Analysis of Management Actions, Human Behavior, and Process Reliability in Chemical Plants. II. Near-Miss Management System Selection

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To understand the behavior patterns of managers, engineers, and operators, in Part II, a game-theoretic decision model is developed for a specific plant to balance the advantages and disadvantages of having a Near-miss Management System (NMMS) with different sophistication levels. Assuming that management and engineering preferences differ from those of the process operators, the tradeoffs between them are balanced. As anticipated, it is shown that the choices of the management and engineering team, and the operators, for the selection of a NMMS, are sensitive to the contributing factors. This article introduces a theoretical approach, illustrated using hypothetical data, which should be effective in industrial operations. Attempts to obtain data for validation of the framework were unsuccessful because of confidentiality and liability issues associated with industrial data. © 2007 American Institute of Chemical Engineers Process Saf Prog 27: 139–144, 2008

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INTRODUCTION

As discussed in Part I, a more quantitative accounting of the role of human behavior patterns, including those of managers and engineers, and process operators, is desired 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. Part I examines the interactions of managers and engineers, with process operators and with processing units, as they impact the failure state of a plant.

In Part II, the conflicts and tradeoffs of management and engineering preferences, as related to 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. As in Part I, it is assumed that management and engineering objectives are similar, with their actions influenced by external and internal events in a similar manner, that is, with their interactions and impact on process operators occurring through similar mechanisms. Hence, the managers and engineers are lumped together in the analyses herein.

The next sections present quantitative analyses of the selection process for NMMSs followed by conclusions.

NEAR-MISS MANAGEMENT SYSTEM SELECTION

In the process industries, a near-miss is defined as an opportunity to improve reliability, safety, security, health, and the environment of an operation based on an abnormal event having the potential for a more serious consequence [1]. Every year, the importance of near-misses is gaining recognition in new disciplines; thus far, in the chemical and petrochemical, mining, nuclear, transportation (including, aviation, railways, and marine), healthcare (including pharmacy operations, and nurses), financial, information technology (IT), and construction industries [2–5]. In addition, near-misses are gaining significant interest in the telecommunications, consumer electronics, forest products, offshore platform, and steel industries [6,7]. Although definitions vary across the disciplines, the main idea is to improve the reliability and reduce the risk for a specific industry/operation through the analysis of observed near-misses.

Near-Miss Management System

When focusing on the chemical industries, the Near-miss Management Project of the Wharton Risk Management and Decision Processes Center has shown that, by identifying, analyzing, and dealing with near-misses, adverse catastrophic events in chemical plants are significantly reduced [1]. Note that near-misses include process-related disturbances, spills, property damages, injuries to employees, and business interruptions, as well as natural disasters, and terrorist events, which occur less frequently. To better identify, analyze, and deal with near-misses, a near-miss management system (NMMS), consisting of seven stages, was developed to help companies evaluate their performance and extract the most benefit from them. These seven stages involve: (i) identification, (ii) reporting, (iii) prioritization and distribution, (iv) causal analysis, (v) solution identification, (vi) dissemination, and (vii) resolution. Recently, stage (iii) was separated into separate prioritization and distribution stages by Muermann and Oktem [3], yielding an eight step process, which proceeds as follows:

1. *Identification*: A near-miss is recognized to have occurred.
2. *Disclosure*: An individual or group reports the identified information/near-miss.
3. *Prioritization and classification*: The near-miss is prioritized and classified depending on its importance for future actions to be taken.
4. *Distribution*: Information pertaining to the near-miss is transferred to those who will act on the follow-up action.
5. *Casual Analysis*: The causal and underlying factors behind a near-miss, which potentially can lead to an accident in the future, are identified.
6. *Solution Identification*: Solutions to mitigate the accident likelihood or limit the impact of a potential accident are identified and corrective actions are determined.
7. *Dissemination*: Both the near-miss and its follow-up corrective actions are relayed to relevant parties. Information is broadcast to a wider audience to increase awareness.
8. *Resolution*: Corrective actions are implemented and evaluated. Also, the results are communicated to the reporter as part of the follow-up action.

NMMSs can be complete and extensive systems that can improve the reliability and safety of chemical companies, as well as benefit companies in other areas, as mentioned earlier. However, the decision to invest resources in a NMMS depends on the safety culture within a company. In this respect, a NMMS can be regarded as either a costly investment with minimum benefits or a fruitful investment with high safety returns. Its perception by a safety engineer and its proper presentation to higher management are closely related to the level of investment in a NMMS. In practice, companies decide to implement none/few/all of the eight stages depending on their views regarding the costs and benefits of having a NMMS. Here, the process of evaluating the number of steps to be implemented in a NMMS is crucial to its success.

In this study, four different types of NMMSs are considered for implementation. These are classified as: (1) *basic*, $NMMS_1$, (2) *intermediate I*, $NMMS_2$, (3) *intermediate II*, $NMMS_3$, and (4) *advanced*, $NMMS_4$. $NMMS_1$ consists of stages (i)–(ii); $NMMS_2$, stages (i)–(v); $NMMS_3$, stages (i)–(vi); and $NMMS_4$, stages (i)–(viii). It is important to realize that managers and engineers, and operators play significant roles in selecting the type of NMMS, with preferences and choices that often differ. Consequently, herein, the management and engineering system (MES) and the operator system (OS) are considered as the two major parties in the decision-making process, with each evaluating its costs and benefits associated with each type of NMMS. Note that each system evaluates its own objectives, which are lumped together in its own objective function.

This study introduces a game-theoretic approach to select the best NMMS as a solution to this multiobjective optimization problem. A two-player game is formulated, involving the MES and OS as players, which accounts for the tradeoffs and the preferences of each player toward the four types of NMMS. While applied herein to the chemical industries, the results of this study are not so limited. They can be applied to almost all situations in which near-miss scenarios can be formulated. Near-misses are defined somewhat differently across the disciplines, but the steps in a NMMS are generally the same. Hence, extensions of the game-theoretic approach can be easily developed involving different players and objective functions.

Game Formulation

Game theory [8–10] is a branch of mathematical analysis used to study decision-making in conflicting situations. It involves the prediction of the outcomes for a group of interacting players, where the action of a single player directly affects the payoffs of the other players. The elements of a game are: (i) several players, (ii) actions/strategies, and (iii) payoffs (objective

Table 1. Game matrix for the selection process of a NMMS tabulating the players, strategies, and payoffs.

		OS			
	NMMS Type	$NMMS_1$	$NMMS_2$	$NMMS_3$	$NMMS_4$
MES	$NMMS_1$	$(VMES_{1,1}, VOS_{1,1})$	$(VMES_{1,2}, VOS_{2,1})$	$(VMES_{1,3}, VOS_{3,1})$	$(VMES_{1,4}, VOS_{4,1})$
	$NMMS_2$	$(VMES_{2,1}, VOS_{1,2})$	$(VMES_{2,2}, VOS_{2,2})$	$(VMES_{2,3}, VOS_{3,2})$	$(VMES_{2,4}, VOS_{4,2})$
	$NMMS_3$	$(VMES_{3,1}, VOS_{1,3})$	$(VMES_{3,2}, VOS_{2,3})$	$(VMES_{3,3}, VOS_{3,3})$	$(VMES_{3,4}, VOS_{4,3})$
	$NMMS_4$	$(VMES_{4,1}, VOS_{1,4})$	$(VMES_{3,2}, VOS_{2,4})$	$(VMES_{4,3}, VOS_{3,4})$	$(VMES_{4,4}, VOS_{4,4})$

functions). In the NMMS selection process, the elements are as follows:

- *Players*: (1) the management and engineering system (MES), and (2) the operator system (OS),
- *Actions/Strategies*: assigned to each player involving selection from amongst $NMMS_1$-$NMMS_4$, and
- *Payoff consequences*: quantitative index measures (objective functions) – one formulated for each player.

The payoff/objective function of the MES, $VMES_{i,j}$, for a particular NMMS is a function of the cost of the system, $Cost_{i,j}$; the incentives provided by insurance companies because of its implementation, $InsuIncent_{i,j}$; and the potential safety enhancement to the company because of the increased involvement of its employees in safety, $SafetyE_{i,j}$:

$$VMES_{i,j} = f(Cost_{i,j}, InsuIncent_{i,j}, SafetyE_{i,j}) \quad (1a)$$

where the counters i and j refer to the choice of $NMMS_i$ by the MES and $NMMS_j$ by the OS. f defines the functionality between the objective function value, $VMES_{i,j}$, and $Cost_{i,j}$, $InsuIncent_{i,j}$, and $SafetyE_{i,j}$.

Similarly, the payoff/objective function of the OS, $VOS_{j,i}$, for a particular NMMS is a function of the incentive given to the operator for using the system, $Incent_{j,i}$; the extra workload for performing the tasks required, $ExWork_{j,i}$; and his/her attitude toward the safety of the plant, $Attitude_{j,i}$:

$$VOS_{j,i} = g(Incent_{j,i}, ExWork_{j,i}, Attitude_{j,i}) \quad (1b)$$

where g defines the functionality between objective function value, $VOS_{j,i}$, and $Incent_{j,i}$, $ExWork_{j,i}$, and $Attitude_{j,i}$. Note that the three factors included in the two functionalities are selected as the most significant from a long list of factors that influence the objective functions. Consequently, it is important to confirm that these functionalities are an effective basis for the decision-making process. Furthermore, while the MES and OS are the key decision makers, their decisions are influenced by stakeholders that are less involved, for example, the insurance providers, the third-party NMMS providers, and the government safety organizations. Hence, when these stakeholders play significant roles (but not sufficiently active to be players in the NMMS selection game), the objectives can be adjusted to account for their influences. Furthermore, they should be involved in validating the payoffs and other aspects of the decision-making process.

The goal of the game is to find the best action/strategy, that is, best NMMS selected by the MES and OS players as defined in the next paragraph. The complete game matrix in Table1, which is used to obtain the optimal solution, is shown in terms of the players, their actions/strategies, and their objectives. Thus, the problem of obtaining the best NMMS is formulated as a *two-player*, *normal-form* (using the table-form rather than the tree-form), *simultaneous-move* (all players move at the same time rather than sequentially, with each player observing the actions/strategies of the other players before making a move), and *noncooperative* (each player tries to optimize their objective function [payoff], ignoring the objective functions of the other players) game.

There are several techniques to implement game theory [8–10], that is, to find the *equilibrium* of a game (the best NMMS). These are: (1) *equilibrium in dominant actions*, (2) *pure strategy Nash equilibrium*, and (3) *mixed-strategy Nash equilibrium*. For example, when each player has a dominant strategy, with its payoffs maximized regardless of the actions/strategies of the other players, the optimal solution is obtained using the *equilibrium in dominant actions* technique. When two or more entries in the table are equally preferred (i.e., where not all players have a dominant strategy), *pure strategy Nash equilibrium* is used. Finally, when *equilibrium in dominant actions* and *pure strategy Nash equilibrium* are insufficient, *mixed strategy Nash equilibrium* is used, with probabilities assigned to each entry. GAMBIT [11], software for game theory, is used herein to obtain the optimal solution.

RESULTS: IMPACT OF STAKEHOLDERS ON NMMS DECISION

In this section, simple linear formulations of the *VMES* and *VOS* objective functions are proposed. Clearly, these formulations need to be validated, especially as they influence the optimal selections of the NMMS.

Let $VMESb_i$ and $VOSb_j$ be the *basic* payoffs for the MES and OS; that is, the payoffs when a change in the action/strategy of a player does not affect the payoffs of the other player. For example, when the MES selects $NMMS_i$, its payoff remains the same regardless of the OS selection; that is, $VMES_{i,j}$ remains unchanged as j changes. Herein, the $VMESb_i$ and $VOSb_j$ are formulated:

$$VMESb_i = \bar{a}_i x + \bar{b}_i x + \bar{c}_i x \quad (2a)$$

$$VOSb_j = a_j y + b_j y + c_j y \quad (2b)$$

Table 2. Values of parameters to estimate the payoffs/objective functions for MES and OS.

$\bar{a}_i$, $i = 1,\ldots,4$	$\bar{b}_i$, $i = 1,\ldots,4$	$\bar{c}_i$, $i = 1,\ldots,4$	a_j, $j = 1,\ldots,4$	b_j, $j = 1,\ldots,4$	c_j, $j = 1,\ldots,4$	
−0.0	0.0	0.0	0.0	−0.0	0.5	$x = 1.0$
−2.0	0.1	3.0	1.0	−0.1	1.5	$y = 0.5$
−3.0	0.15	6.0	2.0	−0.2	2.5	$Sen_{\mathrm{MES}} = 0.1$
−4.0	0.25	12.0	4.0	−0.3	3.5	$Sen_{\mathrm{OS}} = 0.2$

Table 3. Game matrix for the selection process of a NMMS in case of Framework 1.

		OS			
	NMMS Type	NMMS_1	NMMS_2	NMMS_3	NMMS_4
MES	NMMS_1	−0.95, 0.15	−0.52, 1.1	0.29, 2.05	1.88, 3.5
	NMMS_2	1.15, 0.47	1.58, 1.42	2.39, 2.37	3.98, 3.82
	NMMS_3	3.2, 1.195	3.63, 2.145	4.44, 3.095	6.03, 4.545
	NMMS_4	8.3, 3.55	8.73, 4.5	9.54, 5.45	11.13, 6.9

where x is the parameter to estimate the payoff of the MES and $\bar{a}_i x$, $\bar{b}_i x$, and $\bar{c}_i x$ are the contributions of the cost, insurance incentive, and safety enhancement factors, respectively. Hence, $\bar{a}_i, \bar{b}_i$, and $\bar{c}_i$ are fractional contribution coefficients. Similarly, y is the parameter to estimate the payoff of OS and $a_j y, b_j y$, and $c_j y$ are the contributions of the incentive, extra workload, and attitude factors, respectively, with a_j, b_j, and c_j, the fractional contribution coefficients.

To account for the interactions, the $VMES_{i,j}$, and $VOS_{j,i}$, are formulated:

$$VMES_{i,j} = VMESb_i + Sen_{\mathrm{os}} \times j \times VOSb_j \qquad (3a)$$

$$VOS_{i,j} = VOSb_i + Sen_{\mathrm{MES}} \times i \times VMESb_i \qquad (3b)$$

where Sen_{OS} and Sen_{MES} are the sensitivity factors that account for the actions of the OS on the payoff of the MES, x, and the actions of the MES on the payoff of the OS, y, respectively. The values of $\bar{a}_i$, $\bar{b}_i$, $\bar{c}_i$ a_j, b_j, c_j, x, y, Sen_{MES}, and Sen_{OS} have been estimated to account for their relative importance, as shown in Table2. Note that all of the coefficients increase in magnitude with the sophistication of the NMMS. Also, the $\bar{a}_i$ and b_j are negative, as $VMES_{i,j}$ decrease with cost and $VOS_{j,i}$ decrease with extra work. Finally, the value of x is twice that of y assuming that the MES has twice the basic implementation/decision power than the OS, Sen_{OS} is twice that of Sen_{MES} indicating that the OS actions have twice the influence power on the MES payoffs, and the sensitivities are assumed on the order of 10–20% of the base objective function values.

Having defined the formulations of the objective functions for the MES and OS, the optimal NMMS selections for the MES and OS are determined under various frameworks. These frameworks are obtained by focusing on various aspects of the contributing factors. Next, results of the game are discussed for the various frameworks.

Framework 1

The complete Game matrix obtained using Eqs. 3a–3b and parameters in Table 2 is shown in Table 3. To obtain the optimal solution using game theory, dominant actions, if any, for each player are identified first. For the player MES, the *VMES* in the four rows, for NMMS_1-NMMS_4, are compared in Table 3. Clearly, the best *VMES* is in NMMS_4 regardless of the actions of the OS; thus, NMMS_4 is the dominant action for the MES. Similarly, for the player OS, *VOS* is compared for the four actions, NMMS_1-NMMS_4 (in the four columns). Clearly, the best *VOS* are in NMMS_4 regardless of the actions of the MES; thus, NMMS_4 is the dominant action for the OS. From the analysis, the components of the equilibrium in dominant actions solution are (NMMS_4, NMMS_4).

Note that in this framework, the contributions of the safety enhancement factors in the long-term heavily weigh the MES payoffs. Consequently, both the management and engineering team and the operators prefer a highly sophisticated NMMS, that is, NMMS_4. Clearly, the preferences of the MES and OS may differ as the contributing factors in their objective functions change. In the subsequent frameworks, the impact of the contributing factors on the selection process is examined.

Framework 2

In this framework, the contributions of the safety enhancement factors in the long-term are not taken into consideration by the MES; that is, $\bar{c}_i = 0$. Consequently, the objectives/payoffs of the MES are functions of the NMMS cost and the insurance incentives

Table 4. Game matrix for the selection process of a NMMS in case of Framework 2.

	NMMS Type	OS			
		$NMMS_1$	$NMMS_2$	$NMMS_3$	$NMMS_4$
MES	$NMMS_1$	−0.95, 0.15	−0.52, 1.1	0.29, 2.05	1.88, 3.5
	$NMMS_2$	−1.85, −0.13	−1.42, 0.82	−0.61, 1.77	0.98, 3.22
	$NMMS_3$	−2.8, −0.605	−2.37, 0.345	−1.56, 1.295	0.03, 2.745
	$NMMS_4$	−3.7, 3.55	−3.27, 4.5	−2.46, 0.65	−0.87, 2.1

only, and not the safety enhancement factors. Table4 shows the game matrix for this framework in which the dominant action for the MES is $NMMS_1$, regardless of the OS actions. Similarly, the dominant action of the OS is $NMMS_4$, regardless of the MES actions. Thus, the optimal solution, ($NMMS_1$, $NMMS_4$), is obtained using *equilibrium in dominant actions*. Clearly, because the management and engineering team is insensitive to the value of safety enhancement, it is overly influenced by the high costs and sees little advantage through relatively small insurance incentives. To the contrary, the operators assign high values to their safety, low penalties to their extra workload, and their attitudes increase significantly. Consequently, they prefer a highly sophisticated NMMS.

Framework 3

This framework focuses on the workload and operator incentives as well as the insurance company incentives. In this case, the a_j coefficients increase, but level off with NMMS complexity. Similarly, the b_j coefficients decrease more rapidly with NMMS complexity. As a result, the OS payoffs are maximized for $NMMS_3$. For the MES payoffs, $\bar{b}_i$ increase rapidly as NMMS complexity increases, leveling off at high complexity. In such conditions, the optimal solution, ($NMMS_3$, $NMMS_3$), is obtained by *equilibrium in dominant actions*. Note that tables are not provided for the parameters and game matrix associated with Framework 3.

Framework 4

This framework is an extension of Framework 3, in which safety enhancement factors in the long term are excluded from the payoffs of the MES. As expected, the optimal solution, ($NMMS_2$, $NMMS_3$), is obtained by *equilibrium in dominant actions*.

The analyses of Frameworks 1–4 reveal that the preferred NMMSs of the management and engineering team, and those of the operators, agree or conflict depending on the contributing factors in Eqs. 2a and 2b. Furthermore, their individual choices may vary with their contributing factors.

Note that the sequential selection process provides the same solution as the simultaneous selection process when the latter solution is obtained using *equilibrium in dominant actions*. Therefore, the solutions obtained using Frameworks 1–4 can be obtained using the sequential selection process.

In reality, there is another dimension to this approach, as each near-miss step has a varying degree of effectiveness. Since this introduces another level of complexity, it will be included in future studies.

CONCLUSIONS

In Part II, a quantitative model for the selection of Near-miss Management Systems is introduced. Emphasis is placed on balancing the preferences of managers and engineers with those of the process operators using a game-theoretic decision model. It is concluded that:

1. The choices of the management and engineering team, and the operators, for the selection of a NMMS are sensitive to the contributing factors.
2. Both sensitivity analysis and validation of these models are essential.
3. The results are illustrated using hypothetical data. They may differ among companies based on their safety cultures and practices.

NOMENCLATURE

Acronyms

GAMBIT = software to solve problems using Game theory
MES = management and engineering system
NMMS = near-miss management system
$NMMS_i$ = near-miss management system type i
OS = operator system

Notation

a_j, b_j, and c_j = fractional contribution coefficients for estimation of OS payoff
$\bar{a}_i$, $\bar{b}_i$, and $\bar{c}_i$ = fractional contribution coefficients for estimation of MES payoff
$Attitude_{j,i}$ = attitude of operator towards safety of plants
$Cost_{i,j}$ = cost of the NMMS
$ExWork_{j,i}$ = extra workload for the task required by the operator
f = payoff function of MES
g = payoff function of OS
$Incent_{j,i}$ = incentive given to operator for using the system

$InsuIncent_{i,j}$ = incentive provided by insurance companies due to NMMS implementation

$SafetyE_{i,j}$ = potential safety enhancement to the company due to the increases involvement of its employees in safety

Sen_{MES} = sensitivity factor that accounts for the actions of the MES on the payoff of the OS

Sen_{OS} = sensitivity factor that accounts for the actions of the OS on the payoff of the MES

$VMES_{i,j}$ = payoff/objective function of MES

$VMESb_i$ = basic payoff of MES for NMMS i

$VOS_{j,i}$ = payoff/objective function of OS

$VOSb_j$ = basic payoffs of OS

x = parameter to estimate payoff of MES

y = parameter to estimate payoff of OS

Counter

i = counter for NMMS selection for the MES

j = counter for NMMS selection for the OS

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