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Use of Failure Rate Databases and Process Safety Performance Measurements to Improve Process Safety

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Abstract

In this paper, a methodology is proposed to combine process safety performance measurements techniques, decision-making strategies, applications of private and generic databases, reliability calculations, and benchmarking to reduce risk and improve process safety. Increasing performance reliability can require extensive resources. The suggested methodology involves a gradual improvement process that promotes implementation and does not require continuous or complete verification.

Keywords: equipment failure rate databases, reliability, process safety performance, continual improvement

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 of Chemical Process Safety developed a protocol to establish process equipment reliability data by aggregating and processing other generic data sources [11]. A possible application of relational chemical process safety databases [3] for improvement of equipment reliability is to set the generic database mean failure rate as a goal, rather than simply a performance benchmark. This work presents a model that employs private (single facility) and generic databases together with benchmarking procedures and task-based performance evaluation measurements to generate continuous risk reductions and process improvements.

Databases

There are more than a dozen generic databases projects that are currently collecting process safety records from the chemical and related industries, and there are many other databases that are serving other industries, such as the nuclear industry. These databases are fundamentally different from each other, and significant effort is required to use the data for relational database applications. The form of some databases must be altered for certain database applications, especially for development of risk reduction models and process improvements. The methodology described here is based on equipment reliability databases [12].

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

Continuous Process Safety Improvement Process

A methodology that incorporates private and generic databases for risk reduction and process improvement is illustrated in Figure 1. Fahad, et al [3] demonstrated 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 the Fahad concept is that facilities with lower values of failure rates than the database mean do not triggered participation in the improvement process. Assuming that the mean is close to the median, about half of the facilities are not addressed since approximately half of the population is doing better. Also, improvement is limited to the database mean failure rate.

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

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

Where to begin?
Most plants consist of several processes. In different plant entities, improvement methodology is implemented in different processes. 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. 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 the likelihood and consequences combinations and can be presented 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. An expert estimation is required to implement the RRM according to their conclusions.

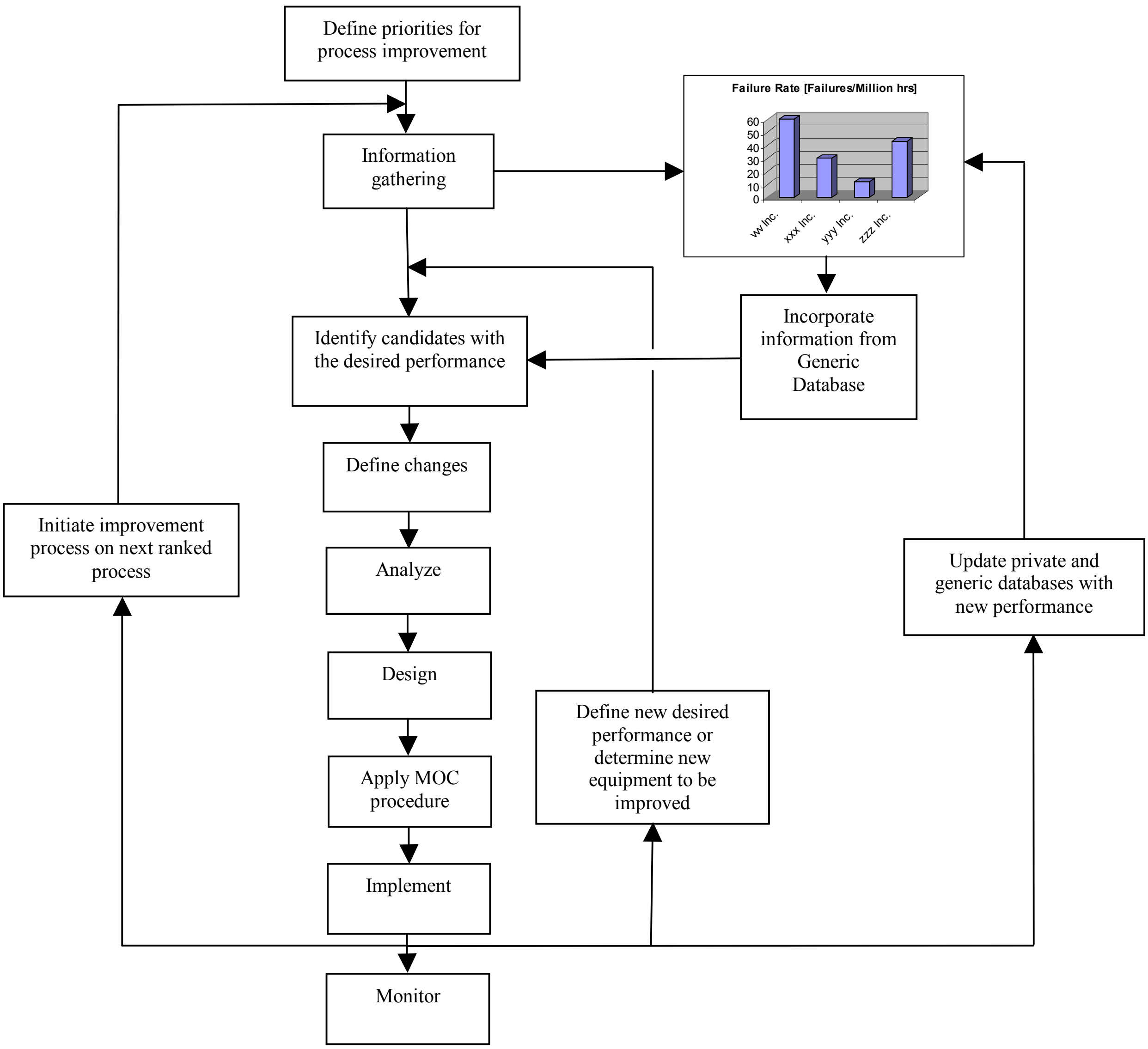

Figure 1: Use of Private and Generic Databases for Risk Reduction and Process Improvement

Risk Ranking Methodology (RRM)

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

- Extant 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 its criteria indices. Hence Mannan and Bily

Priority Index	Extent of process hazards					Number of affected employees	Age of the covered process (years)	Operating history of the covered process	
	Throughput (million lbs/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 & above	4	4	4	above 3000	4 or more	above 30	above 30	above 10

Table 1: Mannan and Bily Priority Indices for Criteria and Sub-Criteria

assumed that all criteria have the same level of importance, but the relative importance of each criterion is represented by weights assigned to 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].

Multi Criteria Decision Making (MCDM)

Multi Criteria Decision Making 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. A MCDM matrix for priority ranking may have the following form:

Criteria	**Weight[2]**	**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%					

Table 2: Multi-Criteria Decision Making Matrix

[1] A few experts that 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, and the results do not reflect all experts. The Operation History of process can be determined in variety of ways, so constrains for a specific plant may require different sub-criteria for evaluation.

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

The process score is calculated as follows:

$$Score\ for\ Process\ i = \sum_{j=1}^{4} \left(W_j \bullet C_{ij} \right) \qquad (1)$$

where,

W_j is the weight of criterion j

C_{ij} is the score for process i for criterion j (i.e., the priority index of the process for criterion j)

In the same way, the Extent of Process Hazards is calculated as follows:

$$\text{Extent of Process Hazards} = \sum_{j=1}^{5} \left(W_j^{Extent} \bullet SC_{ij}^{Extent} \right) \qquad (2)$$

where,

W_j^{Extent} is the weight of sub-criterion j for the Extent of Process Hazards

SC_{ij}^{Extent} is the score for process i on sub-criterion j for the Extent of Process Hazards criterion

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 3: Calculation of the Process Score Extent

and Process Operating History is calculated as follows:

$$\text{Process Operating History} = \sum_{j=1}^{2} \left(W_j^{History} \bullet SC_{ij}^{History} \right) \qquad (3)$$

where,

$W_j^{History}$ is the weight of sub-criterion j of the Extent of Process Hazards

$SC_{ij}^{History}$ is the score of process i for sub-criterion j of the Process Operating History criterion

Sub-Criterion	Weight W_j^{Histor}	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%					

Table 4: Calculation of the Process Operating History Score

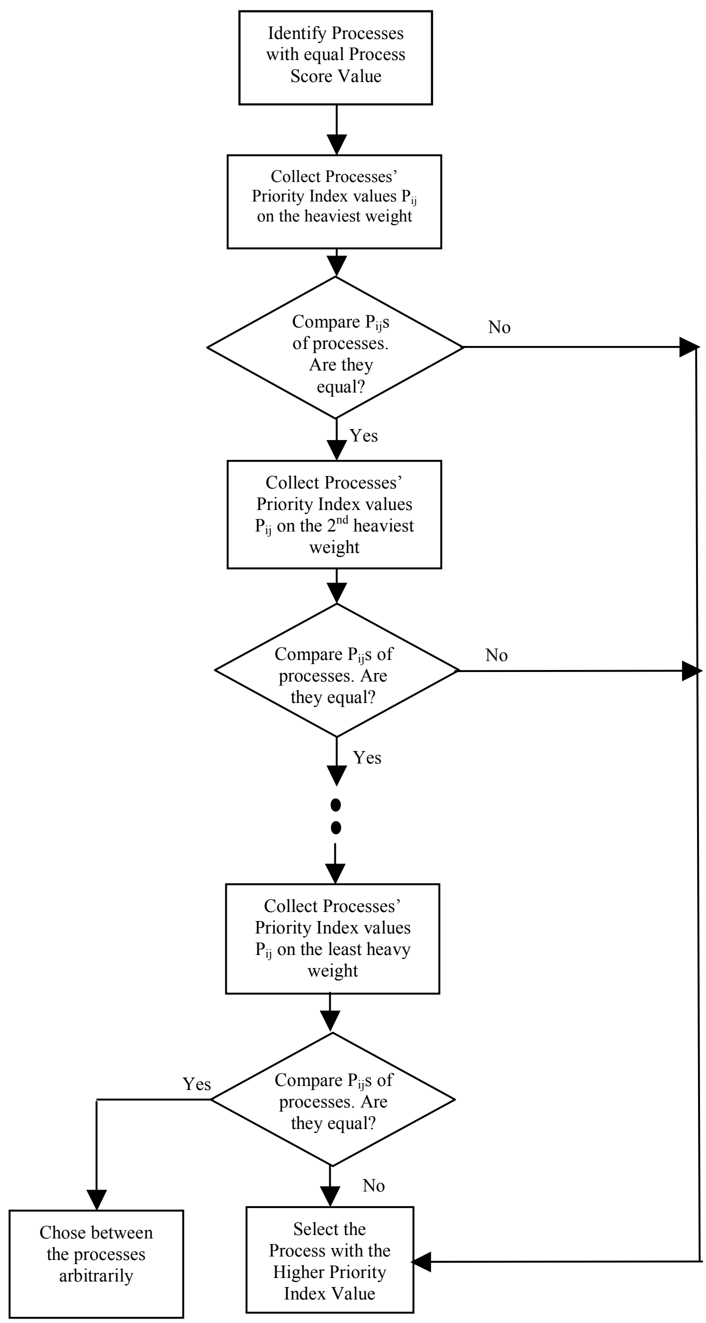

Figure 2: Ranking of Processes with Equal Scores

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 select a temperature measurement array that has much better reliability but is more critical to safety performance, so the improvement cycle should begin with it. Information regarding the equipment and performance of its components should be gathered and the failure rate should be calculated. Parallel to this analysis, a decision should be made regarding the measurement of safety performance using Fault Tree Analysis, Event Tree Analysis, Markov Chain, Dow Index (which may not be sensitive enough for equipment improvement) FMEA, HAZOP, or other methods to evaluate process safety performance.

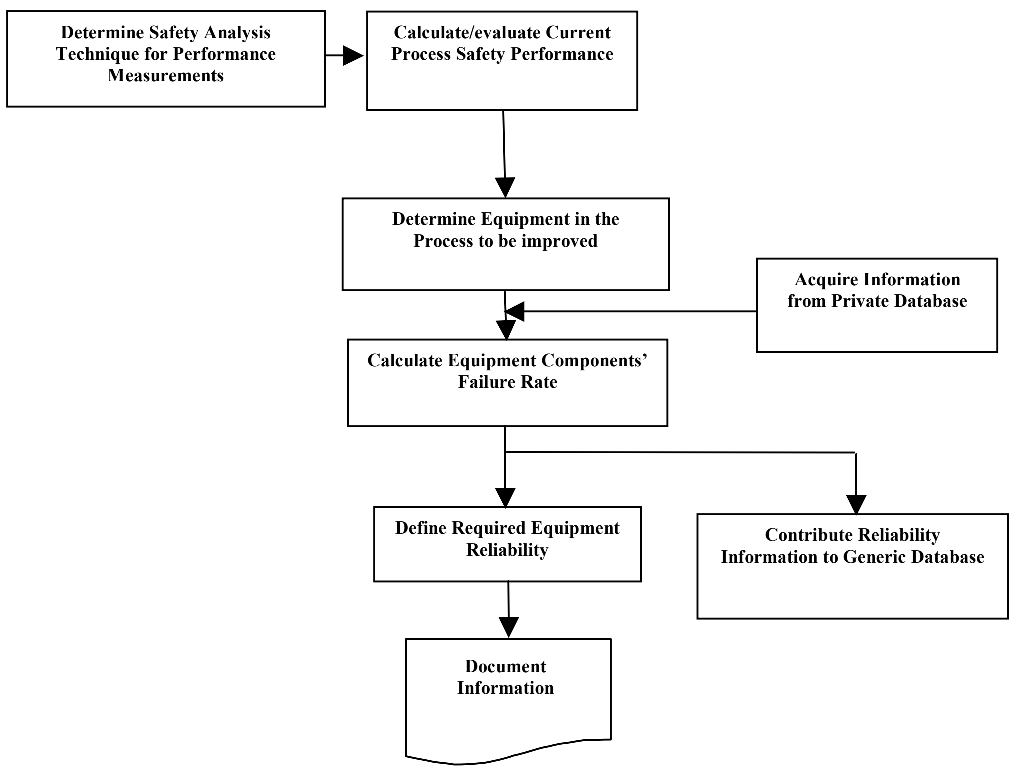

Figure 3: Information Gathering

Current performance should be analyzed using the selected method to evaluate safety performance. An organized plant may have information from previous PHA sessions or from the design stage. After evaluating and calculating safety performance and after preparation of equipment information, the reliability information should be submitted to the generic database management[3].Required reliability will determine the spectrum of technical solutions that will be obtained from the generic database. This value can be modified later if the required changes may

[3] Chapter 7 in Ref [11] provides an example of how failure rate data should be transferred from a private to a generic database.

cause severe disruption or financial problems due, for example, to high resource allocation or extended shutdown. Careful, detailed, and complete documentation of the Gathering Information stage is very important, especially where the improvement process is applied simultaneously to more than one process. Therefore, Document Information is the last protocol of this stage.

Exploring Generic Databases

Generic database exploration is possible when the required equipment reliability value is determined. Deriving a long list of candidates with values that are close to the desired value will increase the number of available solutions. Analysis of the solutions and implications for safety performance can begin with this list.

Changes and Analysis

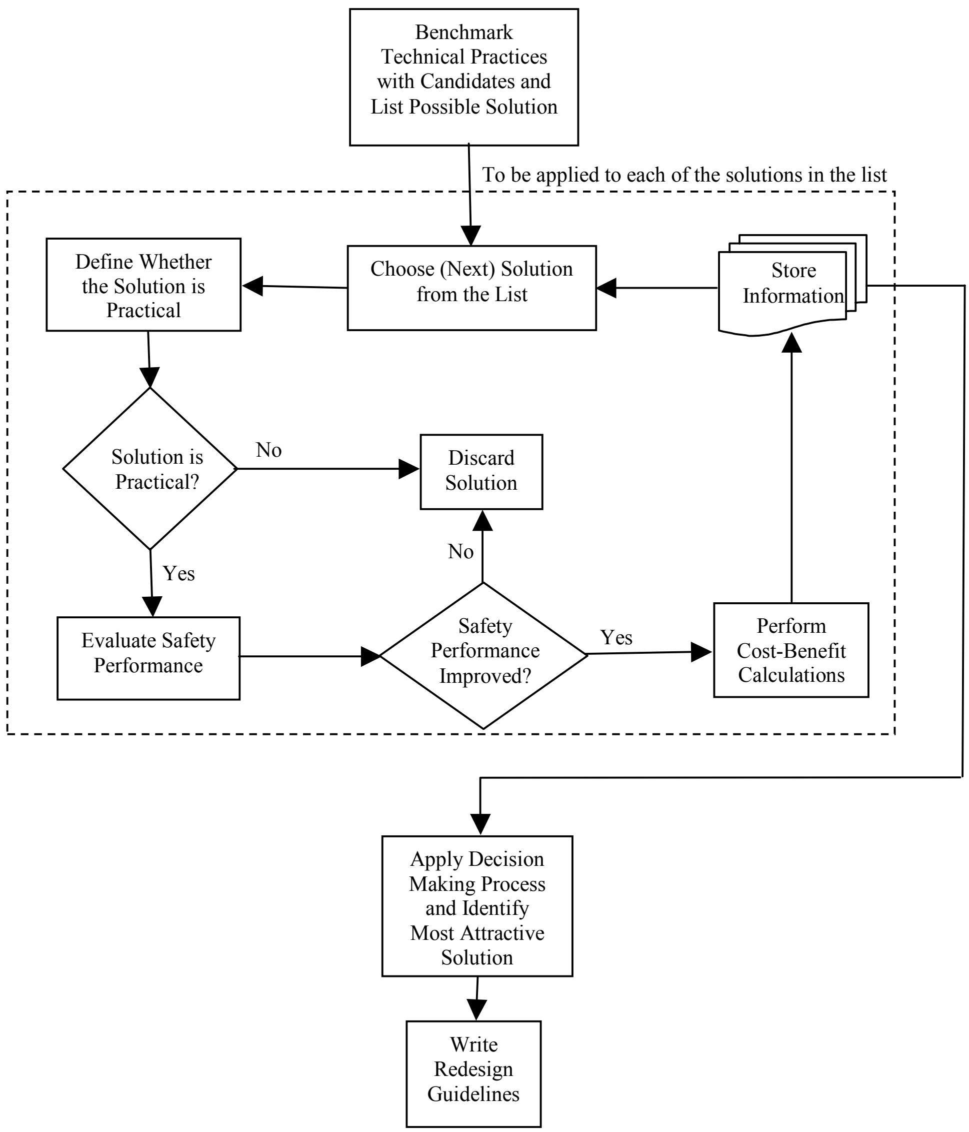

Figure 4: Changes Defined and Stages Analyzed

Design, MOC Procedure and Implementation

Following the Analyze stage are the Design, Applying MOC Procedure, and Implementation of the solution stages. These stages are sealing only the first cycle of the improvement process. The next stage will be definition of better equipment reliability performance and starting the loop from the beginning. In case where the analysis reveals that there is no significant benefit from improving this equipment reliability, the next equipment in the process (or the next ranked process if the analysis shows satisfy performance) will be addressed. Once a new reliability performance achieved, the facility needs to submit this information to the generic database management, so others will be able to benchmark their performance with the facility.

Monitoring

Monitoring the performance will verify that the solution is stable and justified. Successful solutions will result in risk reductions and reliability performance improvements, as illustrated in Figures 5 and 6, respectively.

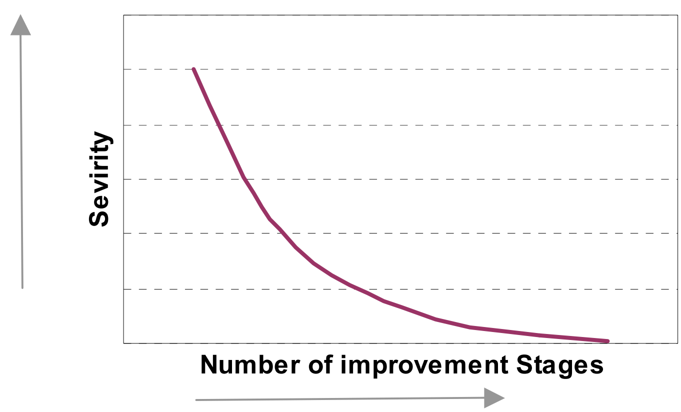

Figure 5: Optimal Risk Reduction Curve

It is important to recognize that these figures are optimal, and actual curves may vary but should still demonstrate consistent improvement. However, if the Monitor stage does not reveal significant improvements after implementing the methodology on several equipment units, the solution

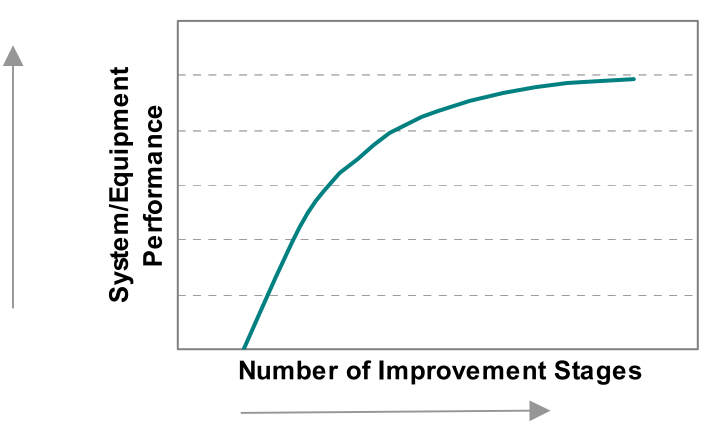

Figure 6: Optimal Performance Improvement Curve

selection procedure, technical evaluation procedure, and the safety performance measurement techniques should be evaluated again to define why the system does not respond to implementation of the methodology.

Relative reliability improvement

Another possible element in the monitoring stage is measurement of the relative improvement of reliability. Assuming that the database consists of a list of participants with different performance, or information regarding the distribution such as the mean and the standard deviation, improvement can be measured in comparison to others, as illustrated in Figure 7:

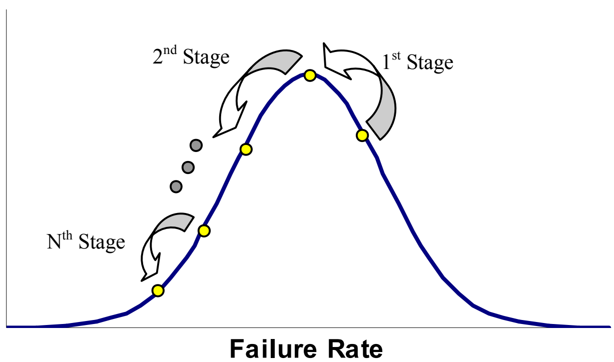

Figure 7: Relatively Reliability Performance Measurement

Next is a hypothetical example of risk reduction via implementation of a database based on improvement methodology.

Example

The system in Figure 8 is a simplified example of a chemical reactor with a cooling system. Two parallel pumps supply brine to the cooling coil while the thermocouple and solenoid valve control the temperature of the reaction by regulation of the brine flow rate to the reactor. In this example, the reaction is exothermic, and a runaway reaction is a credible scenario following loss of coolant or control. Losses of coolant or control are the physical conditions that must be fulfilled before a runaway reaction can be initiated.

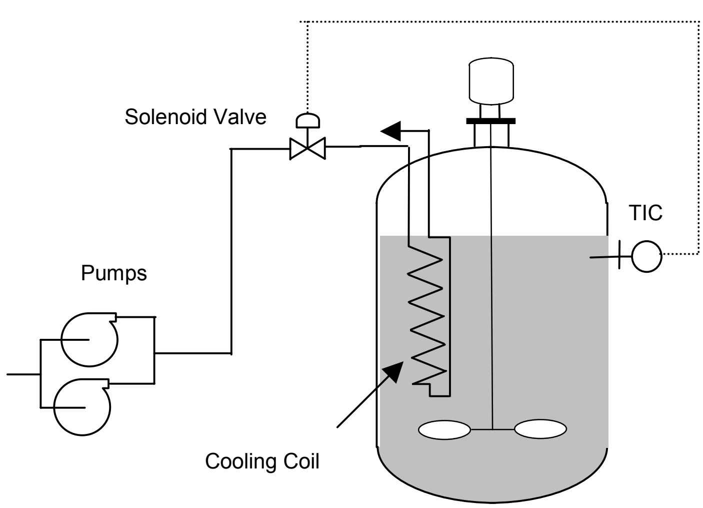

Figure 8: Simplified Chemical Reactor Cooling System

A good routine of data collection is maintained in this facility. An investigation by the maintenance manager revealed that the pumps have an average failure rate of λ = 8.67 [failures/year], which is about one failure every 6 weeks.

Since the likelihood of runaway reaction initiation contributes significantly to the severity in this example, Fault Tree Analysis (FTA) will be employed to measure the system safety performance, and 'Physical Conditions for Run Away Reaction Fulfilled' is defined as a top event. The scheme for FTA construction is given in Figure 9. The analysis demonstrated that the pump high failure rate is the main contributor for the poor process safety performance. The following assumptions are made to demonstrate the method:

- The failure rate λ is constant (i.e., the Infant Mortality and the Old Age[4] period on the bathtub failure rate curve are not considered).
- The Poisson distribution describes the probability that an item will not fail (item reliability) during the time period (0,t):

$$R(t) = e^{-\lambda t} \tag{1}$$

- The failure probability is the complement of the reliability:

$$P(t) = 1 - R(t) = 1 - e^{-\lambda t} \tag{2}$$

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

$$MTBF = \int_0^\infty t \bullet \frac{dP(t)}{dt} dt = \int_0^\infty t \bullet \lambda \bullet e^{-\lambda t} dt = \frac{1}{\lambda} \tag{3}$$

Table 5 summarizes the system prior to applying the improvement methodology:

Item	**λ [Failures/year]**	**R**	**P**	**MTBF [weeks/failure]**
Thermocouple[5]	0.52	0.668	0.332	100
Solenoid valve[4]	0.42	0.722	0.278	124
Pump	8.67	0.001	0.999	6

Table 5: System Details at Stage 0

[4] Crowl and Louvar, [8].
[5] Failure rates for thermocouple and solenoid valves were taken from Lees [9].

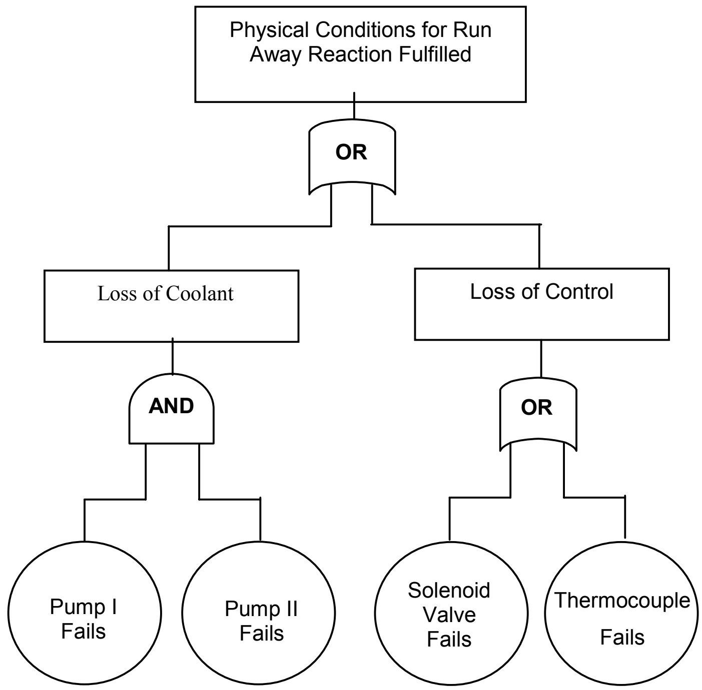

Figure 9: System's Fault-Tree-Analysis Diagram

The probability of failure of items that are in parallel pattern (which is represented by the logical AND function) is given as follows:

$$P = \prod_{i=1}^{n} P_i \tag{4}$$

where,

n- is the number of components
P_i is the private failure probability of item i

The probability of failure of items that are in series pattern (which is represented by the logical OR function) is given next:

$$P = 1 - \prod_{i=1}^{n} \left(1 - P_i\right) \tag{5}$$

Applying Equation 4 on the left branch of the Fault Tree Analysis diagram will yield:

$$P_{left\ branch} = P_{pump} \bullet P_{pump} = P_{pump}^2 \tag{6}$$

Applying Equation 5 on the left branch of the Fault Tree Analysis diagram will yield:

$$P_{right\ branch} = P_{TC} + P_{SV} - P_{TC} \bullet P_{SV} \quad (7)$$

where,

P_{TC} is the thermocouple failure probability

P_{SV} is the solenoid vale failure probability

Applying Equation 5 on the output of both branches will yield the probability of failure of the system:

$$P_{system} = P_{TC} + P_{SV} - P_{TC} \bullet P_{SV} + P_{pump}^2 \bullet [1 - (P_{TC} + P_{SV} - P_{TC} \bullet P_{SV})] \quad (8)$$

The system failure rate will be calculated by substituting P_{system} in Equation 2 and rearranging the equation:

$$\lambda_{system} = -\frac{\ln(1 - P_{system})}{t} \quad Since \quad t = 1\ year, \quad \lambda_{system} = -\ln(1 - P_{system}) \quad (9)$$

The results of the system performance calculations at this stage are listed at Table 6:

Stage	P_{pump}	P_{system}	λ_{System} [Failures/year]	$MTBF_{system}$ [Weeks/failure]
0	0.999	0.999	6.944	7.488

Table 6: System Performance at Stage 0

Stage 1

A study of the pump history demonstrated that failures occur mainly because of failure of the mechanical seals. Research of the generic database yielded that λ = 8.67 [Failures/year] is extremely high value, and that the mean of centrifugal pumps 'Fail While Running' failure rate λ = 2 [Failures/year] [6] with a standard deviation of 0.3 [Failures/year]. Benchmarking performance of facilities with similar performance revealed that installation of a simple flashing system to the mechanical seal mechanism prevents the 1/2 % slurries in the cooling brine from damaging the seal. System performances after implementation a flushing system are shown in Table 7:

Stage	P_{pump}	P_{system}	λ_{System} [Failures/year]	$MTBF_{system}$ [Weeks/failure]
1	0.865	0.878	2.106	24.690

Table 7: System's Performance after the first stage implementation

[6] Databases consist of Time-Related failure rates, which are presented as failures per million hours. Calculation of λ is as follow (Fahad, et al [2]): $\lambda = \frac{total\ number\ of\ time-related\ equipment\ failures}{equipment\ total\ exposure\ hours / 10^6}$

Stage 2

After successfully implementation of the first stage, a failure rate of 1 [Failures/year] was defined as the desired performance. Benchmarking performance with facilities that have similar equipment but with failure rate of 1 [Failure/year] revealed that installation of a thermometer[7] that measures the mechanical seal flashing water temperature and yields an indication of high temperature allows an appropriate reduction of flow rate prior to occurrence of damage. The System performance after installation of a temperature measurement as described is shown in Table 8:

Stage	P_{pump}	P_{system}	λ_{System} [Failures/year]	$MTBF_{system}$ [Weeks/failure]
1	0.632	0.710	1.239	41.959

Table 8: System Performance After 2nd Stage Implementation

Stage 3

Reducing the failure rate to a value of 1/3 [Failure/year] may involve introduction of a new maintenance mode – "Predictive Maintenance". Installation of a Vibration Monitoring System that can identify a problem in an early stage of its development, will leave enough room to eliminate the problem before a failures occurs. Achieving 1/3 [Failures/year] failure rate will improve a performance as follows:

Stage	P_{pump}	P_{system}	λ_{System} [Failures/year]	$MTBF_{system}$ [Weeks/failure]
1	0.282	0.556	0.812	64.010

Table 9: System's Performance After 3rd Stage Implementation

Though the example above is hypothetical, it presents a reasonable scenario of gradual improvement by using private and generic databases, performance measurements, and benchmarking. Figure 10 emphasizes risk reduction of the system by plotting the probability of

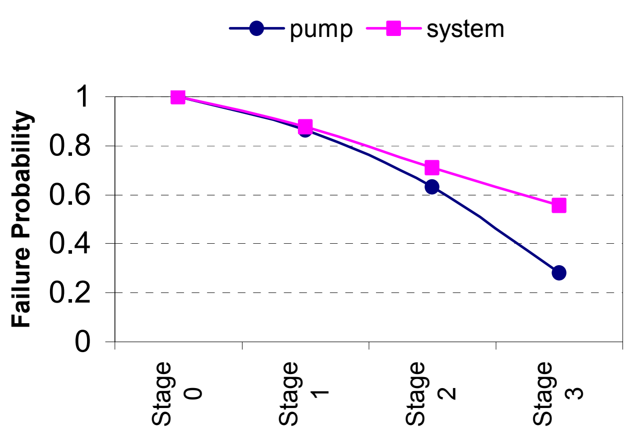

Figure 10: Gradual Risk Reduction

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

system failure. The pump failure probability is plotted also to demonstrate its effects on the system. As can be seen from Figure 10, the effect of improving the pump reliability performance on the safety performance of the system is improved from stage to stage.

It is important to emphasis, therefore, that applying more efforts to improve the pump reliability will lead to minor performance improvements, since the other items failure rates overwhelm any additional reductions of the pump failure rate.

Figure 11 demonstrates the improvement of the system's MTBF:

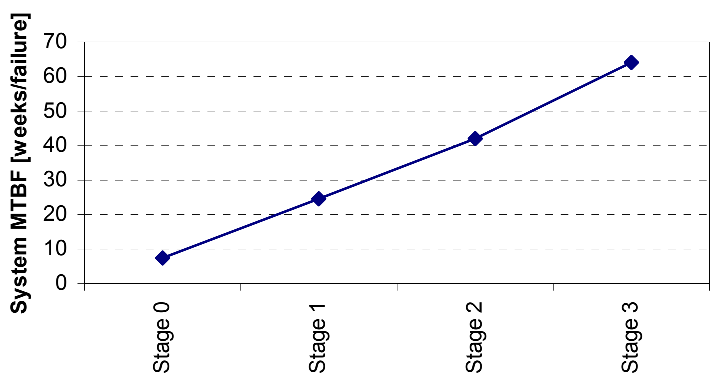

Figure 11: Gradual Performance Improvement

Relative Reliability Performance Improvement

Assume that 200 participants contributed their centrifugal pump "Fail While Running" failure rates to the database, and that the distribution can be approximated as a normal distribution, the improvement can be presented graphically, as demonstrated in Figure 12.

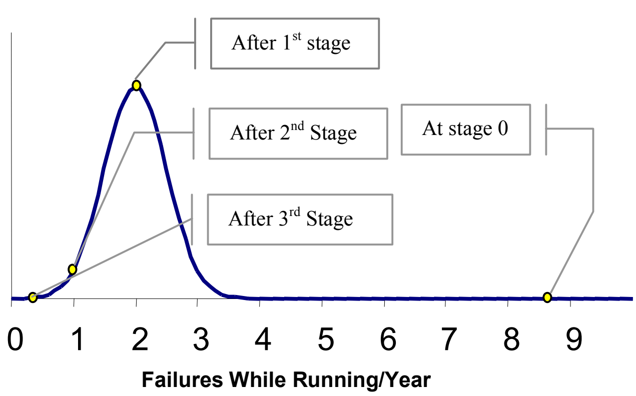

Figure 12: Reliability Performance Measurements

Why Gradual Improvement?

A question may arise regarding the need for the gradual improvement process. Why not benchmark performance with the best in class immediately? Figure 13 demonstrates the cost order of magnitude 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 Stage 3 because of the extensive financial allocations required. Gradual improvement methods, however, will allow combining different stages in the budget and budget allocations for costly future stages.

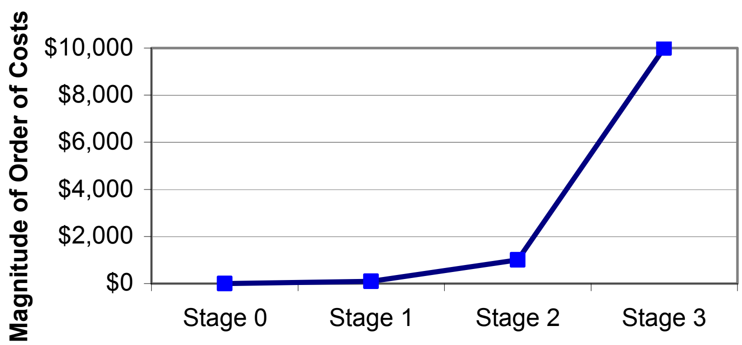

Figure 13: Order of Costs of Improvement for the Different Stages

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 and may even be greater than 1 in 100 – 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.*" [1]. This quotation is an example of the opportunity to improve by learning how others are "doing it".

Techniques such as THERP, HCR, and SLIM [10], can be used constructively to evaluate and measure safety performance the same ways that Fault Tree Analysis and Event Tree Analysis are used. However, 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 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 human performance.

Conclusions

Good will and an open-minded approach are required from generic database stakeholders to establish an effective improvement methodology that is described here. Management systems are unfortunately very suspicious, and mutual improvement processes are conducted only among small groups of common interest stakeholders, mostly by sharing information less than 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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