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Use of failure rate databases and process safety performance measurements to improve process safety

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Abstract

Employing equipment reliability databases can generate a process of continual improvement. This paper suggests a methodology that uses equipment reliability databases, and a process of benchmarking to establish a continual improvement procedure by learning "how others are doing it". A simple decision-making procedure is suggested too, to assist in prioritizing the processes/equipment that are considered to be improved as well as a methodology to measure the improvement.

Keywords: Equipment failure rate databases; Reliability; Process safety performance; Continual improvement

1. Introduction

> There are risks so high that we do not tolerate them, risks so small that we accept them and in between we reduce them if the costs of doing so are not excessive. (Trevor Kletz [1])

Utilization of process safety databases to reduce risk and prevent loss in the chemical industry is currently in an embryonic stage. The American Institute of Chemical Engineers, Center for Chemical Process Safety developed a protocol to establish process equipment reliability data by aggregating and processing other generic data sources [2]. Al-Qurashi et al. [3] suggested an application of relational databases to improve equipment reliability by setting the mean of the failure rates in the generic database as a goal. This work presents a model that employs private (single facility) and generic databases with benchmarking

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procedures and task-based performance measurements to generate continuous risk reductions and process improvements.

2. Databases

Many organizations collect data on process incidents. These organizations differ from each other in their interests, data collection procedures, definitions, and scope. However, major benefits are possible by employing accident databases, as Mannan et al. [4] have suggested. Extensive efforts are required to integrate information from the data sources as well as to identify the effects of the individual aspects of data collection procedures on the quality and completeness of the data. The form of some databases must be altered for certain database applications, especially for development of risk reduction models and process improvements. However, equipment reliability data are much easier to deal with and to integrate. Therefore, the methodology described here is based on equipment reliability databases.

The private database utilized here consists of several modes of equipment failure rates [11] that were analyzed, classified, and recorded. Statistical reliability applications are not the scope of this work, but comparisons of performance values between private and generic databases are demonstrated to result in safety improvements. Such comparison creates opportunities to employ accident history databases for safety performance evaluations, risk reductions, and loss prevention. This paper focuses on the use of databases to generate improvements, and the measure of this improvement, and not on the fundamentals of reliability databases.

3. Continuous process safety improvement procedure

A methodology that incorporates private and generic databases for risk reduction and process improvement is illustrated in Fig. 1. Al-Qurashi et al. [3] demonstrate an application of relational databases for lowering failure rates by setting the mean failure rate value of the generic database as a goal. The major disadvantage of this concept is that facilities with lower values of failure rates than the database mean are not triggered to participate in the improvement process. Assuming that the mean is close to the median, about half of the facilities are not addressed, because they are "doing better". Also, improvement is limited to the database mean failure rate.

The main idea of the proposed methodology is a cyclic process as follows:

- Identify processes (areas) where improvements are necessary to reduce risk.
- Calculate performance.
- Identify equipment in these processes that should be improved.
- Define practical equipment performance.
- Identify other facilities with performance similar to the ideal and benchmark methods of implementation.
- Select solutions according to criteria for implementation.
- Define a new ideal reliability performance value.

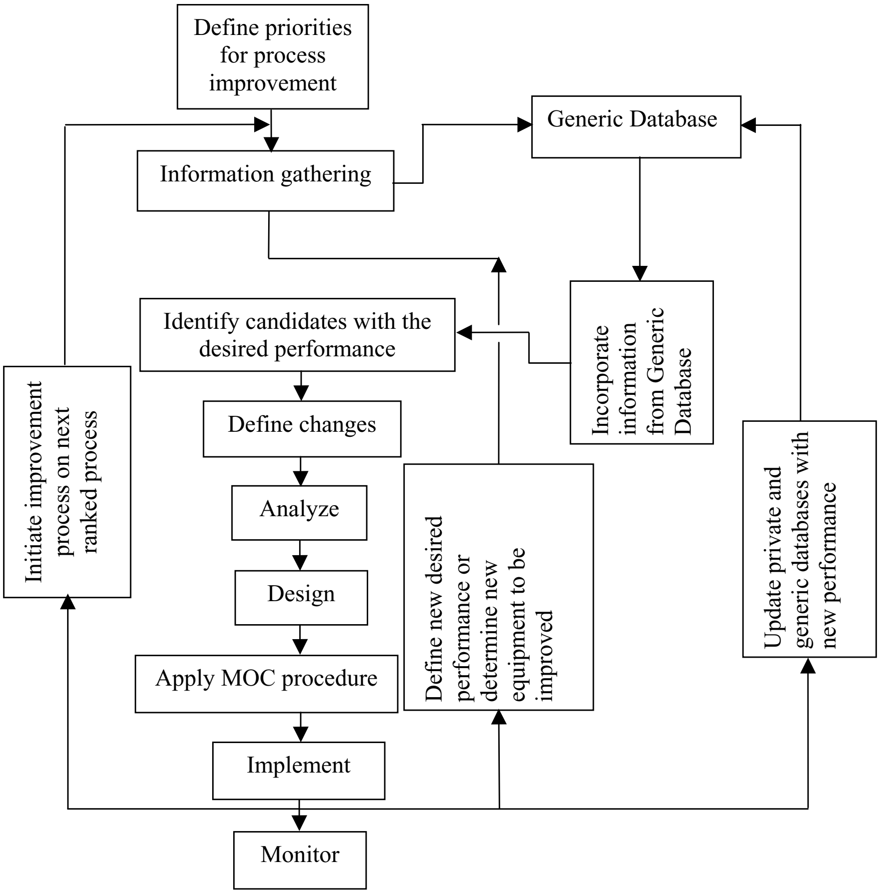

Fig. 1. Use of private and generic databases for risk reduction and process improvement.

4. Where to begin?

Most plants consist of several processes. If the decision with regard to which of the process should be improved first were in the hand of the mid-level managers in the plant, they would probably have different opinions. The maintenance manager will look for processes that are characterized by poor reliability performance. The operations manager might choose a process that is characterized by poor ergonomic features to reduce the likelihood of human error. The plant manager may select the process that is the weakest link in the production system. So *where to begin*?

Our major concern is process safety, and therefore severity is a criterion that should be employed in judging priorities. Severity points to likelihood and consequences combinations and can be approached in several ways. The OSHA PSM standard states that prioritization for conducting a PHA should address at least the following criteria:

- extent of the process hazards,
- number of potential affected employees,
- age of the process,
- operation history of the process.

Mannan and Bily [6] established a systematic, semi-quantitative risk ranking methodology (RRM) to rank processes and to define priorities according to these criteria. According to their conclusions, however, an expert estimation is required to implement the RRM.

5. Risk ranking methodology

While *number of potential affected employees* and *age of the process* are simple numeric values, *extent of the process hazards* and *operating history of the plant* should be defined. Mannan and Bily [6] suggested the following compositions:

- Extent of the process hazards consists of the following sub-criteria:
  1. Throughput,
  2. Flammability,
  3. Toxicity,
  4. Reactivity,
  5. Pressure.
- Following are the 'operation history of the covered process'[1] sub-criteria:
  1. OSHA recordable injuries,
  2. OSHA lost time injuries.

Values from 1 to 4 are assigned to each criterion or sub-criterion according to the ranges listed in Table 1 and the score of a process is the sum of scores of its criteria. Hence Mannan and Bily assumed that all criteria have the same level of importance. However, in this paper a relative weight is assigned to each of the criteria. The scoring process can be achieved by applying the simple multi-criteria decision making (MCDM) methodology, as described below. The criteria weights were obtained by applying the Delphi technique [7] on a panel of experts.

6. Multi-criteria decision making

MCDM methodology is the evaluation of alternatives across a set of criteria to define the most attractive alternative. The process considers the relative importance of the criteria by assigning weights. An MCDM matrix for priority ranking may have the form given in Table 2. The relative importance of the "extent of process hazards" sub-criterion is given in

[1] A few experts who participated in determining the weights of the criteria and sub-criteria did not agree with the content of the 'operation history of the covered process' criterion. Therefore, the results reflect the majority of the experts. The operation history of process can be determined in variety of ways, so constraints for a specific plant may require different sub-criteria for evaluation.

Table 1
Mannan and Bily priority indices for criteria and sub-criteria

Priority index	Extent of process hazards					Number of affected employees	Age of covered process (years)	Operating history of the covered process	
	Throughput (0.5 million kg/day)	Flammability (NFPA rating)	Toxicity (NFPA rating)	Reactivity (NFPA rating)	Pressure (psig)			OSHA recordable injuries	OSHA lost time injuries
1	0–1	1	1	1	0–1000	1	0–10	0–10	0–2
2	1–2	2	2	2	1001–2000	2	11–20	11–20	3–5
3	2–3	3	3	3	2001–3000	3	21–30	21–30	6–10
4	3 and above	4	4	4	Above 3000	4 or more	Above 30	Above 30	Above 10

Table 2
Multi-criteria decision making matrix

Criteria	Weight[a] (%)	Process A	Process B	Process C	Process D	Process E
Extent of the process hazards	38.3					
Number of potential affected employees	20.0					
Age of the process	17.5					
Operating history of the process	24.2					
Process score	100.0					

[a] Weights suggested here result from the first stage of the Delphi technique.

Table 3, and the relative importance of the operating history criterion sub-criterion is given in Table 4.

The total score of each process is calculated as follows:

$$\text{Score for process } i = \sum_{j=1}^{4}(W_j C_{ij}) \tag{1}$$

where W_j is the weight of criterion j and C_{ij} the score of process i with respect to criterion j.

In the same way, the score of the extent of process hazards criterion is calculated as follows:

$$\text{Extent of process hazards} = \sum_{j=1}^{5}(W_j^{\text{Extent}} \text{SC}_{ij}^{\text{Extent}}) \tag{2}$$

Table 3
Calculation of the processes score

Sub-criterion	Weight, W_j^{Extent} (%)	Process A	Process B	Process C	Process D	Process E
Throughput	19.7					
Flammability	14.9					
Toxicity	19.3					
Reactivity	24.9					
Pressure	21.2					
Integrated extent of the process score	100.0					

Table 4
Calculation of the process operating history score

Sub-criterion	Weight, W_j^{History} (%)	Process A	Process B	Process C	Process D	Process E
OSHA recordable injuries	49.2					
OSHA lost time injuries	50.8					
Integrated process operating history	100.0					

where W_j^{Extent} is the weight of sub-criterion j with respect to the criterion extent of process hazards and $\text{SC}_{ij}^{\text{Extent}}$ the score for process i on sub-criterion j with respect to the extent of process hazards criterion.

And the score of the process operating history criterion is calculated as follows:

$$\text{Process operating history} = \sum_{j=1}^{2}(W_j^{\text{History}}\text{SC}_{ij}^{\text{History}}) \tag{3}$$

where W_j^{History} is the weight of sub-criterion j with respect to the process operating history criterion and $\text{SC}_{ij}^{\text{History}}$ the score of process i on sub-criterion j with respect to the process operating history criterion (Fig. 2).

7. Information gathering

The process, to which the improvement methodology is to be applied, is known at the beginning of this stage. The maintenance manager and the operation manager may identify which equipment should be improved first. However, the equipment to be improved should be selected according to a process safety performance analysis. A pump in the process could demonstrate poor reliability, yet a process safety performance analysis may point to a temperature measurement array that has much better reliability, but is more critical to safety performance, so the improvement cycle should begin with it. The frame of the information gathering procedure is detailed in the flow chart in Fig. 3. Information regarding the performance of the equipment and its components is required and failure rates should be calculated. Parallel to this analysis, a decision should be made regarding the technique that will be employed to measure the system's safety performance. Fault tree analysis (FTA), event tree analysis, Markov chain, Dow index (which may not be sensitive enough for equipment improvement), FMEA, and HAZOP, should be considered according to the situation and the characteristics of the system. Once a technique is selected it is possible to calculate the current performance. Also, an organized plant may have useful information from previous PHA sessions or from the plant design stage.

With information on the equipment and its performance, the reliability information should be submitted to the generic database system [2]. The desired reliability value will determine the spectrum of technical solutions that will be obtained from the generic database. This value can be modified later if the changes cause severe disruption or financial problems due to high resource allocation or extended shutdown. Careful, detailed, and complete documentation of the information gathering stage is very important, especially where the improvement process is applied to more than one process simultaneously. Therefore, document information is the last protocol of this stage.

8. Exploring generic databases

Generic database exploration is possible when the desired equipment reliability value has been determined. The longer the list of candidates with values that are close

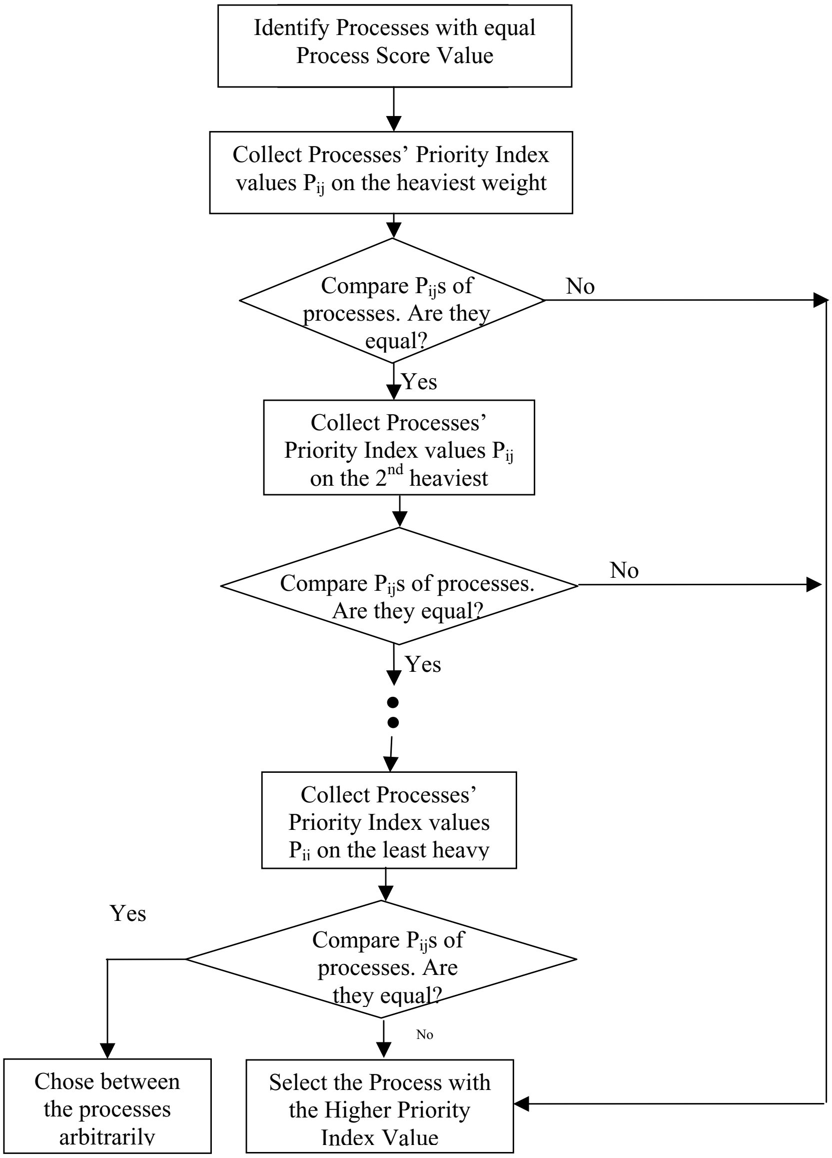

Fig. 2. Ranking of processes with equal scores.

to the desired value, the longer the list of solutions that will be available. Analyzing the effects of the solutions on the safety performance are part of this stage of the improvement process. The exploration of generic databases flow chart is given in Fig. 4.

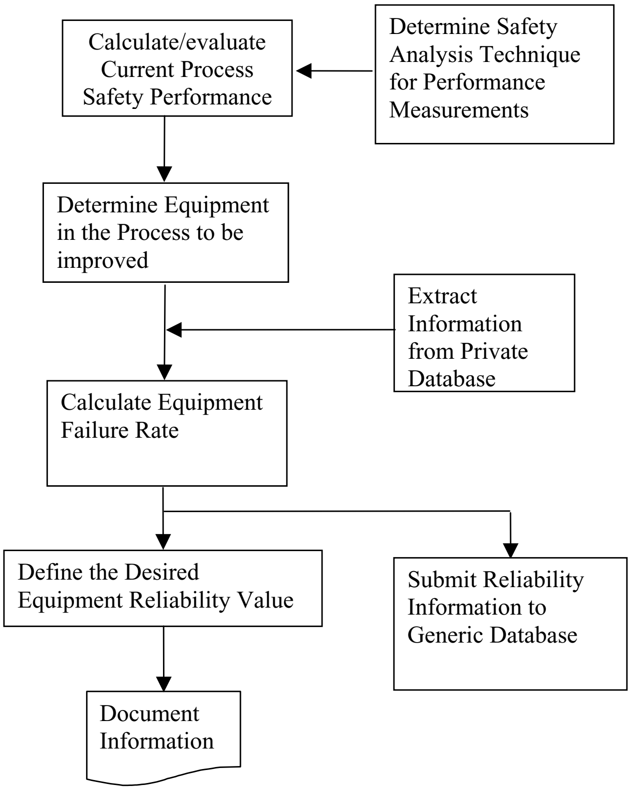

Fig. 3. Information gathering.

9. Design, MOC procedure and implementation

Following the implementation of the analysis are the design, applying MOC procedure, and the solution implementation stages. These are the last stages of the first cycle of the improvement procedure. Defining new desired equipment reliability performance value will lead to the beginning of an additional loop as described above. If the analysis reveals that there is no significant benefit from improving the reliability of equipment the procedure should be applied to other equipment according to the priorities that were defined earlier. Or the next process in the ranked list should be addressed. Once a new reliability performance has been achieved, the facility should submit this information to the generic database systems, so others can benefit by benchmarking their performance against the facility.

10. Monitoring

Monitoring will verify that the performance is stable and that efforts invested to improve the system were justified. Successful solutions will result in risk reductions and reliability performance improvements, as illustrated in Figs. 5 and 6, respectively.

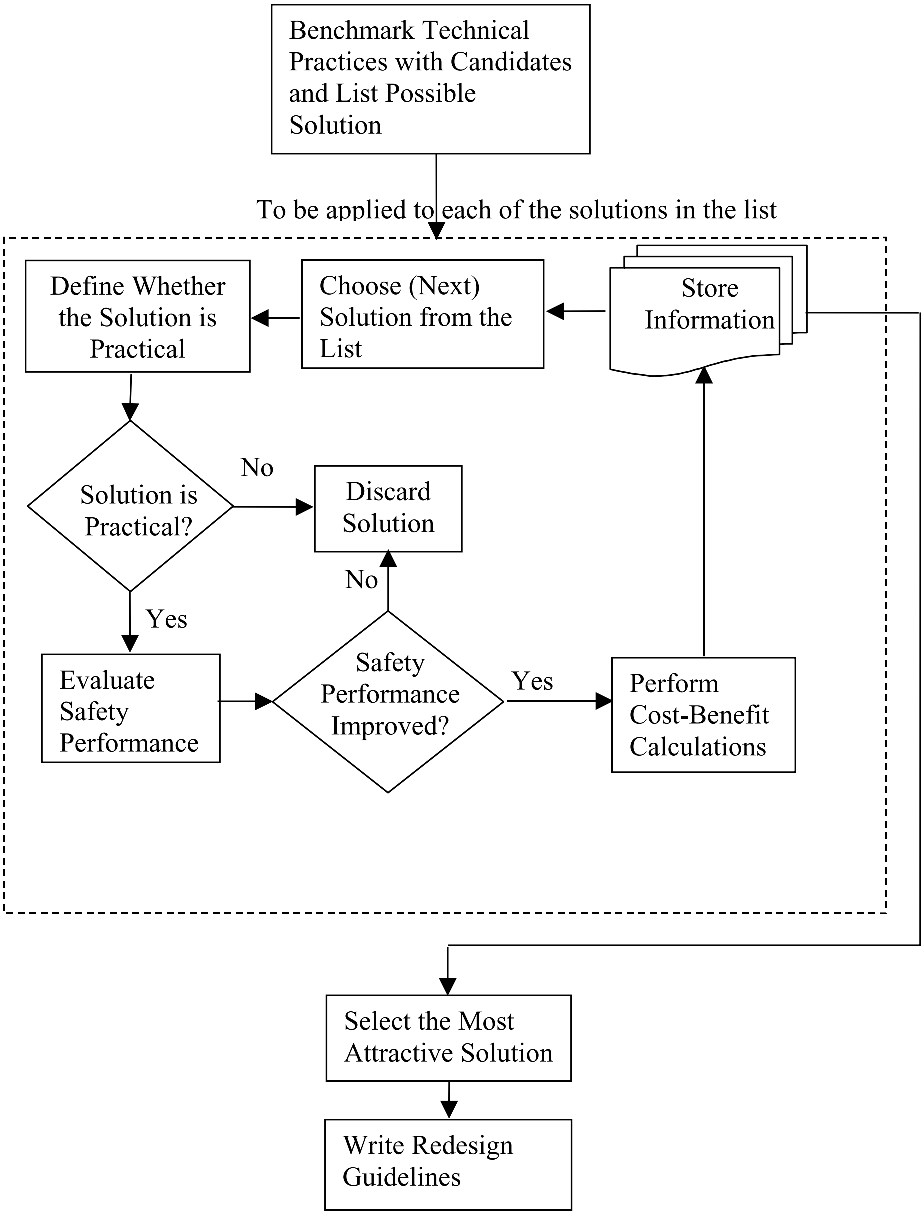

Fig. 4. Exploring generic databases.

It is important to understand that these figures are optimal, and actual curves may vary. However, the performance of the process should demonstrate consistent improvement. If during the monitoring stage, the system reveals no significant improvements after implementing the methodology on several equipment units, the solution selection proce-

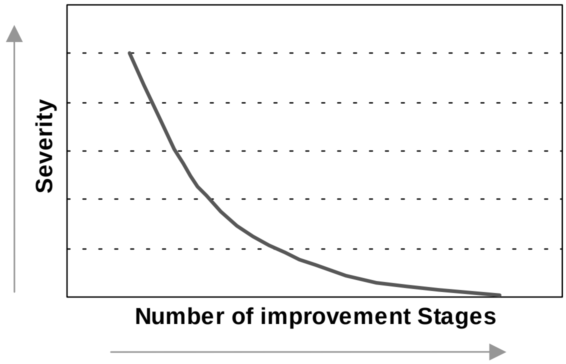

Fig. 5. Optimal risk reduction curve.

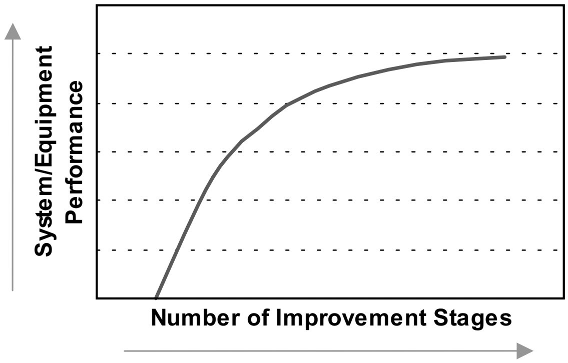

Fig. 6. Optimal performance improvement curve.

dure, technical evaluation procedure, and the safety performance measurement techniques should be re-evaluated to identify factors that prevent the system from responding to the methodology.

10.1. Relative reliability improvement

Another possible element in the monitoring stage is measurement of relative improvement. Assuming that the database consists of a list of participants with different performance, or information on reliability distribution, mean values, and the standard deviation. Improvement can be measured in comparison to other participants, as illustrated in Fig. 7. Following is a hypothetical example of risk reduction via implementation of the methodology described above.

11. Example

The system in Fig. 8 is a simplified example of a chemical reactor with a cooling system. Two pumps in parallel, supply brine to the cooling coil in the reactor. A thermocouple and

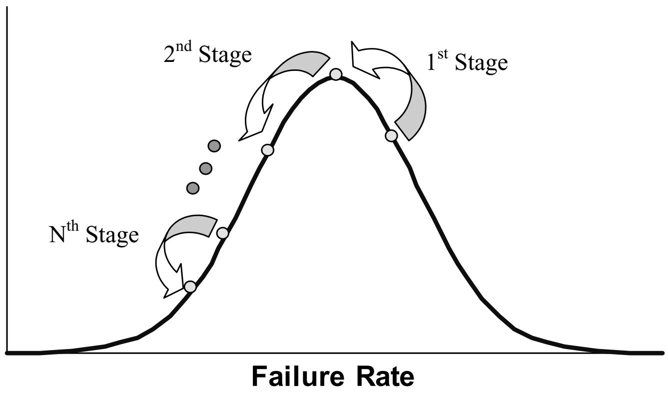

Fig. 7. Relative reliability performance measurement.

a solenoid valve control the temperature in the reactor by regulating the flow of the brine into the coil. Failure rates for the thermocouple and the solenoid valve are given in Lees [9]. In this example, the reaction is exothermic, and a runaway reaction is a credible scenario, following a loss of coolant or loss of control of the reaction. In a case of loss of coolant or control, the physical conditions for the development of a runaway reaction are established.

A good routine of data collection is maintained in this facility. An investigation by the maintenance manager reveals that the pumps have an average failure rate of $\lambda = 8.67$ (failures/year), which is about one failure every 6 weeks.

Since the likelihood of a runaway reaction was suspected to be high, FTA was chosen to measure the system's safety performance. The top event in this scenario was selected as

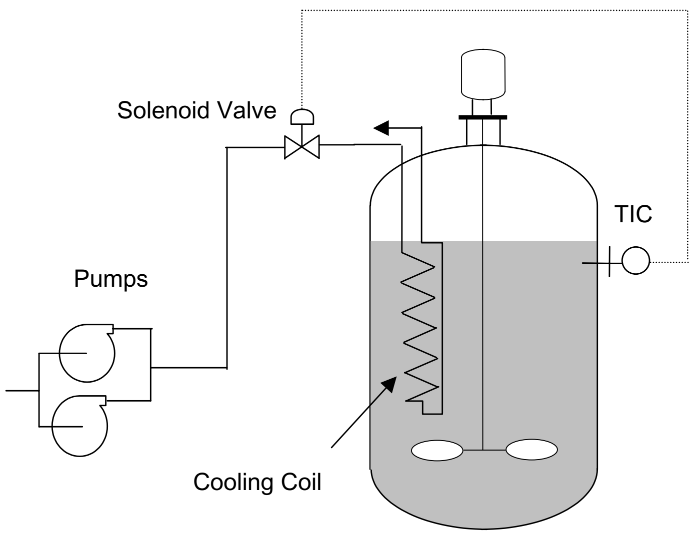

Fig. 8. Simplified chemical reactor cooling system.

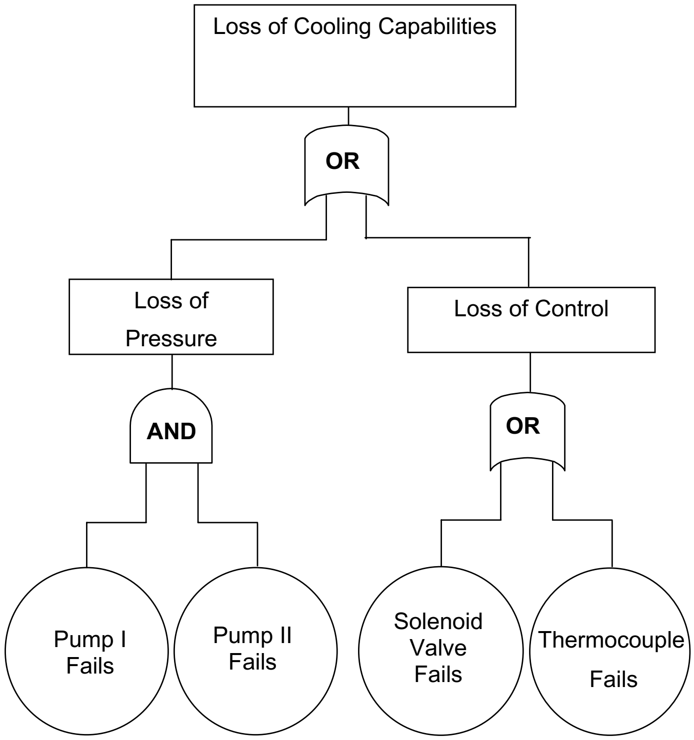

Fig. 9. FTA diagram.

the "loss of cooling capabilities". Fig. 9 demonstrates the FTA diagram. Implementation of the analysis stage revealed that high failure rate of pumps is the main contributor to the system's poor performance.

Following are several assumptions that were adopted to demonstrate implementation of the methodology in this example:

- The failure rate λ is constant (i.e., the infant mortality and the old age [8] period on the bathtub failure rate curve are not considered).
- The Poisson[2] distribution describes the probability of an item not to fail (item's reliability) during the time period (0, t):

$$R(t) = e^{-\lambda t} \quad (4)$$

- The failure probability is the complement of the reliability:

$$P(t) = 1 - R(t) = 1 - e^{-\lambda t} \quad (5)$$

[2] The Weibull distribution better describes the reliability, however, Weibull is a two parameter function and employing it in this example may create difficulties in tracking the changes. Crowl and Louvar [8] used the Poisson distribution in their text book.

Table 5
System's details at stage 0

Item	λ (failures/year)	*R*	*P*	MTBF (weeks/failure)
Thermocouple[a]	0.52	0.668	0.332	100
Solenoid valve (see footnote 4)	0.42	0.722	0.278	124
Pump	8.67	0.001	0.999	6

[a] Failure rates for thermocouple and solenoid valves were taken from Lees [9].

The mean time between failures (MTBF) is the first moment of the failure density function and is calculated as follows:

$$\mathrm{MTBF} = \int_0^\infty t\frac{\mathrm{d}P(t)}{\mathrm{d}t}\,\mathrm{d}t = \int_0^\infty t\lambda\,\mathrm{e}^{-\lambda t}\,\mathrm{d}t = \frac{1}{\lambda} \tag{6}$$

Table 5 summarizes the system data prior to application of improvement methodology. The probability of failure of items that are installed in a parallel pattern (represented by the logical AND function in the FTA diagram) is given as follows:

$$P = \prod_{i=1}^{n} P_i \tag{7}$$

where n is the number of components and P_i the private failure probability of item i.

The probability of failure of items that are installed in series pattern (represented by the logical OR function in the FTA diagram) is as follows:

$$P = 1 - \prod_{i=1}^{n}(1 - P_i) \tag{8}$$

Applying Eq. (4) on the left branch of the FTA diagram yields:

$$P_{\text{left branch}} = P_{\text{pump}}P_{\text{pump}} = P_{\text{pump}}^2 \tag{9}$$

Applying Eq. (5) on the left branch of the FTA diagram yields:

$$P_{\text{right branch}} = P_{\text{TC}} + P_{\text{SV}} - P_{\text{TC}}P_{\text{SV}} \tag{10}$$

where P_{TC} is the thermocouple's failure probability and P_{SV} the solenoid's failure probability.

Applying Eq. (5) on the output of both branches yields the probability of system failure:

$$P_{\text{system}} = P_{\text{TC}} + P_{\text{SV}} - P_{\text{TC}}P_{\text{SV}} + P_{\text{pump}}^2[1 - (P_{\text{TC}} + P_{\text{SV}} - P_{\text{TC}}P_{\text{SV}})] \tag{11}$$

Substituting P_{system} from Eq. (2) and rearranging the equation will be used in order to calculate the system's failure rate:

$$\lambda_{\text{system}} = -\frac{\ln(1 - P_{\text{system}})}{t} \quad \text{since } t = 1\,\text{year},\ \lambda_{\text{system}} = -\ln(1 - P_{\text{system}}) \tag{12}$$

The system's performance prior to improving the system were calculated according to Eqs. (1)–(9) and are listed in Table 6.

Table 6
System performance at stage 0

Stage	0
P_{pump}	0.999
P_{system}	0.999
λ_{System} (failures/year)	6.944
$MTBF_{system}$ (weeks/failure)	7.488

Table 7
System performance after implementation of first stage

Stage	1
P_{pump}	0.865
P_{system}	0.878
λ_{System} (failures/year)	2.106
$MTBF_{system}$ (weeks/failure)	24.690

12. Stage 1

Study of the history of the pumps in the system revealed that failures occur mainly because of failure of the mechanical seals. Research of the generic database yielded that $\lambda = 8.67$ (failures/year) an extremely high value, and that the mean failure rate of 'fail while running' value of centrifugal pumps is $\lambda = 2$ (failures/year)[3] with a standard deviation of 0.3 (failures/year). An investigation of the generic database reveals that installation of a simple flashing system to the mechanical seal mechanism prevents the 1/2% slurries in the cooling brine from damaging the sealing surface. The system's performance after adopting the method and installation of a flushing system is presented in Table 7.

13. Stage 2

After successful implementation of the first stage, a failure rate of 1 (failures/year) was defined as the desired performance. Benchmarking performance against facilities that have similar equipment but with failure rate of 1 (failures/year) revealed that installation of a thermometer[4] that measures the mechanical seal's flashing water temperature, may indicate a high sealing surface temperature, to allow correction of the flow rate and prevention of damage to the mechanical seal mechanism. The system's performance due to the installation of a temperature measurement is shown in Table 8.

[3] Databases consist of time-related failure rates, which are presented as failures per million hours. Calculation of λ is as follows [3]: $\lambda = (\text{total number of time} - \text{related equipment failures})/(\text{equipment total exposure h}/10^6)$.

[4] The mechanical seal TC failure rate is ignored in this example.

Table 8
System performance after implementation of second stage

Stage	1
P_{pump}	0.632
P_{system}	0.710
λ_{System} (failures/year)	1.239
$MTBF_{system}$ (weeks/failure)	41.959

14. Stage 3

Reducing the failure rate to a value of 1/3 (failures/year) may involve introduction of a new maintenance mode—"predictive maintenance". Installation of a vibration monitoring system, can identify problems in early stages of development and will "leave enough room" to eliminate the problem before failures occur, or shut down the system safely to prevent emergencies. A failure rate value of 1/3 (failures/year) will improve the performance, as demonstrated in Table 9.

Although the above example is hypothetical, it presents a reasonable scenario of gradual improvement by using private and generic databases, performance measurements, and benchmarking. Fig. 10 emphasizes the reduction of risk by plotting the probability of failures in the various stages. The failure probabilities of the pumps are plotted also, to demonstrate

Table 9
System performance after implementation of the third stage

Stage	1
P_{pump}	0.282
P_{system}	0.556
λ_{System} (failures/year)	0.812
$MTBF_{system}$ (weeks/failure)	64.010

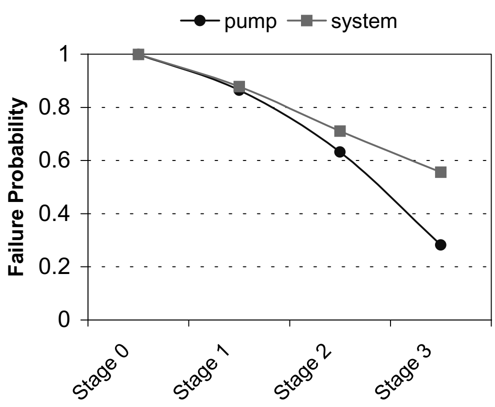

Fig. 10. Gradual risk reduction.

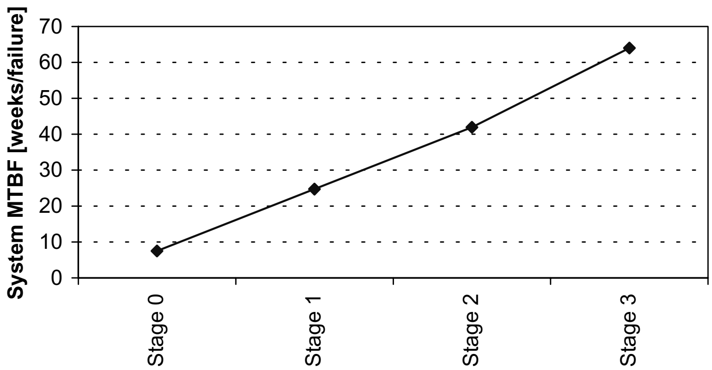

Fig. 11. Gradual performance improvement.

its effects on the system. As can be seen in Fig. 10, improving the reliability of the pumps enhanced the performance of the system in each one of the stages.

However, it is important to emphasize that applying more efforts to improve pump reliability will lead to only minor improvement of the performance because failure rates of other items overwhelm any additional reductions of the pump failure rate. Fig. 11 demonstrates the improvement of the system's MTBF.

15. Relative reliability performance improvement

Assume that 200 participants contributed their centrifugal pump "fail while running" failure rates to the database, and that the distribution of these values in the database can be approximated as a normal distribution. The improvement in the performance can be presented graphically with comparison to the performance of other participants as demonstrated in Fig. 12.

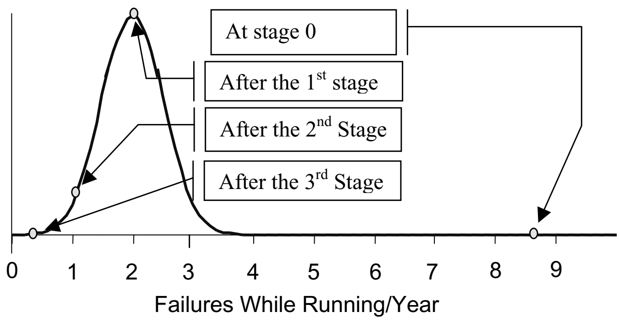

Fig. 12. Reliability performance measurements.

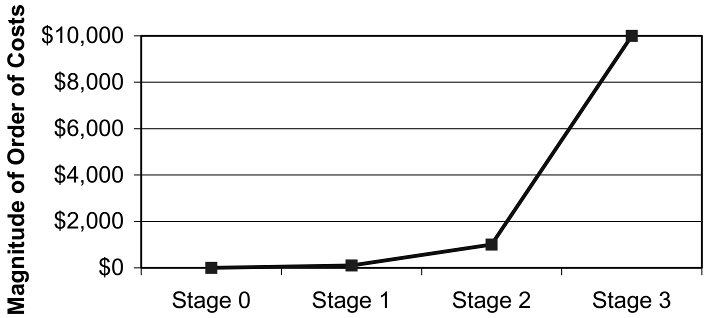

Fig. 13. Order of costs of improvement for the various stages.

16. Why gradual improvement?

A question may arise with regard to the need for a gradual improvement process. Why not benchmark performance with the best in class from the beginning? Fig. 13 demonstrates the magnitudes of costs of the various stages. The chemical industry is a capital extensive industry, and one may be discouraged by the prospect of jumping from Stage 0 to 3 because of the extensive financial allocations required. Gradual improvement methods, however, will allow combining improvement in an existing budget frame, while integrating more extensive cost stages in the future.

17. Human errors

> If the error rate of a single operator is 1 in 100, the error rate of an operator plus a checker is certainly greater than 1 in 10,000—that is, the edition of the checker may actually increase the overall error rate .... One reason suggested for Australia's outstanding good air safety is that they have a culture in which second officers are not reluctant to question the action of the captain. (Trevor Kletz [1])

This quotation is an example of the opportunity to improve by learning how others are "doing it".

CCPS [5], and Kumamoto and Henley [10] discussed the use of techniques such as THERP, HCR, and SLIM, to evaluate and measure safety performance similarly to the use of FTA and event tree analysis. Our research indicates that human error failure rates are not being measured in the chemical industry, and therefore the proposed methodology is not applicable. However, facilities that do measure human reliability can find human reliability values in the literature and can set these values as goals. The current literature provides, however, insufficient information for benchmarking of human error rate performance.

18. Conclusions

Goodwill and an open-minded approach are required from generic database stakeholders to establish an effective improvement methodology that is described here. Managers are unfortunately very suspicious, and mutual improvement processes are conducted only among small groups of common interest stakeholders, more by sharing information, and less by looking for best practices. The main motive of the proposed methodology is to improve process safety performance, which will follow the path of reliability improvement. Applying gradual improvement methodology also can reduce tremendously the effort required of conducting a PHA.

A process safety performance measurement system that measures process safety management elements could make possible implementation of the gradual improvement methodology to enhance benchmarking as a medium for shared information.

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