_{SU}	×1	×2	×1	0.4
$s = 4$	EQ_W, EL_{NSU}	×1	×2	×2	0.1
PS-SS $t = 1$	‘Control syst.-alarms’ (CS-A_A), ‘Emergency relief sys.’ (ERS_A)	×1	×1	×1	$\boldsymbol{p(t)}$ 0.4
$t = 2$	CS-A_A, ERS_{BM}	×2	×1	×3	0.3
$t = 3$	CS-A_{BM}, ERS_A	×3	×1	×2	0.2
$t = 4$	CS-A_{BM}, ERS_{BM}	×4	×1	×6	0.1
	Base-case scenario values	$m_b = 1.0$	$k_{1,b} = 0.0001$	$k_{2,b} = 0.01$	
ME (More emphasized), LO (Less emphasized); H (High), L (Low); N (New), W (Worn-out), SU (Suitable), NSU (Not suitable); A (Advanced), BM (Bare minimum)					