Integrating Six Sigma with Other Reliability Methods
To Improve Plant Equipment Reliability

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Presenter Introduction

- Salman Mishari
- Education
  - B.S. in ME (USA)
  - M.S in Engrg. Mgt (KFUPM)
  - PhD in Reliability (UOB)
  - Black belt certification in Six Sigma
  - Certified TapRoot RCA instuctor
Presenter Introduction

- Salman Mishari
- Affiliation
  - Independent Reliability Consultant
  - Reliability Specialist in S. Aramco
  - Part-time Facult at KFUPM
Presenter Introduction

- **Salman Mishari**
- **Affiliation**
  - 28 years of postgraduate experience
    - Vibration
    - Rotating equipment
    - Reliability Improvement
    - Root Cause Analysis
    - Six Sigma
Brief outline

- Will briefly review a number of reliability improvement methods
- Will look into their strengths and limitations
- We will see how Six Sigma can be used as a Framework
Let’s start with a story
1. Provide a standby Ambulance by the hole
2. Build a hospital near the hole
3. Look for more RELIABLE way of saving people lives
4. Fill the hole
1- Provide a standby Ambulance by the hole

2- Build a hospital near the hole

3- Fill the hole and dig another one near the existing hospital
The Question

- A question like this:
  - If you were requested to recommend a plan to improve failure rate, which approach would you take?
    - RCM
    - RCA
    - Reliability Engineering (RAM)
    - ???
Available Reliability Methods

- We all recognize the need for reliability but what’s the best approach?
  - Reliability Centered Maintenance
  - Root Cause Analysis
  - Total Productive Maintenance
  - Reliability Engineering
Available Reliability Methods

- We will try to go over some of these methods.
- See how Six sigma can be used as a framework to integrate them together.
Simple Example

- Consider your spare tire
  - What would you do to ensure its reliability?
  - Are you all going to have the same strategy?
  - What about driving long vs. short trips?
  - What if you’re experiencing frequent failures?
One method is RCM
Introduction to RCM

- RCM is a process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating contest (John Moubray, RCM II)
Introduction to RCM

- What do you want your car to do?
- Take you from point A to point B
  - Safely
  - With Luxury
Introduction to RCM

- If someone suggests to do a complete overhaul on your car every year.
  - Check every sensor
  - Check every bolt
  - Check the timing chain

- Do you think reliability will increase?
RCM Origins (Cont.)

- Initial RCM development was based
  - Failure history databases accumulated by Commercial Aviation industry.
  - United Airlines determined that most of failures
    - were not age-related
    - As a result, they reduced time-based and increased condition-based
  - leading to significant cost reduction
RCM Origins (Cont.)

- Based on United Airlines experience, the Federal Aviation
  - Accepted the new approach and labeled RCM.
  - Made it a requirement to obtain licensing
As per SAE-J1011, any RCM process shall ensure that the following seven questions are answered satisfactorily and in sequence:

1. What are the functions and associated desired standards of performance of the asset (functions)?
2. In what ways can it fail to fulfill its function (functional failure)?
3. What causes each functional failure (failure mode)?
4. What happens when each failure occurs?
   – How the failure display itself
5. Failure consequences?
6. What should be done to predict or prevent failure
   (proactive task and task interval)?
7. What should be done if a suitable proactive task
   cannot be found (default actions)?
RCM Example

Take a vibration trip on a pump transferring 20,000 GPM of crude oil from Tank1 to Tank2

1. What are the functions and associated desired standards of performance of the asset (functions)?
   - To transfer 20,000 GPM of crude oil from Tank1 to Tank2

2. In what ways can it fail to fulfill its function (functional failure)?
   - Pump unable to transfer (Total failure)
   - Pump transfer at lower pressure (partial failure)
3. What causes each functional failure (failure modes)?

- Severe Unbalance
- Impeller jammed
- Bearing failed
- Clogged suction screen
- Stuck valve
4. What happens when each failure occurs?

- Is the failure evident?
  - Yes, high vibration indication in the control room, the transfer of oil stops which sounds other alarms. It takes a day to troubleshoot and rebalance.

- How does it threaten safety?
  - Maybe none
RCM Example

4. What happens when each failure occurs?
   - How does it affect production?
   - What physical damage?
     ● Maybe none
   - What must be done to repair it?
     ● Rebalance
5. Failure consequences into 4 categories

- Hidden failure consequence:
- Safety and environmental consequences:
- Operational consequence (production Loss)
- No operational consequence (only cost of repair)
Proactive tasks

6. What should be done to predict or prevent failure? (Proactive Tasks)

Proactive tasks are into

- Scheduled restoration tasks
- Scheduled discard tasks
- Scheduled on-condition tasks
Default actions

7. What should be done if suitable task cannot be found (Default Actions)

**Default actions**
- Failure finding
- Redesign
- No scheduled maintenance

- The tasks should be technically feasible and worth doing to be executed.
RCM Selection Logic

**Legend:**
- CM: Condition Monitoring
- TBM: Time Based Maintenance
- PdM: Predictive Maintenance

**RCM Task Selection Logic**
To be conducted for each dominant failure mode:

1. **Is CM Available?**
   - No: \(\rightarrow\) Select PdM Task
   - Yes: \(\rightarrow\) Select Time base task

2. **Is TBM Available?**
   - No: \(\rightarrow\) Re-design
   - Yes: \(\rightarrow\) Select failure finding Task

3. **Is failure Tolerable?**
   - No: \(\rightarrow\) Re-design
   - Yes: \(\rightarrow\) Select failure finding Task

4. **Is failure Evident?**
   - No: \(\rightarrow\) Re-design
   - Yes: \(\rightarrow\) Select failure finding Task
In Summary

- Look into each equipment and each failure mode
- Consider each failure mode
- Assess the risk associated with it
- Use Risk matrix to sustain reliability
Streamlined RCM Approaches

- Classical RCM is very time consuming and labor intensive
- Theretofore, shortened versions emerged to speed up process
Retroactive Approach

- Starts with existing maintenance tasks.
- Assumes the current maintenance program is a good one and it only needs optimization.
- Argument: Traditional RCM for new designs of maintenance programs
Retroactive Approach (Cont.)

- Generates a list of failure modes from the current program
- It starts with all performed tasks and which failure modes they’re intended to deal with and then optimize them.
- It’s claimed to achieve 80% of RCM results with a fraction of the cost.
Reservations on Retroactive Approaches

- It assumes that existing programs cover all failure modes
- With its reverse approach, it is difficult to identify the original motive of selecting a particular tasks
- It assumes that existing programs cover all failure modes
- It focuses more on reducing maintenance workload than establishing an effective maintenance plan
Generic Approaches

- **Identical Systems**
  - Shortcut in the application of RCM
  - Entail applying analysis to identical systems.
  - Reservation:
    - Many identical systems serve different functions
    - They should, therefore, not receive the same level of maintenance attention.
Generic Approaches

- Approaches that focus on critical functions, equipment, or failure modes
  - Only critical functions, equipment, and failure modes are analyzed
  - Reservations:
    - Assumption of criticality without a detailed analysis
    - To make a proper judgment about criticality, full analysis is needed which sets the every thing back to square one.
Pros of RCM

- Simple:
  - Understandable to personnel (unlike RE for example)
- Structured
  - Assumptions are all agreed upon upfront
- Involves multidiscipline
  - Tasks are decided upon together
- Risk based
  - All decisions are linked to assessment of risk
Pros of RCM

- Excellent for PM review
  - In S. Aramco, we were able to save over $50 millions.
    - Deletion of Duplication
    - Deletion of none value-added
    - Extension of intervals
    - Modification of tasks
    - Reassignment of Trades
Cons of RCM

- Very resource intensive
- Some projects take years
- Very fast
  - About 20 min for each failure mode
  - Not enough time for thorough analysis
- Analysis based on subjective judgment
PMO Experience

- Pilot conducted for Gas Turbine Driven Mainline Units
Time Spent

- 1 Day preparing and organising (ARAMCO)
- 1 Day preparing (OMCS)
- 1 Day Process training
- 2 Days Analysis
- 1 Day Review
- ½ day wrap up

- The focus of the workshop was for 1 Mainline
Methodology

– A list of all performed tasks is compiled in a database software (PM, PdM, Operation tasks).
– Attributes of each task are entered
  ● Which equipment
  ● What failure mode
  ● Failure consequences
  ● Who does it (Trade)
  ● Interval
  ● Task type (hard time, condition Monitoring, failure finding, etc)
– Sorted and filtered by different attributes.
Methodology (Cont.)

- Sorted and filtered tasks are examined for:
  - Duplication of tasks
  - Existence of non value-adding tasks
  - Possible extension of intervals
  - Possible modification of tasks
  - Possible reassignment of trades

- The software makes this exercise Easy as compared to manual methods.
PMO Pilot Study

PMO Team Task Analysis Criteria:

- Does this Task add value and is it effective in minimizing failures?
- Is it repeated elsewhere by anyone else?
- Should it be done by somebody else?
- Do we need to do it more/less often?
- Is there anything else we should be doing?
Summary of Reviewed Tasks

<table>
<thead>
<tr>
<th>Task Type</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Admin</td>
<td>27</td>
</tr>
<tr>
<td>Condition Monitoring</td>
<td>120</td>
</tr>
<tr>
<td>Failure Finding</td>
<td>11</td>
</tr>
<tr>
<td>Hard Time</td>
<td>25</td>
</tr>
<tr>
<td>Grand Total</td>
<td>183</td>
</tr>
</tbody>
</table>

**Hard time** – Change out, greasing…  
**Condition Monitoring** – Actions are based on visual inspections, e.g. motor starter compartments, visual inspection for leaks, inspect coupling for wear  
**Failure Finding** – Testing a protection device to ensure it is operating correctly and safely or calibrating devices.  
**Admin** – Activity performed to prepare for or close out a PM. e.g. work permits and house keeping
Summary of Recommendations

- **Use As Is**: 39%
- **Extend Interval**: 25%
- **Delete - On another task**: 15%
- **Delete - Not value adding**: 4%
- **Modify task detail**: 5%
- **Reduce interval**: 3%
- **New Task**: 3%
- **Change Trade**: 3%
- **Delete - Decommission Equipment**: 1%
- **Change Strategy**: 2%
# Results (for one Unit)

<table>
<thead>
<tr>
<th>CRAFT</th>
<th>BEFORE PMO</th>
<th>AFTER PMO</th>
<th>DIFF. (HRS)</th>
<th>DIFF. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>8</td>
<td>12</td>
<td>4</td>
<td>50%</td>
</tr>
<tr>
<td>DG</td>
<td>260.5</td>
<td>194.5</td>
<td>-66.0</td>
<td>-25.3%</td>
</tr>
<tr>
<td>EL</td>
<td>115.6</td>
<td>98.6</td>
<td>-17.0</td>
<td>-14.7%</td>
</tr>
<tr>
<td>MA</td>
<td>269</td>
<td>109.5</td>
<td>-159.5</td>
<td>-59.3%</td>
</tr>
<tr>
<td>TOTALS</td>
<td>653.1</td>
<td>414.6</td>
<td>-238.5</td>
<td>-36.5%</td>
</tr>
</tbody>
</table>
Total PM Reduction

- PM Man-hours = 14,500 Man-Hours
- This represents 15% of overall total PM work-load.
- Equates to 8 full-time technicians
Example PM Modifications

- **Example New activity:**
  - Turbine lube oil system
  - TCV fails and gives fault lube oil high temp and shuts down machine
  - Replace valve element every 2 years

- **Example Extension of Interval**
  - ILD of Fuel vaporizer Skid
  - Fail to indicate due to out of calibration
  - Equipment is mothballed, PM can be extended from 1-year to 2-year without additional risk.
Example PM Modifications

- **Example of Reducing Interval**
  - Fuel system strainer
  - Accelerated filter blockage due to black powder
  - Reduce interval from 1-year to 6 months

- **Example of modifying task details**
  - Mainline valve actuator
  - Fails due to lack of lubrication
  - Grease actuator by applying 2-3 shots by hand grease gun
Example PM Modifications

- **Example of deleting duplication**
  - Turbine
  - Internal wear or corrosion due to normal use
  - This failure mode is already managed by Borescope inspection

- **Example strategy change**
  - Fuel System Flow Control Valve
  - Blocked filter due to normal use
  - Change strategy from condition based to Hard Time. Cost of filter is low and the time to change filter is minor.
What is different about PMO

It’s basically much faster due to:

- The start with existing PM list rather than from scratch
- Sorting and filtering being done through software rather than hardcopies; which makes the process faster.
- Use of database features (such as filtering) which makes it easy to find duplication.
Conclusions:

- Significant savings opportunities through PM review and optimization.
- PMO Exercises should be carried out periodically.
- Use of software simplifies and speeds up the whole process but requires training and a license.
- The Facilitator/Team Leader should be familiar with the equipment and the PM Program.
- Senior Technicians participation is essential.
Root Cause Analysis

- RCM assumes that SME know the cause
  - Is this always true?
- Let’s take an example
  - A pump experiences six Thrust Bearing failures in a one-year period.
    - What is the root cause?
  - What if there was a repetitive High Discharge indication?
    - What would you say the RC is?
Root Cause Analysis

- What if the pump specialist says high discharge should still not fail the bearing that fast. It must be Wrong Installation.
  - What would you say the RC is?

- What if further investigation shows that it was the wrong type of bearing? Then What is the RC?

- What if the wrong type was entered into the CMMS?
Root Cause Analysis

- You see that a good RCA is necessary and RCM alone not sufficient
- In RCM, there is not enough time to address such issues
- RCM can only provide generic solution.
What is Root Cause Analysis

A method to find out why a particular failure exists and to effectively correct it.
Linear Method (5 whys)

- The 5 Whys is a questions-asking method used to explore the root cause of a particular problem.

- It is believed that if you ask why 5 times, you will arrive at the root cause.

- You should keep asking why until a management system failure.
Linear Method (5 whys)

- Let’s take the bearing failure example, we can ask
  - Why bearing failure?
    - Because it is the wrong type.
  - Why the wrong type?
    - Because the wrong type was entered to the CMMS
  - Why?
    - Planning group not careful.
Linear Method (5 whys)

- Bearing failure example (Cont.)
  - Why?
    - Accountability problem
  - Why?
    - Lousy Management
  - Why?
    - Stop
Linear Method (5 whys)

- Linear method may not be effective
  - Focuses on blaming rather than effective solutions
  - Need to think on more causes for every effect
2. Fault Trees

- Thrust Brg Failure
  - Thrust load
    - Defective Valve
    - Signal Ignored
    - Undetected
    - Accountability Problem
    - No Enforcement
    - Low Maint
    - Adherence to Procedure
  - Wrong Brg
    - Lack of Awareness
    - Inexperienced
    - Design
    - Design Practices
    - No Procedure
    - Inadequate Training
    - No Enforcement
    - Fits well
    - Wrong Brg Exists
    - Cataloging Problem
    - No Enforcement
2. Fault Trees

Thrust Brg Failure

- Thrust load
  - Defective Valve
  - Signal Ignored

- Lack of Awareness
- Undetected

- Accountability Problem
- No Enforcement

Low Maint

- Adherence to Procedure
  - Frequency Inadequate
  - No Enforcement

Wrong Brg

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Wrong Brg Existed

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2. Fault Trees

Thrust Brg Failure

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- Low Maint (Adherence to Procedure)

- Frequency Inadequate

Wrong Brg

- Signal Ignored
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  - Design
    - Design Practices

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Wrong Brg Existed

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- Wrong Brg
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  - Design Practices
  - No Enforcement

- Low Maint
  - Adherence to Procedure

- Inexperienced
  - Inadequate Training
  - No Procedure

- Lack of Awareness
  - Inadequate Training

- Wrong Brg Existed
  - Cataloging Problem
  - No Enforcement
Threshold Criteria

- Injury or fatality
- Significant Production Losses
- Bad Actor
- Fall of a reliability index
- What else.
3. Safeguard Analysis Method

This method is more systematic and procedure-based.
2. Safeguard Analysis Method

William Haddon
(Traffic Accident Theory)
1963

Barrier Analysis
(US Dept. of Energy
Accident Model) 1985

Hazard

Multiple Failed Safeguards

Target
3. Safeguard Analysis Method
3. Safeguard Analysis Method

Root Cause is defined as:
The absence of *best practice* or the failure to apply knowledge that would have prevented the problem.

*TapRoot helps you find this best practice*
From a set of categories through a series of expert system questions.
3. Safeguard Analysis Method

**Example:**
Dry friction *(hazard)* attacking a bearing *(target)*.

- What are the current safeguards?
  - Check valve to prevent Anti-Rotation *(failed - passing)*.
  - MOV (failed – was not closed).
  - Auxiliary lube pump *(failed – put on manual)*.
3. Safeguard Analysis Method

**Example:**
Dry friction *(hazard)* attacking a bearing *(target)*.

- What caused safeguards to fail?
  - Procedures?
  - Human Engineering?
  - Communications?
  - Training?
  - QA?
  - Management Systems?
  - Work Directions?

TapRoot provides a set of expert questions to help you find which category? And proper correction Action.
3. Safeguard Method Features

- Step-by-step process (7 steps)
- Uses Pre-established categories of Causes.
- Uses expert system questions to guide through the process.
- Makes use of a dictionary for consistency.
- Make use of corrective action helper (a book of best practices against each root cause)
- Features analysis for generic causes.
- Advocates flow charting.
7 Step Process

1. Plan Investigation – Get Started!

2. Determine Sequence of Events

3. Define Causal Factors

4. Analyze Each Causal Factor's Root Causes

5. Analyze Each Root Cause's Generic Causes

6. Develop & Evaluate Corrective Actions

7. Present / Report & Implement Corrective Actions

Tools:
- Spring SnapCharT®
- Root Cause Tree®
- Equifactor®
- Summer SnapCharT®
- Equifactor®
- CHAP
- Change Analysis
- Autumn SnapCharT®
- Equifactor®
- Safeguards Analysis
- Root Cause Tree®
- Corrective Action Helper®
- Corrective Action Helper®
- SMARTER Matrix
- Safeguards Analysis
- Winter SnapCharT®
- TapRooT® Software
TapRooT® Root Cause Tree® Basic Cause Categories

PROCEDURES
- Not Used / Not Followed
  - no procedure
  - procedure not available or inconvenient for use
  - procedure difficult to use
  - procedure use not required but should be

TRAINING
- Wrong
  - typo
  - sequence wrong
  - facts wrong
  - situation not covered
  - wrong revision used
  - second checker needed
- Followed Incorrectly
  - format confusing
  - > 1 action / step
  - excess references
  - multi unit references
  - limits NI
  - details NI
  - data/computations wrong or incomplete
  - graphics NI
  - no checkoff
  - checkoff missed
  - misused second check
  - ambiguous instructions
  - equip identification NI
- No Training
  - task not analyzed
  - decided not to train
  - no learning objective missed required training
- Understanding NI
  - learning objective 
  - lesson plan NI
  - instruction NI
  - practice/repetition NI
  - testing NI
  - continuing training NI
- No Inspection
  - inspections not required
  - no hold point
  - hold point not performed

COMMUNICATIONS
- No Comm. or Not Timely
  - comm. system NI
  - late communication

STANDARDS, POLICIES, OR ADMIN CONTROLS (SPAC) NI
- no standard
- turnaround process
- turnover process not used
- turnover process NI
- standard terminology
- not used
- standard terminology NI
- repeat back not used
- long message
- noisy environment
- drawings/prints NI
- standard
- terminology
- not used
- standard terminology NI
- repeat back not used
- long message
- noisy environment
- drawings/prints NI
- no SPAC
- not strict enough
- confusing or incomplete
- technical error
- drawings/prints NI

MANAGEMENT SYSTEM
- Comm. of SPAC NI
- recently changed
- enforcement NI
- no way to implement accountability NI
- Corrective Action
  - infrequent
  - audits & evaluations (a & e)
  - a & e not independent
  - employee communications NI
  - employee feedback NI
  - correctional action NI
  - corrective action not yet implemented
  - trending NI

HUMAN ENGINEERING
- Quality of Work Environment
  - housekeeping NI
  - hot/cold
  - wet/slick
  - lights NI
  - noisy
  - obstruction
  - cramped quarters
  - equipment guard NI
  - high radiation/contamination
  - knowledge-based decision
  - errors not detectable
  - errors not recoverable
  - monitoring too many items

WORK DIRECTION
- Preparation
  - no preparation
  - work package/permit NI
  - pre-job briefing NI
  - walk thru NI
  - scheduling NI
  - lock out tag out NI
  - fall protection NI
- Selection of Worker
  - not qualified
  - fatigued
  - upset
  - substance abuse
  - team selection NI
- Supervision During Work
  - no supervision
  - crew
  - teamwork NI
  - no supervision
  - crew
  - teamwork NI

Back
Root Cause Tree

Human Performance Troubleshooting Guide

Basic Cause Categories (on back) to investigate

Individual Performance

1. Was a person excessively fatigued, impaired, upset, bored, distracted or overwhelmed?
   - Yes: HUMAN ENGINEERING
   - No: WORK DIRECTION

2. Should the person have had and used a written procedure but did not?
   - Yes: PROCEDURES
   - No: HUMAN ENGINEERING

3. Was a mistake made while using a procedure?
   - Yes: PROCEDURES
   - No: HUMAN ENGINEERING

4. Were alarms or displays to recognize or respond to a condition unavailable or misunderstood?
   - Yes: HUMAN ENGINEERING
   - No: PROCEDURES

Team Performance

1. Did verbal communications or shift change play a role in this problem?
   - Yes: COMMUNICATIONS
   - No: TRAINING

2. Did failure to agree about the authorization/where of performing the job play a role in this problem?
   - Yes: COMMUNICATIONS
   - No: WORK DIRECTION

3. Was communication needed across organizational boundaries or with other facilities?
   - Yes: COMMUNICATIONS
   - No: WORK DIRECTION

Management System

1. Was a task performed in a hurry or under stress?
   - Yes: MANAGEMENT SYSTEM
   - No: WORK DIRECTION

2. Had management been warned of this problem or had it happened before?
   - Yes: MANAGEMENT SYSTEM
   - No: WORK DIRECTION

3. Were policies, safety controls, or procedures not used, missing, or in need of improvement?
   - Yes: MANAGEMENT SYSTEM
   - No: PROCEDURES

4. Should an independent quality control check have caught the problem?
   - Yes: QUALITY CONTROL
   - No: MANAGEMENT SYSTEM

Continue on back by analyzing the indicated Basic Cause Categories.
Dictionary
Corrective Action Helper
From Root Cause to Generic Cause

Root Cause:

- **Equipment Difficulty**
  - Equipment/Parts Defective
  - Storage

(Pump bearing corroded due to pump storage outside without adequate protection)

Generic Questions:

Was other machinery stored this way?
Has it been checked?
Do we have a systematic way to prevent this?
If we did, why didn't it work?

Corrosion on internal bearing race due to condensation & acid formation in lubricant
Find Generic Cause

Root Cause: Equipment - Storage

1. Ask: “Do we have any more of these?”

2. If the answer is yes, ask:
   “Do a significant number of __________ have similar problems?”

3. If the answer is yes, ask:
   “What in the system (inventory control) is allowing __________ to exist?”
Example of a Generic Cause

Root Cause:

Equipment Difficulty - Storage

Corrective Action would include:
Store this pump in a controlled environment.

Generic Cause:

Our inventory control system does not specify proper storage of pumps.

Corrective Action would include:
Develop policy for proper storage of pumps and other critical equipment.
Events: Employee Walks to Car → Employee Steps in Pothole → Employee Sprains Ankle
Incident: Employee Sprains Ankle
Events: Another Employee Notifies Security → Employee Transported to Emergency Room & Treated & Released
Easier to analyze this chart

These are proven facts and questions, NOT opinions, judgments, etc.

Amplifying info about an Event
What? & Why?
Hazardous Spray Exercise

Initial Conditions: Thursday, January 3, 2007, 10:35 AM. Normal plant operations. Removal and replacement of Line “A” pressure detector number 2 was in progress.

Description of Incident: Two pressure detectors (to provide a redundant capacity) are available on each of three feed inlet lines. Pressure detector number 2 on Line "A" failed low at 11:15 PM on Wednesday (01/02). Maintenance and Operations management decided to replace the detector with a pre-calibrated spare during the day shift on Thursday.

The midnight-shift Unit Operator prepared the work request and tagout for detector A2 and had it authorized by the midnight-shift Shift Supervisor. The midnight-shift Unit Operator says that on Thursday, at about 6:30 AM, she isolated detector A2, drained the hazardous fluid into an approved container, and placed appropriate isolation tags and locks on the A2 isolation valves. She then called the Shift Supervisor and informed him that detector A2 was ready for removal and replacement.

At 8:00 AM shift turnover occurred. The day-shift Unit Operator and Shift Supervisor were told detector A2 was ready for removal and replacement. The day-shift Shift Supervisor contacted the Maintenance Foreman to get the work started. The Maintenance Foreman assigned two pipeliners to the job.

At 10:00 AM, the two pipeliners arrived at the control room and talked to the Shift Supervisor. He gave them permission to install the new A2 detector and told them to inform the Unit Operator about the replacement.

They then went to the unit, found the Unit Operator (making hourly reading checks) and informed him that they were there to replace detector A2. The Unit Operator said that he told them the off-going shift had drained the system and that it was ready for work. The Unit Operator did not go to the work site and review the work with the pipeliners (required by plant policy).

The pipeliners then went to the detector platform (an elevated platform that provides easy access to the detectors which are approximately 10 feet above floor level) and began to loosen the detector's connecting flange bolts. They did not hang their own locks or tags on the isolation valves or trace the lines (required by plant policy). When the third bolt was about three turns loose (they had already removed two of four bolts), hazardous material began spraying from the flange onto the pipeliners. They re-tightened the third bolt, but the spray continued until one of the previously removed bolts was inserted and tightened. Overall, the spray lasted about one to two minutes.

The Unit Operator, who had just come by, took them to a nearby eyewash and wash down station.

Both rinsed the fluid off their skin.

The Unit Operator notified the Shift Supervisor of the problem who had the two pipeliners report to the site first-aid station. The pipeliners were referred to the county hospital where they were observed overnight and released the next morning.

Both pipeliners were wearing safety glasses but not full face shields nor protective gloves as required by MSDS. One received first degree burns to his face and hands. The other received a first degree burn to one hand. Both returned to work the next day on a restricted work basis.

Further investigation showed that the detectors were not within sight of the locked-out isolation valves (isolation valves were at floor level underneath the platform), there were no equipment identification labels on the detectors, and the senior pipeliner, who was familiar with this type of unit, said he thought he was disconnecting detector A2 because he believed the detector arrangement was the same as the "identical units" he was used to working on. However, he disconnected detector A1 instead of A2 because the arrangement is backward to the other "identical units". The company's line break procedure requires pipeliners to loosen all bolts and break the line away from them before they remove any bolts.
Pipefitters A&B talk to Operator A who says detector is ready

Pipefitters A&B disconnect detector

Pipefitters A&B remove 2 bolts and loosen 3rd bolt on detector flange

Hazardous material sprays pipefitters

Pipefitters A&B are burned

Pipefitters A&B retighten bolt & insert & tighten 2nd bolt to stop spray

Pipefitter stay in spray approximately 2 minutes

Operator A does not go to job site with pipefitters (required by plant policy)

Pipefitters go to work without Operator

Pipefitters do not do lockout / tagout (required by plant policy)

Pipefitters do not trace lines

Pipefitters wear safety glasses but not full face shields or gloves

No labels on detectors

Pipefitter A thinks detector arrangement is same as another unit he is familiar with

Pipefitter A disconnects A1 (thinks it is A2)

Detectors on platform 10' off floor and not near isolation valves

Required by MSDS
3. Software

- Software
  - To speed up the process
  - To document completed cases.
  - To use for trending purposes.
Certification Program

- Specific to Equipment Reliability Application.
Objective of Certification Program

- To provide the Company with a sufficient number of qualified RCA practitioners who can successful complete RCA projects relating to *plant equipment reliability*. 

*plant equipment reliability.*
Program Outline

- Attendance of one-week training.
- Completion of a real RCA project.
- Final Exam.
Program Benefits

- Resolution of real problems as part of the certification.
- Expertise gained for other future problems.
- Documentation of Root Cause problems to serve as a database for future similar problems.
Pilot Results

- Significant savings as a direct result of resolutions of real problems.
- Projects were a variety of stationary and rotating equipment.
# Project List and Estimated Savings

<table>
<thead>
<tr>
<th>#</th>
<th>Project Title</th>
<th>Saving $</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Injection Pump internal failure causing low performance.</td>
<td>1,000,000</td>
</tr>
<tr>
<td>2</td>
<td>Refrigerant Gas Compressor Low Lube Oil Header Pressure.</td>
<td>200,000</td>
</tr>
<tr>
<td>3</td>
<td>Scrubber Pump and Piping Erosion/Corrosion Investigation.</td>
<td>200,000</td>
</tr>
<tr>
<td>4</td>
<td>Repetitive tube failure of DGA reclaimers at two Gas Plants.</td>
<td>300,000</td>
</tr>
<tr>
<td>5</td>
<td>Acid gas near miss investigation.</td>
<td>250,000</td>
</tr>
<tr>
<td>6</td>
<td>Trap Condensate Pumps Mechanical Seal Failure.</td>
<td>500,000</td>
</tr>
<tr>
<td>7</td>
<td>Stripper Reboiler Pumps mechanical seals failures</td>
<td>100,000</td>
</tr>
<tr>
<td>8</td>
<td>Extractor column sight glass chemical and hydrocarbon leak.</td>
<td>Intangible</td>
</tr>
<tr>
<td>9</td>
<td>Storm Water Pumps Failures at Utility Plant.</td>
<td>55,000</td>
</tr>
</tbody>
</table>
Certification Passing Requirement

1. Properness of Problem Definition
2. Completeness of Snap chart
3. Credibility of gathered data
4. Determination of Causal Factors
5. Determination of Root Causes
8. Final Presentation
10. Proponent satisfaction
Lessons Learned

- A significant gap to be bridged between attending a course and the application of knowledge learned during that course.

- Close mentorship and group discussions are invaluable toward mastering the know-how especially for first timers.

- It makes a big difference in participant attitude and momentum when the work is toward a certification or a degree.
Reliability Engineering

- Say out of RCM or RCA, you decide to replace a bad actor component. How much more reliability will be added?

- We need to have MODELS
- Need to be able to estimate model parameters
What is Reliability?

Reliability is the probability of achieving a certain mission under a specified condition.

- What is the probability of your car making it to Saudi Border?
- What is it to Riyadh?
- What is it to Jordan?
- What about Cyprus?
Reliability

Reliability is a function of mission
- (this case kilometers)
- Other case (time)

\[ R = e^{-t/MTBF} \]

Question
- What is the probability of achieving the MTBF?
Availability

What is Availability?
Availability is the average uptime over the total time

\[
\text{Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MDT}}
\]
MTBF & MDT

- Best estimate of MTBF is
  \[ \text{MTBF} = \frac{\text{total time}}{\# \text{ of failures}} \text{ for single item} \]
  \[ = \frac{\text{Population} \times \text{Period of analysis}}{\text{number of failures}} \]

- Best estimate of MDT is the average
Systems In series:

Rs = R1 R2 R3 ...
Rs = 0.9 x 0.9 X 0.9 = 0.729
Reliability Engineering

- Systems In Parallel:

\[ R_s = 1 - (1 - R_1) (1 - R_2) (1 - R_3) \]

\[ R_s = 1 - (0.1 \times 0.1 \times 0.1) = 0.999 \]
Example

- So, What is the reliability of the existing system?
Reliability Engineering Example

- Reliability of existing system
  - $R_{(A_1,B_1)} = 0.95 \times 0.95 = 0.9$
  - $R_{(A_2,B_2)} = 0.6 \times 0.95 = 0.57$
  - $R_{sys} = 1 - [(1 - 0.9)(1 - 0.57)] = 0.96$
Reliability Engineering Example

- What is the reliability of proposed system
  - \( R_{(A1,B1)} = 0.95 \times 0.95 = 0.9 \)
  - \( R_{(A2,B2)} = 0.95 \times 0.95 = 0.9 \)
  - \( R_{sys} = 1 - [(1-0.9)(1-0.9)] = 0.99 \)
Example

- Seven low lift pumps running in parallel are used to pump sea water to inlet canal
- Water in inlet canal is picked up by high lift pumps to provide cooling for whole plant
- Four have a flow rate of 35,000 GPM
- Three are rated at 60,000 GPM.
Low-Lift Pumps

Two or three pumps are normally needed depending on the capacities of the available pumps.
Low-Lift Pumps

The normal mode of operation is one low and one high capacity pumps giving a combined flow rate of 95,000 GPM.
The flow requirement is only about 80,000 GPM so the excess amount is diverted to the outlet canal, and it is considered a waste of energy.
Low-Lift Pumps

Two or three pumps are normally needed depending on the capacities of the available pumps.
Reliability Engineering

- **Background**
  - The pumps are very old with some being over 50 years of age.
  - Time spent to repair has been very long due to major component failures and waiting for custom-made spare parts.
  - All of this raised concerns about their future capability to sustain the required level of availability.
Reliability Engineering

● Data Gathering And Analysis
  – Six-year worth of failure data history was collected from the Company computerized maintenance management system (CMMS).
  – They all averaged about five-year MTBF and one-year MDT.
  – The current MTBF value of five years was considered acceptable.
  – The MDT of one year was, however, considered to be on the high side.
Reliability Engineering

• Alternative
  - As per Company design practice, the replacement alternative, if found necessary, is three 50% pumps
Reliability Engineering

- Analysis
  - One of the big-capacity pumps is not in operation so it’s not included in the analysis.
  - The required flow rate is 80,000 GPM so any scenario that is capable of providing the required flow is considered a success state.
Reliability Engineering

- Analysis
  - Success states,
    - All pumps being operable is an obvious success state.
    - Two small pumps being operable is a failure state they can provide only 70,000 GPM (2X35,000) when the requirement is 80,000 GPM.
Reliability Engineering

- Success Scenarios
  - There are 16 possible scenarios
    - 12 of which are success states and
    - 4 are failed states.
## Success States

<table>
<thead>
<tr>
<th>State #</th>
<th>No. of Small Pumps</th>
<th>No. of Big Pumps</th>
<th>State Label</th>
<th>Success/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>3</td>
<td>P33</td>
<td>Success</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>2</td>
<td>P32</td>
<td>Success</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>1</td>
<td>P31</td>
<td>Success</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>0</td>
<td>P30</td>
<td>Success</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>3</td>
<td>P23</td>
<td>Success</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>2</td>
<td>P22</td>
<td>Success</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>1</td>
<td>P21</td>
<td>Success</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>0</td>
<td>P20</td>
<td>Fail</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>3</td>
<td>P13</td>
<td>Success</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>2</td>
<td>P12</td>
<td>Success</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>1</td>
<td>P11</td>
<td>Success</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>0</td>
<td>P10</td>
<td>Fail</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>3</td>
<td>P03</td>
<td>Success</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>2</td>
<td>P02</td>
<td>Success</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>1</td>
<td>P01</td>
<td>Fail</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>0</td>
<td>P00</td>
<td>Fail</td>
</tr>
</tbody>
</table>
# Markov Solution

\[
\begin{array}{cccccccccccccccc}
\text{P33} & \text{P32} & \text{P31} & \text{P30} & \text{P23} & \text{P22} & \text{P21} & \text{P13} & \text{P12} & \text{P11} & \text{P10} & \text{P03} & \text{P02} & \text{P01} & \text{P00} & -1 \\
\hline
\text{P33} & -0.4 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.6704 \\
\text{P32} & 0.2 & -1.4 & 2 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.13408 \\
\text{P31} & 0 & 0.2 & -2.4 & 3 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.01341 \\
\text{P30} & 0 & 0 & 0.2 & -3.2 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.00089 \\
\text{P23} & 0.2 & 0 & 0 & 0 & -1.4 & 1 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.13408 \\
\text{P22} & 0 & 0.2 & 0 & 0 & 0.2 & -2.4 & 2 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.02682 \\
\text{P21} & 0 & 0 & 0.2 & 0 & 0 & 0.2 & -3.4 & 3 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0.00268 \\
\text{P20} & 0 & 0 & 0 & 0.2 & 0 & 0 & 0.2 & -4.2 & 3 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 0.00018 \\
\text{P13} & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 & 0 & -2.4 & 1 & 0 & 0 & 3 & 0 & 0 & 0 & 0 & 0.01341 \\
\text{P12} & 0 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 & 0.2 & -3.4 & 2 & 0 & 0 & 3 & 0 & 0 & 0 & 0.00268 \\
\text{P11} & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 & 0.2 & -4.4 & 3 & 0 & 0 & 3 & 0 & 0 & 0.00027 \\
\text{P10} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 & 0.2 & -5.2 & 0 & 0 & 3 & 0 & 0 & 1.8E-05 \\
\text{P03} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 & 0 & -3.2 & 1 & 0 & 0 & 0.00089 \\
\text{P02} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 & 0.2 & -4.2 & 2 & 0 & 0.00018 \\
\text{P01} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 & 0.2 & -5.2 & 3 & 0 & 1.8E-05 \\
\text{P00} & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1.2E-06 \\
\end{array}
\]
Availability Solution

- Solution of current system
  - Availability is the sum of the success states and it was equal to 99.98% for the subject system.

- Solution of alternative
  - Similar availability analysis was done for the replacement alternative; i.e., the 3X50% pumps.
Feasibility Assessment

- The result was a similar level of availability (99.98%).
- It was, therefore, concluded that replacement on the basis of availability was not economically feasible.
Economic Replacement Analysis

So, Availability is not a feasible basis for replacement.

What about other factors
- Unnecessary Extra Capacity
- Maintaining 3 pumps instead of 7

All this savings need to be assessed against Capital investment.
The engineering economic approach is used to evaluate the economic feasibility.
Economic Replacement Analysis

- Estimated replacement capital investment
  - This cost was estimated to be $1000,000

- Return on investment
  - Return on investment is realized through savings of:
    - Unnecessary Extra Capacity
    - Maintaining 3 pumps instead of 7
Unnecessary extra capacity

- The current mode of operation is
  - One small and one big giving a combined flow rate of 95,000 GPM
  - Requirement is only about 80,000 GPM.

- Excess Energy:
  \[
  \text{PSI X GPM} = 7.58 \text{ psi} \times 15,000 \text{ GPM} \\
  \text{HP} = \frac{\text{PSI X GPM}}{1714 \times \text{eff.}} = \frac{7.58 \times 15,000}{1714 \times 0.86} = 77 \text{ hp} = 58\text{KW}
  \]

- This translates to an annual cost savings of about
  - Annual Cost = 58 X 24 hrs X 365 days X $.026 = $13,000
Difference in maintenance costs

- The replacement alternative is three pumps while the current set up is seven.
- Maintaining three pumps should be cheaper than maintaining seven.
- Maintenance history indicates that the average maintenance cost per pump has been about $1000,000 for seven pumps over 18 years. Therefore,
Difference in maintenance costs

- Annual maintenance cost =
  \[
  \frac{1,000,000}{7 \text{ pumps}} \div 18 \text{ years} = \$8,000/\text{pump}
  \]

- Alternative is four pumps less,
  Maintenance savings = 4 \times \$8,000 = \$32,000

- Total return on investment =
  \$13,000 + 32,000 = \$45,000

What do you think? Is this attractive?
The Minimum Attractive Return

- The estimated return is compared to the minimum attractive return

- This is calculated using Compound Interested Tables.
  - Project life window of 20 years
  - Minimum attractive rate of return of 9%,

- This corresponds to 0.11282.
The Minimum Attractive Return

For an investment capital of $1,000,000,

The minimum attractive return

\[ = \$1,000,000 \times 0.11282 = \$112,820 \]

Estimated is less than attractive

Replacement of current system is not economically infeasible.
Six Sigma as Framework
Six Sigma as Framework

- We reviewed a number of reliability improvement approaches (What are they?):
  - Reliability Centered Maintenance
  - Root Cause Analysis
  - Reliability Engineering

- If you had a mechanical seal, which one would you chose?
Six Sigma as Framework

- Which one would you chose for Mechanical Seal?

- How about RCM?
Mechanical Seal & System

MOV

Logic

Dumping ZV

Press Switch

CR

Accumulator

Check Valve

Process

Solenoid Valve

S/O sys

Tank
Six Sigma as Framework

- What about RCA?
Six Sigma as Framework

- We find a number of potential failure modes
  - MOV’s
  - Dump ZV
  - Solenoid
  - Accumulator
  - Instrumentation
Six Sigma as Framework

- So, we recommend monitoring and more stringent PM
- But PM is not free.
- The Question is:
  - Does it Pay off

- To do this, we need Reliability Engineering.
To set optimal PM frequencies, we need to know:

The failure probability and severity at a particular time of:

- a particular component, say MOV
- a combination of components, say MOV&

To build a good model, we need

Reliability Engineering
Need for a framework

So we realize that it’s not one concept that gives us the competitive advantage.

- It’s a mixture of concepts
- We need, however, to put them in a framework

An excellent tool to put them together is Six Sigma.
What is Six Sigma?

Mean arrival time: 6:40
Std. Deviation: 5 min.

6:50
1 min.
What is Six Sigma?

Mean arrival time: 6:40
Std. Deviation: 5 min.
Sigma level: 4 sigma
Less reliable

6:50
1 min.
10 sigma
More reliable
What is Six Sigma?

- Based on SPC concept
- Uses Sigma (std dev) measurement
What is Six Sigma?

- What is Sigma?
- What does it mean?
What is Sigma?

- Let’s take this vibration example,

![Fig-1][1]

![Fig-2][2]

- Which one would you feel more comfortable with?
What is Sigma?

- What is the mean of each?

- Does a better mean always indicate better performance? What else is needed?
What is Sigma?

- At what sigma level is each?

<table>
<thead>
<tr>
<th>Mean</th>
<th>St. dev</th>
<th>Sigma level</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.5</td>
<td>(3-2)/0.5 = 2</td>
</tr>
</tbody>
</table>

What Sigma Level is this?

2.3  0.03
What is Sigma?

- At what sigma level is each?

| Mean     | 2          | 2.3        |
| St. dev  | 0.5        | 0.03       |
| Sigma level | [(3-2)/.5] = 2 | [(3-2.3)/.03] = 23 |
Control Limits

- Would you be surprised if the level falls below 1 mil?
- What about if you see it above 3?
- At what level would you be surprised?
Control Limits

- Would you be surprised if the level falls below 1 mil?
- What about if you see it above 3?
- At what level would you be surprised?
Why Six Sigma?

- What are Control limits
  - What levels make you surprised?
  - Statisticians say it should be +/-3 sigma
  - So, what is it for the first and the second figures?
Why Six Sigma?

● Why 2X?
  - Founders of Six Sigma decided they want
    ● a double car garage.

● Do we need to achieve Six
  - In some situations yes.
    ● Flight accidents
    ● Medical surgeries
  - In plant equipment
    ● Why not? Need to work on both
      - Performance
      - Expectation
Six Sigma DMAIC process

- Six Sigma employs a five-phase process
  - DEFINE
  - MEASURE
  - ANALYZE
  - IMPROVE
  - CONTROL
Define Phase
Define Phase

- Define phase is into three elements
  - Significance of problem
  - Scoping
  - Baseline performance
Significance of Problem

- A new manager briefed MS activities in 3 consecutive morning reports,
- He gets concerned with MS reliability
- MS received attention by plant personnel
- MS proposed for Six Sigma study
- Careful examinations revealed minor maintenance
  - Total Cost $25,000 dollars over a period of 27 months;
  - Average = $11,000.
- How much can we save out of this?
Significance of Problem

Can you think of any other stories to support this.
Scoping

Problem should be scoped down

- To manageable size
- Can’t boil the ocean
- Good tool is Pareto

What is Pareto?
Example Pareto Chart

What are the features of a Pareto Chart?

![Pareto Chart of Component](chart.png)
The above chart is a Pareto of total number of failures by motor type. The charts shows that the Type-A motors have the highest number of failures.

Is Pareto by Count enough?
Process Capability

PC is based on two things

- Performance
- Customer Specs
  - Need to ask Customer
  - What he expects or what’s bothering him
Process Capability

- What are Customer Specs?
- What are reliability indicators?
  - MTBF
  - Availability Index
  - Trip rate
  - Bad actors
  - Rework
Process Capability

- What are reliability indicators?
  - Vibration levels
  - Lubrication lab results
  - Temperature readings
  - Pressure readings
Process Capability

- Process Capability
  - Defect rate
    \[= \% \text{ of those not meeting spec}\]
  - Sigma level
    Can obtain from look up tables
- Overall Capability
  - \( P_P, \ P_{PL}, \ P_{PU}, \ P_{PK} \)
    As per formulas
Process Capability

- Sigma level - 2\textsuperscript{nd} Example

<table>
<thead>
<tr>
<th></th>
<th>Left</th>
<th></th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2</td>
<td></td>
<td>2.3</td>
</tr>
<tr>
<td>St. dev</td>
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<td>Sigma level</td>
<td>[(3-2)/.5] = 2</td>
<td></td>
<td>[(3-2.3)/.03] = 23</td>
</tr>
</tbody>
</table>
Process Capability

Overall Capability
A relative measure of Spec Limits to Control Limits

Is this process Capable?

[Diagram showing UCL and LCL with USL and LSL markers]
Overall Capability
A relative measure of Spec Limits to Control Limits

How about this process?
Process Capability

Overall Capability
A relative measure of Spec Limits to Control Limits

How about this one?
Process Capability

Overall Capability
A relative measure of Spec Limits to Control Limits

How about this one?
Process Capability

Overall Capability

\[ P_{PU} = \frac{(USL - \text{mean})}{3 \text{ StdDev}} \]
Overall Capability

\[ P_{PL} = \frac{\text{mean} - \text{LSL}}{3 \text{ StdDev}} \]
Process Capability

Overall Capability

\[ P_P = \frac{(USL - LSL)}{6 \text{ StdDev}} \]

\[ P_{PK} = \text{minimum} \left( P_{PU}, P_{PL} \right) \]
Process Capability

**Overall Capability Example**

Level data collected on lube oil tank has an average of 75 cm and a standard deviation of 10 cm. The maximum and minimum allowable limits are 100 and 60 cm.

\[
P_{PU} = \frac{(100-75)}{(3 \times 10)} = 0.83
\]
\[
P_{PL} = \frac{(75-60)}{(3 \times 10)} = 0.50
\]
Process Capability

**Overall Capability Example**

Level data collected on lube oil tank has an average of 75 cm and a standard deviation of 10 cm. The maximum and minimum allowable limits are 100 and 60 cm.

\[
P_P = \frac{(100 - 60)}{(6 \times 10)} = 0.66
\]

\[
P_{PK} = \text{minimum} \ (0.83, 0.50) = 0.50
\]
Measure Phase
Elements of Measure

Measure is into two elements

- Ensuring Good Data
- Measuring the Factors
Integrity of Data

- Available data sources:
  - SAP work order system
  - PI data
  - DCS data
  - Oil Condition Monitoring database
  - Vibration data
Ensuring Good Data

What are some problems with Data Integrity

- Is all important data logged?
- Is it logged accurately?
- Does number of WO indicate number of failures?
- What are other problems with data?
Measure Phase

- CMMS work order system
  - Important fields
    - Check breakdown indicator
    - Failure mode
    - Cause of failure
    - Downtime
    - Correction made
Display PM Notification: Malfunction Report

Subject:
Failure Mode: 
Description: K-303 overcall due to vibration

Malfunction data:
Malfunc. start: 03/23/2005 MalfStrt: 12:26
Malfunc. end: 04/04/2005 Malf.end: 00:08
Breakdown dur.: 0.00

Effect on the system:
Funct. loc. affected: B81-SU-ZP0-D0101 Equipment affected: 2628085
D101 SULFUR STORAGE TANK D101 SULFUR STORAGE TANK

System availability:
Avail. bef. malfunc.: 0 Cond. bef. malfunc.: 
Avail. aft. malfunc.: 0 Cond. aft. malfunc.: 
Avail. after task: 0 Cond. after task: 
Display PM Notification: Malfunction Report

<table>
<thead>
<tr>
<th>No.</th>
<th>Code gr...</th>
<th>Obj...</th>
<th>Object part</th>
<th>Code gr.</th>
<th>Da...</th>
<th>Damage</th>
<th>Text</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PM011</td>
<td>S008</td>
<td>SHAFT/ROTOR- ROTATI</td>
<td>PM011</td>
<td>S003</td>
<td>SEIZED</td>
<td>Repair k-303 due to stickey</td>
</tr>
</tbody>
</table>

Catalog Display

- **Damage**: Overview of damage
- **PM011**: PM/plants/ general(all)

- B001: BENT/KINKED
- B002: BLOWN (eg. Fuse)
- B003: BROKEN
- B004: BURNT
- B005: BURST
- B006: BLISTER (ed), (ing)
- C001: CHIPPED
- C002: COLLAPSED
- C003: CRACKED/FRACTURED
- C004: CORRODED
- C005: CRUSHED
- C006: CUT
- D001: DENT/DENTED
- E001: ERODED
- G001: GALLED
- H001: HOLED
- H002: HOT SPOT (Infrared Survey)
### Display PM Notification: Malfunction Report

**Notification**: 20082525 M2 K-303 overhaul due to vibration

**Status**: NOCO ORAS

**Order**: 10268209

#### Item Activities

<table>
<thead>
<tr>
<th>No.</th>
<th>Code group</th>
<th>Activity code text</th>
<th>Activity text</th>
<th>A.</th>
<th>Q.</th>
<th>Start date</th>
<th>Time</th>
<th>End date</th>
<th>Time</th>
<th>Created by</th>
<th>Created on</th>
<th>Cre.</th>
<th>Changed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PM011</td>
<td>R002</td>
<td>REPAIRED (IN KIND)</td>
<td></td>
<td></td>
<td>08:00</td>
<td>11/15/2005</td>
<td>08:33</td>
<td>HASH00YF</td>
<td>11/14/2005</td>
<td>13:54</td>
<td>SAEEA10</td>
<td></td>
</tr>
</tbody>
</table>

#### Catalog Display

- **Activity PM**
  - PM011
    - PM/plants/ general (all)
      - A001: ADJUSTED
      - A002: ALIGNED/ALIGNMENT
      - B001: BACKFILLED
      - B002: BALANCED
      - B003: BABBIT
      - C001: CALIBRATED
      - C002: CLEANED
      - F001: FABRICATED
      - F002: FILLED
      - H001: HYDROTESTED
      - I001: INSPECTION PERFORMED
Measuring the Factors

Soft Tools:
- Brainstorming
- Old reports
- Shop visits
- Can you think of others?
Six Sigma as Framework

- We find a number of potential failure modes
  - MOV’s
  - Dump ZV
  - Solenoid
  - Accumulator
  - Instrumentation

- We make a survey,
Six Sigma as Framework

- Survey Results
  - MOV’s       87%
  - Dump ZV     29%
  - Solenoid    87%
  - Accumulator 70%
  - Instrumentation 0%
Analyze Phase
Analyze Phase

- In Six Sigma, we rely heavily in statistics as possible.
- We trust SME but we like to verify.
- If told that a specific bearing has a better life, we like statistical proof if possible.
- If data is not available, then we may have to depend solely in SME
Analyze Phase

- We, therefore, need some good background in Statistics.
A piece of equipment has a mean life of 5 years & Std Dev of 1 year
Probability Distribution

If we take a new data point and find it above 5 years, Can we say we improved?

No, because there is a 50/50 chance to be above 5yr any way
What about if we find it above 6 years, Can we say we improved?

Maybe, but we’re only 84% confident
What if we want to be 95% confident?
Improve Phase
Improve Phase

- Improve phase is into 2 elements
  - Coming Up with improvement recommendations
  - Proving that they work
    - Through testing before and after
    - Simulation
  - Ensuring they’re cost effective
    - Economic Analysis
Improve Phase

- Evaluation Criteria of recommendations
  - Prevent reoccurrence
  - Within control
  - Meet objectives
  - Do not transfer problem somewhere else
Exercise from Measure Phase

- Trip on LL brg pressure
- Low tank level
- Misleading glass indicator
- Emptying tank is big job
- Ops not reporting leak (minor)
Exercise

A critical pump experienced a number of trips caused by low bearing oil pressure. Investigation showed it was due to low level in the lube tank. The Operator said he was misled by oil build up on glass indicator. PM technician was not cleaning the glass indicator because that required emptying the tank which is a major job. When Operator blamed for not reporting leaking bearing, he advised it’s only a minor one.
### Improve Phase

#### Example evaluation (Lube oil tank - low level)

<table>
<thead>
<tr>
<th>Recommendation</th>
<th>Meets Objective</th>
<th>Within Control</th>
<th>Doesn’t Transfer elsewhere</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modify to detectable sight glass</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Install level Switch</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Training to Operator</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proper PM tools</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Improve Phase

- Ensuring effectiveness of solutions
  - After coming up with what are thought to be effective solutions, their effectiveness should be ensured
  - Six Sigma strongly encourages reliance on statistical evidence
Improve Phase

- Possible ways of ensuring effectiveness of solutions
  - Test before and after
  - Simulation
Simulation

- Simulation simply means simulating the solutions before implementation
Low-Lift Pumps

Sea

Outlet Canal

4 X 60,000 GPM pumps

3 X 35,000 GPM pumps

Excess Capacity
Feasibility Assessment

- The result was a similar level of availability (99.98%).
- It was, therefore, concluded that replacement on the basis of availability was not economically feasible.
The Minimum Attractive Return

For an investment capital of $1,000,000,

The minimum attractive return

\[ = $1,000,000 \times 0.11282 = $112,820 \]

Estimated is less than attractive

Replacement of current system is not economically infeasible.
End of Improve Phase
Control Phase

- So you,
  - Look at a key process
  - You define it well
  - You measure all critical factors
  - You analyze your situation very well
  - You make recommendations and you ensure they work

Is this enough?
Control Phase

- Things often go back to where they were.
- It’s important to sustain the improvement.
- This is why we need good CONTROL
Control Phase

- For good Control, we need to understand
  - The Capability of our system
  - Monitor this capability for shifts and drifts
Control charts

- To illustrate, let’s look at real story

![C Chart of C4](image)

- $C = 9.25$
- $UCL = 18.37$
- $LCL = 0.13$

Sample Count

Sample

1 2 3 4 5 6 7 8 9 10 11 12
The first two months, a few trips reported. The manager decided to award everybody.

After the award, things started to get bad so he regretted the award and decided to do punishment instead.

Things started to go well again. So he’s now sure that this is what they really need.

Few months later, things started to go bad again.

What’s wrong?

Nothing, this is only normal process variation.
Control Phase

- The only one worth investigating is point 11
Control Phase

- After knowing the process capability, we need to put a control plan to ensure:
  - Sustainability
  - Controllable shifts and drifts
Control Phase

Control is into two elements

- Control Plan
- Control Charts
Control Plan

- Control Plan:
  - Provides Memory and a reference point to what is being controlled
  - Provides timely troubleshooting of process
  - Documents project action items
  - Control plan is a living document
  - It ensures that a Six Sigma project is ready to be implemented
Control Plan

- **Example:**

<table>
<thead>
<tr>
<th>Sub process</th>
<th>Step</th>
<th>LSL</th>
<th>USL</th>
<th>Freq.</th>
<th>By Who</th>
<th>Where Recorded</th>
<th>Correct Action</th>
<th>SOP Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lube Oil Pressure</td>
<td>Measure Tank level</td>
<td>80 cm</td>
<td>100 cm</td>
<td>Every 7 days</td>
<td>Ops</td>
<td>Ops Log book</td>
<td>Refill</td>
<td>SOP 101</td>
</tr>
</tbody>
</table>
Control Charts

- Control Charts:
  - A tool for early detection of shifts and drifts
  - Distinguishes special from random causes of variation
  - Helps process performs consistently
  - Provides a common language
Types of Control Charts:
- Many types
- We’ll discuss two
Control Charts

- X-bar Chart
  - A control chart showing the upper and the lower control limits around the mean of the output of a production process.

\[
\text{UCL} = \text{mean} + 3 \times \text{SE}_M \\
\text{LCL} = \text{mean} - 3 \times \text{SE}_M
\]
Example

The vibration levels at the inboard bearing have been known to be 0.12 ips with a standard deviation of 0.04 ips. The reliability engineer collected a sample of 24 readings (every hour) for 7 days.

What are the UCL and LCL.
X-bar Chart

- Solution
  - \( SE = \frac{0.04}{\sqrt{24}} = 0.008 \text{ ips} \)

\[
\begin{align*}
\text{UCL} &= 0.12 + 3 \times 0.008 \quad = 0.144 \\
\text{LCL} &= 0.12 - 3 \times 0.008 \quad = 0.096
\end{align*}
\]
If one-week samples are as follows:

0.104, 0.136, 0.112, 0.112, 0.128, 0.104, 0.112
Six Sigma Infrastructure

- Three possible ramps
  - Business Transformation Approach
    - Full Scale and examines all key processes
    - Break away from old habits
    - Regain lost customers and heal from heavy losses
  - Strategic Improvement Approach
    - Addressing a couple of key processes
  - Problem Solving Approach
    - Tap into benefits without major change. Wherever there is an opportunity, we will grab it.
Six Sigma Infrastructure

- Once an approach is selected, collection of key personnel is charted
  - **Black Belts** are responsible for leading the projects
  - **Green Belts** are trained in a subset of the methodology
  - **Master BBs** are experts and they coach BBs and GBs
  - **Champions** select the projects and provide logistic Support & sustain momentum
  - **Process owners** take ownership of completed projects & maintain gains
  - **Finance champions** establish clear financial criteria and certify savings.
    - Tap into benefits without major change.
Six Sigma Infrastructure

Part of the infrastructure is also

- Management Support
- Intensive training
- Software
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+966546459548