CONSIDERATION OF THE EFFECTIVENESS OF THE SAFETY MANAGEMENT SYSTEM IN QRA CALCULATIONS

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Quantitative Risk Analysis (QRA) is an important tool for understanding and managing risk in the process industry. QRA produces quantitative results for the risk from installations, often by using generic failure frequencies for the components or the accidental events. Little or no adjustment is made for the effectiveness of the safety management activities of the industrial site. However accidents in the past point out that managerial and/or organisational problems were the influencing causes of major accidents. Consequently to avoid such accidents and increase safety in the process industry, it is necessary to consider organisational and management aspects in risk analysis. To allow for this problem, procedures for the assessment of the effectiveness of safety management activities are required.

This paper describes a computer based method for the quantification of the effectiveness of the SMS and its integration into the QRA. The method is composed of the SMS audit, the scoring system and a management factor. Using a single management factor the method links the results of the quantitative assessment of the SMS to QRA results. A specific feature of the method is that it points out the strengths and especially the weaknesses of the SMS so that it gives the possibility to identify opportunities for improvements. A case study of an installation that has been audited demonstrates the application of the method and the lessons learnt from the weaknesses of the local SMS.

KEYWORDS: integrated risk assessment, QRA, safety management system, effectiveness score, management factor

INTRODUCTION

The analysis of accidents which have occurred in major hazard process plants indicates that the majority of them are caused by organisational and/or managerial problems (Seveso 1997). To allow for this problem major hazard process plants in the European Union are required by the Seveso II directive (Seveso 1997) to demonstrate a major-accident prevention policy (MAPP) and a safety management system (SMS). Furthermore, the directive requires besides procedures for the systematic assessment of the MAPP and the effectiveness of the SMS an accidental risk analysis. Existing risk analysis methods concentrate on technical systems. In computing risk, generic failure frequencies for the components or the accidental events are used, which are based on historical data from databases like OREDA (Oreda 2002) or EIREDA (Eireda 1998). In fact, data are used which do not consider the organisational and managerial features. However in order to fully analyze the risk from installations, organisational and managerial aspects have to be considered, otherwise risk analysis will not provide reliable risk values and information for reducing the risk. But until now it has been difficult to assess the effectiveness of the SMS, because the SMS deals with less concrete aspects, such as attitudes, habits etc. (Hauptmanns 2000). Methods for assessing the quality of safety management are therefore less developed.

The management of safety is influenced by many factors. Annex III of the Seveso-II directive (Seveso 1997) formulates the main requirements on SMS. Accordingly the following issues should be addressed by the SMS: organization and personal, identification and evaluation of major hazards, operational control, management of changes, planning for emergencies, monitoring the performance, audit and review. These requirements can be related to the "Plan-Do-Check-Act" (PDCA) cycle, a methodology of management systems in common. PDCA supplies a framework for continuous improvement by repeating the cycle and is therefore a dynamic model. As a result the SMS is also a dynamic process. This must be fulfilled by the developed methodologies for its assessment.

In previous works a number of methods have been developed for the quantification of the quality of safety management, also to link it to QRA results. MANAGER (Pitblado 1990), PRIMA (Hurst 1996) and a methodology in the ARAMIS project (Aramis 2004) are some approaches. These approaches are based on audit procedures which summarizes the safety factors relevant for management and organisational influences on risk. These methods are very demanding for small and medium-sized companies in terms of professional, time and costs. They are very complex to apply and require external auditors. Without a doubt important aspects of safety management are incorporated in these methods, but the requirements of the Seveso-II directive (Seveso 1997) were not fulfilled to the full extent. Due to the aforementioned reasons these methods are not fully accepted in practice. This calls for an approach to quantify the effectiveness of the SMS in order to integrate it into the QRA in a simply and pragmatically way.

For the consideration of the effectiveness of the SMS in QRA calculations the method described in the sections 2–4 of this paper is used (Acikalin 2009). By fulfilling the legal requirements of the Seveso-II directive (Seveso 1997) this approach provides a quantitative value for the SMS. The results of a questionnaire based audit gives a single score which, after transforming it into a management factor, modifies the assessed risk using generic failure rates. The method demonstrates how well the MAPP and the SMS are implemented in the organisation. Furthermore, it reflects the strengths and weaknesses of the local SMS.

THE SMS AUDIT METHODOLOGY

The SMS audit is mainly designed to be used in the process industry. It can be carried out quickly whereas the audit should have a leader who can be either from inside or outside the company. The internal auditor can be, for example, the organization's SMS manager. For a simple application of the method a computer program is available.

For the development of the SMS audit several literary sources (NRW 2006, RWTÜV 2002, Schiefer 2007, Seveso 1997, SFK-GS-24 2002) were used. The audit has a multi-level structure and covers seven key audit areas (A–G). These areas are similar to the issues set out in Annex III of the Seveso-II directive (Seveso 1997). They where supplemented by the safety policy and the organisation of safety-related measures for risk reduction. The seven audit areas (A–G) are divided into a number of sub-areas (A1, A2, …, B1, B2, …) and these are divided into several audit points (A1.1, A1.2, …, B1.1, B1.2, …). The audit points are to be assessed and are completed with detailed questions to give support for their scoring. Furthermore they demonstrate the depth of detail of the audit. The question set covers organisational and managerial aspects for preventing accidents in the process industry.

The developed methodology fulfils the main requirements of management systems in common and obeys the PDCA-Cycle. This is done by the formulation of the audit areas and the audit points. Table 1 shows the audit areas and the sub-areas of the SMS audit and Figure 1 presents an example of an audit point.

The seven key audit areas (A–G) contribute with different importance to the safety of and the risk from an installation. This must be considered in the quantification of the effectiveness of the SMS. On this account the several audit areas were weighted by the Analytic Hierarchy Process (AHP) of Saaty (Saaty 1990). AHP is a method for solving multi-criteria decision-making problems by building a hierarchy of elements and constructing pairwise comparison matrices in order to derive the weights of the compared elements. In the frame of this work, the top of the hierarchy is the SMS. The influencing elements are the seven key audit areas (A–G).

The weights of the elements were determined from the pairwise comparison matrix by using the eigenvalue

Table 1. Audit areas and sub-areas of the assessment method

Audit area	Sub-area
A Organization and Personal	A1 Safety policy
	A2 Safety organization
	A3 Personal management
B Identification and evaluation of major hazards	B1 Safety related plant components
	B2 Plant identity and conformity
	B3 Hazard analysis
	B4 Preventive, protective and mitigating control measures
C Operational control	C1 Procedures and instructions for safe operation
	C2 Maintenance
	C3 Purchasing of equipments
D Management of changes	D1 Planning modifications
	D2 Information and communication
	D3 Recommissioning
E Planning for emergencies	E1 Procedures to prepare and follow-up of emergency plans
	E2 Instructions about contents of emergency plans
	E3 Emergency training
	E4 Information and communication
F Monitoring performance	F1 Monitoring of compliance with achievement of objectives
	F2 Corrective actions in case of non-compliance with objectives
	F3 System for reporting accidents and near-misses
G Audit and review	G1 Audit and review of the MAPP
	G2 Audit and review of the effectiveness an suitability of the SMS
	G3 Information and communication

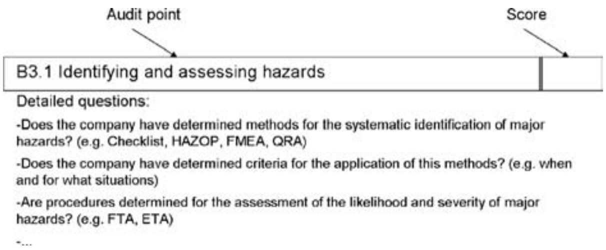

Figure 1. Example of an individual audit point assessed in the audit

method. This is done by solving the following equation:

$$w_i = \frac{1}{\lambda_{max}} \sum_{j=1}^{n} a_{ij} w_j, \quad i = 1, \ldots, n \tag{1}$$

λ_{max} is the largest eigenvalue of the pairwise comparison matrix, $a_{ij} = w_i/w_j$ (for $i, j = 1, \ldots, n$) represents the strength of importance of one element over another element with respect to the objective, $a_{ji} = \frac{1}{a_{ij}} w_i$, $i = 1, 2, \ldots, n$ are the priority weights of the elements, which are to be determined (Islam 2006). The entries of the matrix are normally taken from a scale ranging from 1 to 9 (Saaty 1990), respectively from equally important to absolutely important for the uneven numbers, whereas even numbers are intermediate values between adjacent scale values.

Following (Gitahi 2007) the entries of the matrix were obtained from experts selected from industry, research institutes and experts on plant safety. For each expert matrix of pairwise comparisons were developed for the elements. The several weights evaluated from the judgement of expert opinion were then averaged to obtain the final weights (Gitahi 2007). The consistency of the pairwise comparisons was checked by Saaty's consistency ratio CR (Saaty 1990).

$$CR = \frac{CI}{RI} \tag{2}$$

CI is the consistency index and is calculated as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

RI in equation (2) is the random consistency index and depends on the order of the matrix. Saaty generated this index for matrices of order 1 to 10. For example, for a matrix order of $n = 7$ the random consistency index is $RI = 1.35$. Saaty considered a consistency ratio of $CR = 0.1$ or less as acceptable. Otherwise a revision of the matrix must be done. In this work consistency ratios from $CR = 0{,}004$ to $CR = 0.03$ were determined.

The resulting weights for the audit areas of the SMS are illustrated in Table 2.

The element B has a basic role in the formulation and implementation of the SMS. Among the legal requirements the risks from an installation and the measures for their prevention are the basis for the SMS. Therefore the greatest weight resulted for element B.

Table 2. Weights of the audit areas

Audit area	Weight φ_i
A – Organization and Personal	0.12
B – Identification and evaluation of major hazards	0.26
C – Operational control	0.12
D – Management of changes	0.23
E – Planning for emergencies	0.14
F – Monitoring performance	0.07
G – Audit and review	0.06

THE VALUATION OF THE SMS AUDIT

The aim of the developed audit was to quantify the effectiveness of the SMS for the purpose of integrating it into the QRA. The quantification is carried out on the basis of the audit points by giving each audit point a score. The scores quantify how well the audit point meets predetermined requirements. The result of the rating is a percentage illustration of the maximum obtained points for each audit area or for the entire SMS.

The scoring system for the audit is formulated according to the performance maturity levels in EN ISO 9004 (EN ISO 9004 2000). The explanations and corresponding scores are presented in Table 3.

The effectiveness of the several audit areas are quantified by the ratio of the calculated points for each area to the maximum available points for this area. As an example the effectiveness (E) for audit area (A) is calculated as follows:

$$E_A = \frac{\text{Sum of points for area (A)}}{\text{maximum available points for area (A)}} \times 100\% \tag{4}$$

The effectiveness of the entire SMS is calculated as follows:

$$E_{SMS} = \sum_{i=A}^{G} \varphi_i E_i \quad i = A, \ldots, G \tag{5}$$

φ_i is the weight factor according to Table 2.

The effectiveness score lies on a scale from 0 to 100 and is benchmarked as follows according to (Eurocontrol 2006):

- $E_{SMS} = 0\%$, represents a hypothetical absence of activity in the area
- $E_{SMS} = 40\%$, represents a minimum effectiveness level, which is "legally compliant"
- $E_{SMS} = 70\%$, represents a good effectiveness level
- $E_{SMS} = 100\%$, represents an excellent effectiveness level.

Table 3. The annotations and corresponding scores

Score	Definition	Requirements
0	Inspection point is poor achieved	Regulations and activities are not at acceptable level; rules and measures are determined verbally; no systematic approach evident; problem- or corrective-based approach
1	Inspection point is fair achieved	Regulations and activities are at minimum level; rules and measures are determined; in some areas problem- or corrective-based approach; minimum data on improvement results are available
2	Inspection point is good achieved	Improvement process in use; regulations and instructions are determined and implemented; no notable deficiencies observable
3	Inspection point is very good achieved	All issues to be considered are put into effect without weakness or deficiencies; strongly integrated improvement process

THE MANAGEMENT FACTOR

In the frame of this work a global management factor (MF) as a function of the SMS effectiveness is used to link the audit results to the QRA calculation. By this approach an integrated risk measure can be derived under consideration of technical, organisational and managerial aspects. The resulting risk is then calculated as follows:

$$R = R_{gen} \times MF(E_{SMS}) \tag{6}$$

R_{gen} is the risk assessed by using generic failure data from past experiences or databases.

The influence of the effectiveness of the SMS on to the risk is defined by assigning effectiveness scores to management factors at two points:

- Good effectiveness, where $E_{SMS} = 70\%$ and $MF = 1$
- Excellent effectiveness, where $E_{SMS} = 100\%$ and $MF_{max} = 0.1$.

MF_{max} is the maximum modification factor and represents the upper limit. It reflects the already high level in the process industry and the high effort necessary to obtain a change in this direction.

In order to make consistent predictions between the effectiveness of the SMS and the management factor a logarithmic-linear relationship is supposed following (Eurocontrol 2006):

$$MF(E_{SMS}) = 10^{\left[\frac{E_{SMS} - 70}{30} \log MF_{max}\right]} \tag{7}$$

Using equation (7) a factor of 100 results between the excellent effectiveness $E_{SMS} = 100\%$ and the minimum effectiveness $E_{SMS} = 40\%$, respectively $MF = 0.1$ and $MF_{min} = 10$. The factor of 100 is based on case studies. There is no doubt that accident rates for different plants of similar design vary widely. Case studies done by several authors (Hurst 1996, Papazoglu 1999, Taylor 1994) show that a factor of 100 is a well-founded quantitative measure for the variations between the very best and the very worst.

THE RELIABILITY OF THE ASSESSMENT

For the integration of the effectiveness of the SMS into the QRA reliable rating results are necessary. Generally results of assessments should be reproducible under different conditions. But in many cases, different observers may reach different conclusions. This problem particularly exists for safety auditing, too. Only very few experiences were reported on the reliability of safety auditing and safety audit tools. To allow for this problem the reliability of the developed audit and the rating results were estimated by the weighted Kappa Coefficient of Cohen (Cohen 1968). Cohen's Kappa is a statistical measure of interrater agreement and measures the agreement between two observers who each classify N items into several categories. The concept of reliability provides an estimation of how consistently the studied behaviour is assessed and scored. In addition to this, the agreement between observers reflects whether the facts of the case are defined well enough. According to Fleiss (Fleiss 2003) the weighted Kappa can be employed as a measure of reliability for quantitative scales. The formula for weighted Kappa is:

$$\kappa_w = 1 - \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \cdot f_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \cdot e_{ij}} \quad i, j = 1, \ldots, n \tag{8}$$

w is the weight assigned to the i, j cell and f_{ij} and e_{ij} are the observed and expected proportions in the i, j cell in the matrix of agreement. The weight function is restricted such that $0 \leq w_{ij} \leq 1$ with $w_{ij} \rightarrow 1$ indicating stronger agreement. In this study, quadratic weights were used as follows:

$$w_{ij} = 1 - \frac{(i - j)^2}{(k - 1)^2} \quad i, j = 1, \ldots, k \tag{9}$$

The Kappa-value was interpreted according to Altmann (Altmann 1991), which is shown in Table 4.

In the frame of this work, reliability considerations were arranged using interrater reliability tests in different

Table 4. Interpretation of the Kappa-value

Value of Kappa	<0.2	0.21−0.40	0.41−0.60	0.61−0.80	0.81−1.00
Strength of agreement	Poor	Fair	Moderate	Good	Very good

case studies. The reliability computations provided values of weighted Kappa between $\kappa_w = 0.7$ and $\kappa_w = 0.75$. These results indicate good agreements, so that the reliability of the developed audit and the audit results is given.

CASE STUDY

The developed method has been applied to different establishments such as to pharmaceutical and chemical companies. The results of the audit process were discussed with the organization's SMS manager of each company. In these discussions the results were examined and the reliability and validity of the developed method was checked. During the audits good responses from the safety managers were noticed. The method was found to be easy to apply. The audit results reproduced good findings of the local SMS; they pointed out their strengths and foremost weaknesses. Opportunities for corrective, preventive and/or improvement measures could be identified. Therefore the audit results were accepted by the operator for the improvement and follow-up of their local SMS. In this section the results for a chemical company are presented. Written material of the SMS audit was sent to the SMS manager two weeks before the audit date. The audit was then carried out stand-alone by the author and the safety manager. According to equation (8) the agreement between the audit results was good ($\kappa_w = 0.7$).

The Figures 2 and 3 illustrate the audit results.

It can be seen from the Figure 2 that most of the audit areas have effectiveness scores of E > 70%, which indicates good effectiveness according to section 3 of this paper. Nevertheless room for improvements can be seen from the Figure 3. Especially in the sub-areas D1, E1, A2 and B4 there are needs for improvements. The planning of modifications (sub-area D1) was done only on the basis of a problem- or corrective-based approach mostly without regulations. The classification of safety related changes are built on "Good-Practice". The implementation of a new process was based on long time experiences; a compatibility check was not specified. In the sub-area E1 (procedures to prepare and follow-up of emergency plans) a lot of audits points were not considered. The emergency plans were implemented on the basis of long time experiences, too. In the sub-area B4 only preventive measures for fire protection were considered, the actions after fires, for example the protection of the fire area, were not regulated.

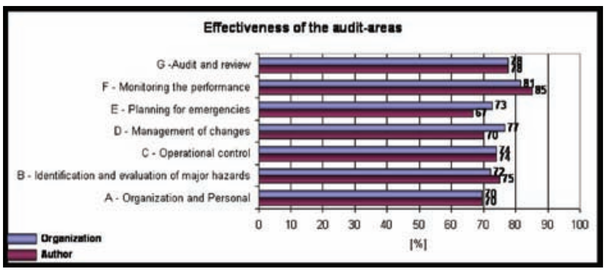

Figure 2. Effectiveness of the audit areas

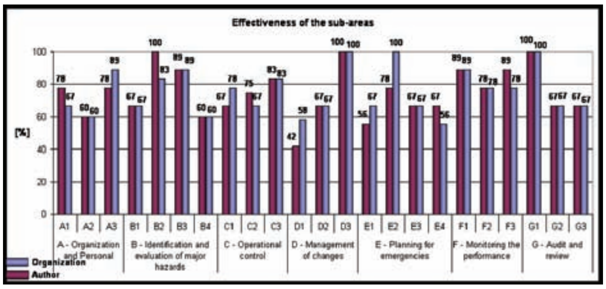

Figure 3. Effectiveness of the sub-areas (for explanation of the sub-areas see Table 1)

There were deficiencies in the checking of the procedures and activities, for example in the sub-areas A2 (safety organisation) and D1 (planning modifications). Some regulations were over regulated so that a systematic approach in the regulations couldn't be seen. On the other hand parts of inspection points and their regulations were not being provided. These points were implemented on the basis of long time experiences, sometimes even on the long time experiences of one person. This was the case for sub-area E1 as mentioned above and also for the dealing with results from analysis and reporting. These points are critical with regard to the hold up of the continual improvement process for a long-lasting effective SMS.

The quantification of the SMS provided an effectiveness of $E_{SMS} = 73\%$. According to Equation (7) a management factor of MF = 0.79 results. This factor decreases the risk obtained from generic data for the failure frequencies. By applying this method to another company an effectiveness score of $E_{SMS} = 69\%$ was obtained. This relates to a management factor of MF = 1.1 and increases the risk as determined with Equation (6).

As an illustration the minimum effectiveness level of $E_{SMS} = 40\%$ would result in a management factor of MF = 10 and will increase the risk significantly.

The other case studies carried out pointed out similar lacks of strengths. In general for a long lasting effective SMS clear tasks and responsibilities should be specified to all hierarchical levels in the company concerning the safety activities. A systematic approach regarding to the organisation's structure, responsibilities, rules and processes are a compelling requirement in addition to the process of continuous improvement.

CONCLUSIONS

This paper described a computer based method for the quantitative assessment of the SMS and the integration of the obtained effectiveness score to a QRA by using a single management factor. The quantification of the effectiveness of the SMS in order to consider it in QRA calculations was the main goal, but the developed method is also a tool to guide the company to improve those audit areas which are currently at the lowest level. As shown in the case study the method indicates the strength and weaknesses of the local SMS and enables for goal-oriented requirements on specific SMS elements for the purpose of improvements. Under fulfilling the legal requirements of the Seveso II-directive the method provides good guidance for the local SMS on how to progress and is a strong reminder for the organization not to relax on their commitment to safety. In this manner accidents caused by organisational and/or management factors can be avoided. Linking these factors to the QRA results, which are obtained from historical data from data bases, gives reliable information of the overall hazards and the corresponding risk from installations. Finally, integrating the effectiveness of the SMS into QRA calculations yields an integrated conclusion of the risk under consideration of technical, organisational and managerial aspects.

NOMENCLATURE

a_{ij}	[–]	strength of importance
CI	[–]	Consistency index
CR	[–]	Consistency ratio
E_{SMS}	[%]	Effectiveness of the SMS
MF	[–]	Management factor
N	[–]	Number of audited points
R	$[y^{-1}]$	Risk
R_{gen}	$[y^{-1}]$	Risk by using generic failure data
RI	[–]	Random consistency index
e_{ij}	[–]	expected proportions of agreement
f_{ij}	[–]	observed proportions of agreement
n	[–]	Order of matrix
w_{ij}	[–]	Matrix of weights
λ_{max}	[–]	Maximum eigenvalue
κ_w	[–]	Weighted Kappa Coefficient of Cohen
φ_i	[–]	Weight factor

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