

Use Criticality-Based Maintenance for Optimum Equipment Reliability

Here is a systematic approach to regulatory compliance and optimization of process capacity and quality. The premise is prioritizing maintenance programs based on projected consequences of equipment failure. This results in better use of limited resources for improved plant operation.

V. Anthony Ciliberti,
Berwanger, Inc.

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Criticality-based maintenance (CBM) is a prioritized approach to the maintenance of process equipment in the chemical process industries (CPI). CBM equally weighs process and safety issues in establishing criticality, which gives companies a return on investment for mechanical integrity efforts, while establishing compliance with governmental regulations. This approach optimizes the effectiveness of mechanical integrity programs by focusing on the most important, or critical, equipment items.

CBM uses a criticality ranking process which is similar to the methodology used in a process hazard analysis (PHA) study. All process equipment items are evaluated and, then, each is given a relative value in an overall criticality hierarchy. With all equipment evaluated for criticality, prioritization of maintenance activities begins.

Maintaining mechanical integrity of process equipment is important in the CPI for continuous output of quality products and for safe, environmentally sound plant operation. Recent trends and developments in industry have increased the difficulty of implementing mechanical integrity programs while, on the other hand, making their fulfillment mandatory. Cost-reduction measures at corporate and plant levels have reduced the already limited resources used in establishing these programs. Governmental rules and regulations, such as the U.S. Occupational Safety and Health Administration's (OSHA's) Process Safety Management regulation and the U.S. Environmental Protection

Agency's (EPA's) Risk Management Plan, now require that companies establish mechanical integrity programs to ensure environmental compliance, and the safety and health of plant personnel.

Current maintenance philosophies reflect the need for mechanical integrity, as shown by an emphasis on proactive measures such as predictive and preventive maintenance, failure analysis, corrective maintenance, and reliability analysis. These proactive measures are effective, but challenging to implement due to the large number of equipment items that must be addressed with limited resources. To meet this challenge effectively and remain profitable, companies must maximize the utility of their resources. Companies should prioritize mechanical-integrity efforts and resources by concentrating on the most important or critical equipment items. Compliance programs should not focus strictly on reducing hazards, but also should focus on process-related issues, so as to give a return on investment.

CBM is a systematic approach for prioritizing maintenance. All process equipment items are evaluated with equal emphasis on hazard (health, safety, and environmental) and process criteria. Each equipment item receives a composite rating based on the hazard and process inputs. The composite rating is used to establish a process and hazard criticality ranking (PHCR) for that item. The PHCR value is a relative ranking in an overall criticality hierarchy that is used to determine priorities for maintenance programs, inspections, and repairs.

PHCR

In a PHCR study, each equipment item is evaluated with a "what if it fails" scenario. This requires personnel with thorough knowledge of the process and equipment under study. PHA teams are an excellent choice. It makes good sense to integrate criticality ranking into a PHA study, with the criticality ranking done at the end of each node, after all key words have been covered and risks discussed.

A PHCR study requires up-to-date equipment records, piping and instrument diagrams (P&IDs), and material safety data sheets (MSDSs). Other pre-work includes compiling a study worksheet, training the analysis team on PHCR procedures, and tailoring the ranking tables to fit the facility in which they will be applied. A study worksheet is typically downloaded from maintenance computer files into a spreadsheet application such as Microsoft Excel. Viewing and entering data on the worksheet is most efficiently done with a computer projection panel. Training the analysis team and tailoring the ranking tables can be done simultaneously and normally takes about one day. Table 1 presents guidelines for preparing the team for the criticality ranking study. (Some of the terms in the table will be explained later on.)

The ranking procedure

Assume full rates for the process unit(s) under study. Evaluate each equipment item individually. Following is the procedure for PHCR evaluation:

1. Determine the hazard criticality rating (HCR). Evaluate chemical hazards and physical hazards on a scale from 4-0, four being the worst case. Select the worst case scenario and give credit for factors that mitigate risk (Tables 2 and 3).

2. Determine the process criticality rating (PCR). Evaluate the process' impact of equipment failure using the same scale used in Step One. Select the worst case and give credit for spare equipment that mitigates risk (Tables 3 and 4).

3. Determine the PHCR. Input

Table 1. Preparation for an equipment criticality ranking study.

1. Define study segments. Segments can be plant areas, units, etc. These should be prioritized.
2. Determine makeup of study teams. Teams should include knowledge and expertise in the areas of operations, maintenance, and environmental and regulatory. Keep in mind that buy-in from all plant departments is crucial for the success of this program.
3. Compile study materials
 - 3.1 P&IDs and MSDS sheets
 - 3.2 Complete equipment listing in criticality ranking worksheet format
 - 3.3 Handout on criticality ranking procedure
 - 3.3.1 Computer projection unit (for displaying worksheet)
4. Establish team norms
 - 4.1 Personnel functions
 - 4.1.1 Facilitator
 - 4.1.2 Scribes (two needed; one to enter values and text into the study worksheet, the other to keep minutes)
 - 4.2 Meeting dates, times, duration, break schedule
 - 4.3 Requirements for a quorum
 - 4.3.1 Minimum number of people
 - 4.3.2 Personnel required to be present
5. Customize ranking procedure
 - 5.1 Review ranking tables
 - 5.1.1 Discuss criteria for obtaining HCR and PCR ratings
 - 5.1.2 Review guidelines table
 - 5.1.3 Review ranking matrix and discuss the logic behind it
 - 5.2 Modify tables and guidelines to reflect criteria specific to the facility in which they will be applied. In other words, what is important in your facility? Note that guidelines should be continually updated as the ranking studies progress and "standard approaches" on how to handle specific equipment types are identified.
6. Become familiar with criticality ranking worksheet
 - 6.1 Function of columns for data entry. Note that use of comments is important to convey the thought process of the group to others
 - 6.2 Spreadsheet management procedures
 - 6.2.1 Filtering data
 - 6.2.2 Searching for specific information
7. Determine who will facilitate for the next study assignment

HCR and PCR values into Table 5 to give a PHCR value. The rankings are in alpha-numeric form, with the first character (alpha) identifying the criticality category (A-D, "A" being most critical) and the second and third characters (numeric) identifying the hazard and process ratings, respectively. The alpha-numeric designation identifies not only equipment criticality ranking, but also why it is critical with respect to process and hazard criteria.

The average time for evaluation is two minutes per equipment item. When done in conjunction with a PHA study, equipment criticality ranking adds approximately 10% to the length of the study.

Adjusting PHCR based on product demand

PHCR is evaluated assuming full operating rates for the process unit under study. However, if product demand dictates lower rates, capacity-related process criticality will decrease for all equipment in that unit.

Quality-related process criticality and hazard criticality change only if the process unit is not in operation.

Incorporation of variable product demand into equipment criticality rankings requires a five-character criticality ranking field. The first three characters indicate the criticality category, HCR, and process criticality rating, respectively. The fourth character indicates

the demand rating, and the fifth character indicates whether or not the equipment item impacts product quality. The combination of process and demand ratings determine a revised alpha value for the criticality category.

Following is the procedure for incorporating product demand into equipment criticality rankings (Table 6):

1. Using a five-character ranking field, complete the process and hazard criticality ranking as described in Tables 2-5. Flag equipment items that are product quality related with a "Q" in the fifth character of the ranking field (otherwise, leave the fifth character blank). Although demand is variable, assume full unit capacity (product demand rating equal to "4") for the initial evaluation.

2. Update the fourth character of the ranking field as the product demand rating varies. Use Table 7 to determine the product demand rating.

The following steps apply only to equipment items that are not product-quality related:

3. Determine net process criticality rating (PCR'). Enter the values of PDR and PCR into Table 8 to give a PCR' value.

4. Determine a revised alpha value for the criticality category using PCR' in place of PCR in Table 5. Substitute this alpha value in the first character of the ranking field.

Repeat Steps 2-4 for all affected equipment each time product demand changes.

Table 2. Hazard criticality rating (HCR) study.

1. Assess the chemical hazard (CH). Select the highest value of NFPA fire, health, and reactivity ratings for chemicals handled by said equipment item.
2. Assess other hazards (OH) with an arbitrary number (0-4). The following list gives examples, but is not all inclusive:
 - Highly hazardous (4): Temperatures > 1,000°F or < -50°F; pressures > 500 psig or < 1 atm where oxygen ingress may cause explosion potential; rotational speeds > 5,000 rpm; regulated chemicals; critical safety devices; pollution-control systems where failure would result in environmental damage.
 - Hazardous (3): Temperatures > 500°F or < -20°F; pressures > 250 psig; rotational speeds > 3,500 rpm; hazardous chemical releases that can be contained; chemicals with moderate vapor-cloud potential and with densities greater than air; pollution-control systems where failure might result in environmental damage.
 - Moderately hazardous (2): Temperatures > 212°F; pressures > 150 psig; rotational speeds > 3,500 rpm; chemical releases with potential for long-term health or environmental impacts; dilute hazardous chemicals.
 - Slightly hazardous (1): Pressures greater than 15 psig; equipment rotational speeds greater than 200 rpm.
 - Not hazardous (0).
3. Hazard criticality (HC) is the greater value of the CH and OH.
4. Hazard risk reduction factor (HRR):
 - HRR = 0: Potential for an incident is high, or serious health, safety, or environmental consequences might result.
 - HRR = 1: Potential for an incident is low and minimal health, safety, or environmental consequences would result.
 - HRR = 4: No possibility exists for an incident, nor for health, safety, or environmental consequences.
5. Hazard spare equipment factor (HSE):
 - HSE = 1: If an in-line spare or process option exists that mitigates the hazard, otherwise, HSE = 0.
6. Hazard criticality ranking (HCR):
 - $HCR = HC - HRR - HSE$ (round negative numbers to zero).

Equipment criticality and maintenance

PHCR values are based only on process and hazard criteria. Other parameters such as equipment reliability and repair costs, while not a consideration in the ranking study, must be correlated with criticality ranking values when determining certain maintenance priorities. Ex-

bility and repair costs, while not a consideration in the ranking study, must be correlated with criticality ranking values when determining certain maintenance priorities. Ex-

Table 3. Guidelines for process and hazard criticality ranking (PHCR).

- | | |
|---|---|
| <ol style="list-style-type: none"> 1. Instrumentation 2. Evaluate criticality of the function which the instrument controls. <ol style="list-style-type: none"> 2.1 Shutdowns and alarms have the same criticality as the function criticality. 2.2 Status/indication instruments with output to the control room have a criticality one (1) less than the function criticality. 2.3 Status/indication instruments with local output have a criticality two (2) less than the function criticality. 2.4 Credits for risk reduction and spare equipment still apply where applicable. 3. Two-out-of-three trips receive no spare equipment credit. | <ol style="list-style-type: none"> 4. Mechanical <ol style="list-style-type: none"> 4.1 Main/auxiliary lubrication oil pumps on critical rotating equipment receive no spare equipment credit. 5. General <ol style="list-style-type: none"> 5.1 Process chemical hazard <ol style="list-style-type: none"> 5.1.1 This is not applicable (N/A) where both of the following apply: <ol style="list-style-type: none"> 5.1.1.1 There is no contact with the process chemical. 5.1.1.2 There is no possibility for release resulting from the equipment function failure. 5.1.2 For chemicals with no NFPA ratings available, evaluate ratings using NFPA 704 and note that this was done in the comments. 6. PHCR does not include consideration of maintenance work. Maintenance work is covered by safe job procedures |
|---|---|

Table 4. Process criticality rating (PCR).

- Assess the process criticality (PC):
 - PC = 4: Equipment critical for process capability. Failure of equipment will cause complete loss of production capacity or cause unacceptable product quality resulting in total product loss.
 - PC = 3: Equipment needed for full process capability. Failure of equipment will result in loss of one stream or require product to have a waiver with delivery.
 - PC = 2: Equipment helpful to process capability. Loss of equipment forces recirculation or immediate storage, or causes long-term loss of efficiency or reliability.
 - PC = 1: Equipment minimally impacts process capability. Loss of product optimization or advanced control.
 - PC = 0: Equipment does not affect process capability.
- Process spare equipment factor (PSE):
 - PSE = 1: If an in-line spare or process option exists that mitigates the process consequence, otherwise PSE = 0.
- Process criticality ranking (PCR):
 - PCR = PC - PSE (round negative numbers to zero).

amples include determination of equipment inspection frequencies and spare parts stocking requirements. Tables 9 and 10 illustrate the procedure for correlating equipment criticality with reliability to determine inspection requirements for rotating equipment.

PHCR values are fixed quantities, while the other parameters discussed above are variable and most likely will change with the implementation of mechanical-integrity measures. Preventive maintenance inspection, for example, should increase reliability and result in extended inspection windows and a reduction in stock quantities.

Application of CBM

CBM applies to any maintenance program or system in which equipment importance can be used as a basis for establishing priorities. One set of criticality ranking tables, if designed properly, will cover rotating equipment, fixed equipment, electrical equipment, instrumentation, piping, and any other types of process equipment. In addition to the examples given above, CBM can be used to prioritize maintenance work orders, equipment-specific training, failure and reliability analyses, and corrective maintenance efforts.

Table 5. Process and hazard criticality ranking (PHCR) matrix.

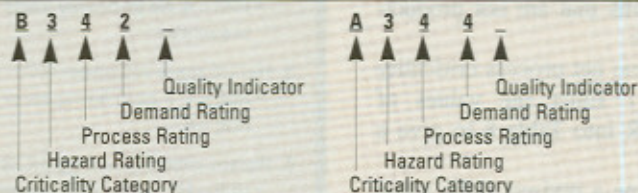
PCR	HCR				
	4	3	2	1	0
	PHCR				
4	A44	A34	A24	A14	A04
3	A43	B33	B23	B13	B03
2	A42	B32	C22	C12	C02
1	A41	B31	C21	D11	D01
0	A40	B30	C20	D10	D00

The alphabetical character designates the category, the first numeric value designates the hazard criticality rating, and the second numeric value designates the process criticality ranking. Category "A" is the most critical and category "D" is the least critical.

Example

The following illustrates the procedure for criticality ranking and determination of inspection frequencies for a wastewater pump: tag number PU-LIFT.

PU-LIFT transports process wastewater from a lift station

Table 6. Adjusting equipment criticality and inspection intervals based on product demand.

Shows how variation in demand rating impacts criticality category

Adjust the criticality category using Tables 7 and 8. Determine a new CRI using Table 9. Determine new inspection intervals using Table 10.

Changes in product demand can be classified and handled as follows:

- Regular fluctuations (not urgent)
 - Determine average PDR value over a set period of time. Use arithmetic mean or moving average
 - Determine revised inspection interval
 - Schedule next inspection date from current inspection date using the revised inspection interval
- Sudden upward or downward shift (urgent)
 - Use revised PDR value (no averaging)
 - Determine revised inspection interval
 - Revise current inspection date from last inspection date using the revised inspection interval

Note the following definitions:

- Last inspection date (LID): the last time predictive/preventive inspection was conducted
- Current inspection date (CID): the current scheduled date for upcoming predictive/preventive inspection (LID + inspection interval)
- Next inspection date (NID): the next scheduled inspection following completion of the currently scheduled inspection (CID + inspection interval)

A change in product demand normally impacts a large number of equipment items. Therefore, varying criticality and inspection intervals manually is not practical. Electronic manipulation of plant database files can easily accomplish this task, but it is outside the scope of this article. Contact the author for details on how this can be accomplished at your facility.

Table 7. Product demand rating (PDR).

PDR = 4: Product demand requires process unit to operate from 91–100% of full capacity.
 PDR = 3: Product demand requires process unit to operate from 70–90% of full capacity.
 PDR = 2: Product demand requires process unit to operate from 40–69% of full capacity.
 PDR = 1: Product demand requires process unit to operate at < 40% of full capacity.
 PDR = 0: Process unit is not in operation.

to a wastewater storage tank. Failure of this pump to operate can result in process waste overflow into a nearby bayou, which would, in turn, cause severe environmental consequences. This pump has two in-line spares. Mean time between failure for PU-LIFT is 23 mo. Rankings for process wastewater were determined by the facility according to National Fire Protection Association (NFPA) Standard 704, "Standard System for the Identification of the Hazards of Materials for Emergency Response," NFPA, Quincy, MA (1996). The values are 3, 0, 0, 4 for health, fire, reactivity, and other, respectively. "Other" is rated so highly because it is a permanent violation if the lift station overflows.

1. From Table 2, the chemical hazard rating (CH) = 3 (highest of NFPA ratings for health, fire, and reactivity). The other hazards (OH) rating = 4, due to potential for environmental damage. The hazard criticality (HC) = 4 (greater of the chemical and other hazard ratings). The hazard risk reduction factor (HRR) = 0 (serious consequences would definitely result from a lift station overflow). The hazard spare equipment factor (HSE) = 1 (in-line spares mitigate the hazard). The hazard criticality rating (HCR) = HC - HRR - HSE = 4 - 0 - 1 = 3.

2. From Table 4, the process criticality rating (PCR) = 0 (pump not needed

in making product). The process spare equipment factor (PSE) = 1 (in-line spares exist that would mitigate any process consequence). The process criticality rating (PCR) = 0 - 1 = -1, which is rounded up to zero; PCR = 0.

3. From Table 5, the process and hazard criticality ranking (PHCR) = B30.

4. From Table 9, the criticality and reliability index (CRI) = b2.

5. From Table 10, this pump requires vibration monitoring on 90-day intervals, and lubrication sampling on 180-day intervals.

Table 11 shows a typical study worksheet for equipment criticality ranking and contains data for this example. ♦

V. A. CILIBERTI is a senior staff engineer with Berwanger, Inc., Houston (713/570-2900; Fax: 713/570-2999; E-mail: va.ciliberti@berwanger.com). He works in the areas of process safety management, maintenance engineering, and consulting. His background includes 10 years' plant experience, in which he developed and implemented mechanical-reliability programs at Lubrizol Corp. and Aristech Chemicals Corp. In implementing these programs, Ciliberti developed a process and hazard criticality ranking system for use in prioritizing maintenance programs and activities. This ranking system is the basis of CBM. He holds a BS in chemical engineering from Texas A&M University, and is a member of AIChE and ISA.

Table 8. Net process criticality rating (PCR').

	PDR				
	4	3	2	1	0
	PCR'				
PCR	4	3	2	1	0
4	4	3	2	1	0
3	3	2	1	0	0
2	2	1	0	0	0
1	1	0	0	0	0
0	0	0	0	0	0

Table 9. Criticality and reliability index (CRI) values for rotating equipment.

	Mean Time Between Failure (mo)			
	0-6	6-12	12-24	> 24
	CRI			
PHCR	A	B	C	D
A	a4	a3	a2	a1
B	a3	b3	b2	b1
C	a2	b2	c2	c1
D	a1	b1	c1	d1

Table 10. Rotating equipment inspection intervals based on CRI values.

	Inspection Frequency (d)				
	7	30	90	180	360
	CRI				
a3, a4	V	L			
a1, a2		V	L		
b1-b3			V	L	
c2, d1					V

V = vibration monitoring
 L = lubrication sampling/testing

Table 11. Process and hazard criticality ranking worksheet.

Equipment Number	Equipment Description	NFPA Ratings				HC	HRR	HSE	HCR	PC	PSE	PCR	PHCR	Comments
		H	F	R	O									
PU-LIFT	Process wastewater lift pump	3	0	0	4	4	0	1	3	0	1	0	B30	Failure will cause overflow to bayou: environmental impact

H = hazard F = fire R = reactivity O = other