Designing for Reliability in Capital Projects

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An Introduction to a Common Sense Strategy

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Your system is perfectly designed
to give you the results
that you get.

W. Edwards Deming
Harrington reported that large capital projects typically take 20% longer than planned, and are up to 80% over budget. See the chart below.

![Chart showing estimated overrun in capital expenditure, % of original quoted capital expenditure vs. delay beyond original schedule, years.]

Source: Chris Harrington, ARMS Reliability, Role of Simulation To Support Reliability in Design, IMC-2019

Source: Global Projects Database, IHS Herold, Nov 19, 2013; herold.com; McKinsey analysis
Market Survivor Profile

(Prices trend down over time. We create a future by driving unit costs down, through continuous Improvement, or “little” innovation. How will we minimize our unit costs, in the design?)

Market Price

Profit = (Price – Cost) x Volume

Market Share

Unit Cost = Cost/Capacity

“Big” Innovation-
Your Future

“Little” Innovation
Drives costs down

A

B

C

The RM Group, Inc., Knoxville, TN
Unit Cost = \frac{Total\ Manufacturing\ Cost}{Total\ Capacity\ (throughput)}

- Low cost requires ease of operation and maintenance

  *Built into the design*

- High capacity requires high reliability and availability

  *Built into the design*
Cost Management is not the same as cost cutting

• Costs are a consequence of your practices – Your system’s design

• How will we provide for ease of operation and ease of maintenance, for maximum capability?

• How will we manage our unit costs, in the design?
AU/OEE & Loss Accounting - How will we use this data to reduce our losses in this design?

- **Scheduled Downtime** (minimize through better PM, PdM, planning)
- **Unscheduled Downtime** (minimize through better operating practices, defect elimination, PM, PdM)
- **Process Rate Losses** (minimize through better process control, consistency, standards)
- **Quality Losses** (minimize through better standards, control, conformance)
- **Changeover/Transition Losses** (minimize through quicker changeovers, better production planning)
- **No Demand/Market Losses** (lower costs, better alignment-marketing and manufacturing)

AU and OEE measure capital efficiency - Why spend more capital? Find your hidden plant! We must understand all losses from ideal and make business decisions to reduce them.

The RM Group, Inc., Knoxville, TN
Relationship between Reliability and Safety (and Costs)

How will we assure reliability, and reduce the risk of injury and costs,

*in the design?*
Injury Rate v. AU/OEE over Time - Company A

![Graph showing the relationship between Injury Rate and OEE/AU over time.](image)

- **R = 0.80**
- **R² = 0.64**

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The RM Group, Inc., Knoxville, TN
PM & PdM Work Orders vs. Injury Rate – Plant No. 1

Source: Large Chemical Plant - A
Total Recordable Injury Rate vs. Reactive Maintenance

TRIR vs. Reactive Mtce

Reactive Mtce Levels,
Best 25%, Middle 50%, Worst 25%
(Emergency + Unplanned, Avg of Four Quartiles)

Source: K. Blache, Reliability and Maintainability Center, University of TN, 2019
Mtce Costs vs. Reactive Mtce, 140 Companies w/3,000 Facilities

(Mtce Costs vs. Reactive Mtce)

Reactive Mtce Levels, %
(Emergency + Unplanned, Avg of Four Quartiles)

Source: K. Blache, Reliability and Maintainability Center, University of TN, 2018
Cost Effectiveness - Reliability Index $\text{v.}$ Production Unit Costs

Reliability Index (composite of design, procurement, operating and maintenance practices)

Source: Large Industrial Manufacturer-B
Equipment & Process Defects Reduce Reliability, Increase Hazards

Reliability Pyramid - Ledet

10 losses
6,500 repair work orders
20,000 defects
Numerous Minor Process Errors
Operational Discipline is essential to eliminate defects and process errors

Process Safety Pyramid - Hopkins

Major Accident
Loss of Containment
Process Safety Breach
Major Incident
The Reliability Process

A Commitment to Safety Requires a Co-Commitment to Reliability and Related Policies and Practices,

Beginning with the Design
Source: In Cooperation with Andrew Fraser, Reliable Manufacturing Ltd.
SMRP and SAE have definitions focused on equipment/maintenance – not sufficient

Maintenance does not control reliability; it’s essential for support

Downtime is not a good measure of reliability – it misses issues

Think *Process Reliability – the ability of a system to deliver the maximum in quality product, on time, in full, at the lowest sustainable cost*

OEE – the best measure of reliability
Design/Capital Projects
Assure Reliability, Operability, Availability, and Maintainability
(avoid Minimum Adequate Design – MAD; it depends on your viewpoint)
Phases of Life-Cycle Cost Commitment

- **Planning**: 66%
- **Preliminary Design**: 30%
- **Final Design**: 50%
- **Construction/Startup**: 65%
- **Operation & Maintenance**: 85%

Sources:
2. John Schultz, Allied Reliability, Charleston, SC
Life Cycle Cost and Cash Flow Considerations

- **Life Cycle Cost Policy**
- **Cash Flow ($)**
- **Time**
- **ROI**
- **Invest (~10%)**

Minimum Life Cycle Costs => Maximum Long Term Profits

The RM Group, Inc., Knoxville, TN
BUY/PURCHASE -
For Reliability using
Good Specifications & Standards, Strategic Alliances

Does capital projects focus on price, or Total Cost of Ownership?
• Total Cost of Ownership- costs include:
  • Price
  • Drawings, bill of material, manuals, etc.
  • Selection effort, including company staff, travel, etc.
  • Procurement transaction, freight, duties
  • Delivery, assembly, installation, startup
  • *Performance capability, efficiency, operability*
  • *Maintenance/PM requirements, maintainability*
  • *Parts stocking, inventory, warranty*
  • *Service levels (or lack thereof)*
  • Other costs…

• Only ~25% of total cost of ownership is price!
STORES

How will projects assure reliability and availability of spares?
What parts do you need?

• Make a list of your critical equipment
• For each equipment, ask:
  • What fails most often? Usually it’s belts, bearings, seals, fuses, o-rings, gaskets, filters, etc.
  • Make sure you have these in adequate quantity!

• Now ask - What doesn’t fail very often, but when it does it’s really a serious problem?
• Now, make a business decision about the risk of having or not having the spare, i.e., the capital/carrying cost vs. the probability and consequence of failure

• Balance the risk of loss, in maintenance efficiency and production, vs. cost of capital
Don’t Assume Vendor PM is correct: Review of Vendor PM Recommendations—964 Tasks Analyzed (Identified 96 new failure modes)

Source: Steve Turner, OMCS International, Australia
• Design the warehouse to retain reliability:
  • Bar coding for ease of tracking
  • Well lit and tidy storeroom
  • Ease of storage and access
  • Staging area for kitted parts; receipt inspection
  • Humidity and static control
  • Covered bearings, seals
  • Shelf rotation as needed
  • Proactive coating/covering etc.
  • Shaft rotation of machinery

• Receipt inspection: At one large company, 14% of parts received did not match the PO’s

• Beware of counterfeit parts – Some 10-15% of parts are counterfeit (See thecounterfeitreport.com, and stopfakebearings.com)
INSTALL and STARTUP

The greatest risk of defects/failures is at startup. How will projects minimize that risk?
Rohm & Haas says you’re 7-17 times more likely to introduce defects during startup (than normal operation)

BP says incidents are 10 times more likely during startup

The chemical industry reported process safety incidents are 5 times more likely during startup

New equipment can have twice the number of infant mortality defects as existing equipment

92% of rotating machinery is reported to have defects at startup that result in premature failure

Precision is Critical -

How will projects assure precision installation – in balancing, alignment, lube oil, foundations, etc.?
OPERATE RELIABLY – with care and precision, and within process limits

How will projects provide for ease of operation?
Most losses from ideal production (AU/OEE losses) are *not* related to equipment downtime. Of those that are equipment related, most are due to poor operation; Only ~ 10% of production losses are typically maintenance-controlled.

Sources: 1) Author’s experience with clients; 2) Similar findings reported by BASF-UK (Stevens), and Borg-Warner-US (Cerny)
To address these issues, we must have:

• Production and maintenance partnership- good communications, teamwork, common measures
• Consistency of operation across shifts
• Process Conformance and Capability
• Good shift handover practices
• Operator care/PM, training and skills
Operator Care/PM vs. Maintenance Costs
(Avg data at each level for 200 plants)
How will capital projects support operator basic care – ease of operation and maintenance?

Level 1 – None/Starting
Level 2 – Some PM checks
Level 3 – Regular PM checks
Level 4 – Regular PM checks & some repairs

Source: Reliability and Maintainability Center Newsletter, University of TN, July 2009
MAINTAIN

Will projects provide reliability (fewer failures) and maintainability?
Common Maintenance Practices
Excess Defects Lead to Reactive Practices

Benchmark Maintenance Practices

Eliminate or Detect & Manage Defects;
Cost half as much; fewer injuries /incidents

You will not achieve this without a production and maintenance partnership, one that is production led

But, most failures are random (80-90%+)(see the component histogram below)
How do we manage this, in the design?

Random Failure Pattern is Common;
84% of failures are caused by poor work practices,
resulting in random failures (W. Ledet)

Source: Component Manufacturer
### Age Related Failure Curves

**How will we manage these in the design?**

<table>
<thead>
<tr>
<th>Source</th>
<th>UAL Bromberg 1968</th>
<th>US Navy '93 / '01</th>
<th>Plucknette 2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>(United Airlines)</td>
<td>4%</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>(Surface/Sub)</td>
<td>2%</td>
<td>1%</td>
<td>17%</td>
</tr>
<tr>
<td>(Mfg Industry)</td>
<td>5%</td>
<td>4%</td>
<td>3%</td>
</tr>
<tr>
<td>3 / 2%</td>
<td>17 / 10%</td>
<td>17%</td>
<td>6.5%</td>
</tr>
<tr>
<td>3%</td>
<td>3.5%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Sources:**
1. S. Nowlan and H. Heap
2. L. Pau
3. American Management Systems
4. T. Allen
5. D. Plucknette
Random Failure Curves

How will we manage these in the design?

UAL 
1968
(United Airlines)
7%
7%

Bromberg
1973
7%

US Navy
’93 / ’01
6 / 9%
6%

Plucknette
2005
13%

(Surface/Sub)
(Mfg Industry)

Sources:
1. S. Nowlan and H. Heap
2. L. Pau
3. American Management Systems
4. T. Allen
5. D. Plucknette
Maintenance Strategy Redefined
(in the design)

• Some 67% of eqpt. - infant mortality failure pattern
  • Startup and commissioning must be superb!
  • We *must* avoid unneeded maintenance which can re-start
    infant mortality failures

• As much as 80-90% of failures occur randomly:
  • We *must design* condition monitoring into our processes
    and equipment to detect and/or prevent onset of failure
Understand the Degradation Process
(Avoid or Minimize the Risk and Consequence of Failure in the design)

Sources: Ivara Corp, Hamilton, Ontario
*R. Baldridge, Cargill

Onset of Failure
Detect Potential Failure - System Meeting All Requirements
Functional Failure - System Not Meeting All Requirements

Pending Failure Not Detected (PM- too much, too soon?)
Prioritize, plan, schedule, do "PF Interval"
Performance Losses (too little, too late)

Proactive* Stop/Delay Onset of Failure*
Predictive*
Protective*

Broken- $$$

Time
Maintenance Costs v. PdM% (Typical Correlation)

Database - minimum of 25 plants; minimum of 5 companies

R² = 0.96

Source: John Schultz, Allied Reliability, Inc.; Charleston, SC
Maintenance Costs v. % PM

(Same study)

Source: John Schultz, Allied Reliability, Inc.; Charleston, SC
Don’t Assume Vendor PM is Correct

Review of Vendor PM Recommendations—964 Tasks Analyzed
(Identified 96 new failure modes)

Source: Steve Turner,
OMCS International, Australia
Planning and Scheduling must be supported in the design

- Asset registry and criticality analysis is done, incl. spare parts and PM/PdM/CM requirements and maintenance plans for each equipment
- OEM manuals and bills of material are available electronically on all equipment
- Capital and routine spares are in the warehouse
- Maintenance program is loaded in the CMMS when commissioning is complete, a milestone in the project schedule
- Budget 2 – 5% of the installation cost for preparing the maintenance strategy

Source: Antonie Jacobs, ARMS Reliability
Case Study – Fishman Chemicals (not its real name)
Applying Reliability Based Design
Fishman Chemicals had previously built a large process plant, Noki 1, experiencing numerous problems during startup and initial operation.

- Required some 18 months to come fully on line
- Repeated process instability events
- Numerous equipment failures
- Inadequate parts to support repairs
- Inadequate training of ops. and mtce. staff contributed to all this
• In spite of all this, market demand was excellent, and a second plant was anticipated in ~3 years

• They were determined not to repeat the previous experience with this plant, Noki 2

• They followed reliability based design principles:
  • Additional funds were budgeted for additional work, during the planning phase
  • A process was created for engaging staff from Noki 1
  • The same project manager from Noki 1 ran Noki 2!
Changes were made in the new design applying the learning from Noki 1, e.g.:

- Improved process control systems
- Stainless steel vs. carbon steel
- Standardized reliable pumps with a wider operating range
- More robust equipment in general
- Improved access to equipment
- Better installation criteria for fitups, access, etc.
• Results were remarkable:
  • The plant came fully on line within two months
  • It was consistently more reliable, having lower operating and maintenance costs than Noki 1
  • The extra budget for applying reliability based design up front was NOT spent
  • Less re-work during construction resulted in lower construction and startup costs
  • A culture shift occurred – people started believing that the processes worked to make their lives easier
  • However, feedstock quality and availability were growing poorer, necessitating further changes for Noki 1, 2, & 3
**2ND Case Study - Impact of Designing for Reliability on Total Cost of Ownership (LCC)**

The RM Group, Inc., Knoxville, TN

Source: Ramesh Gulati, Jacobs Engineering
Reliability Based Design
Design for Reliability, Operability, Availability and Maintainability
Harrington reported that large capital projects typically take 20% longer than planned, and are up to 80% over budget. See the chart below.

Source: Chris Harrington, ARMS Reliability, Role of Simulation To Support Reliability in Design, IMC-2019

Source: Global Projects Database, IHS Herold, Nov 19, 2013; herold.com; McKinsey analysis
Are you applying the following to your capital projects:

- Lowest Life Cycle Cost? or Installed Cost?
- Specific goals for asset utilization, availability, reliability?
- RCM/FMEA for reliability, PM and spares?
- Ease of operation and maintenance
- Disciplined process for shop floor input?
- “Hurdle” rate for existing overall asset utilization (AU) before new capital?
- 2-5 year post project review as to actual Return on Investment?
Design and Project Objectives

• You must have good specifications, standards, procedures, budgets, schedules, etc.

• Most projects are rigorous on this, especially for budgeting and scheduling, but often do not address reliability needs.

• What questions should we be asking regarding reliability, operability, and maintainability?
Key Questions to Ask
Reliability Based Design Requirements

• Key questions- Do our processes include:
  • A policy statement for applying life cycle cost and reliability principles?
  • Specific life cycle cost models? (See Table 1)
  • Specific reliability requirements?, e.g.:
    • Availability of 99%
    • OEE/AU of 85%+
    • Mean time between repair of say 360 days
    • Mean time to repair of say 8 hours
    • First Pass-First Quality of 99%
    • Effective Yield of 98%, etc.
Reliability Based Design Requirements (cont.)

- Specific maintainability requirements, e.g.,
  - access
  - lifting
  - monitoring, etc. (See Table 2)
- Minimum AU/OEE requirements for existing equipment before authorizing new capital for increasing capacity, e.g. >80%?
- The use of software models, e.g., Raptor, for predicting the reliability of our designs based on historic performance of similar equipment?
- Explicit rigorous definitions and goals for reliability and maintainability? AU/OEE? (See Table 4)
Reliability Based Design Requirements (cont.)

• Review of similar plants and equipment: their losses and equipment failures due to poor operability, maintainability and reliability?

• Key design parameters which will assure high reliability, or result in low reliability?

• Development and use of “best practice” procedures and standards for this type plant/equipment?
Reliability Based Design Requirements (cont.)

- Process for a thorough review of the *preliminary* design by the shop floor, **before** project authorization?
  
  (Drawings “over the wall” late Thursday, and expecting comments by early Monday, is **NOT** a review process)

- Shop floor project team members, where appropriate?

- Adequately skilled project staff to address all the issues herein?

- Requirement for supplier performance of RCM or FMEA analysis on critical equipment to eliminate failure modes?

- Application of RCM or FMEA by suppliers or designers for determining PM and spare parts, as part of the design?
Reliability Based Design Requirements (cont.)

• Considering the relationship between safety and reliability explicitly in our design efforts?
• Review of the assumptions being made regarding process control:
  • process or physical transients?
  • sensitivities of the equipment and processes to these transients?
  • inherent control limits, and capability?
• From this, is there adequate (kind and quantity) instrumentation for process control?
• Do we have clear set points, alarm limits, and calibration requirements, all reviewed by sr. operators?
Reliability Based Design Requirements (cont.)

- Explicit training requirements for operators? For skilled trades? How and when will this be accomplished?
- Addressing any specific ergonomic issues for plant and/or equipment?
- Requirement for using standard supplier partners? And a rigorous policy for any exceptions?
Reliability Based Design Requirements (cont.)

• Requirement for suppliers to include a detailed bill of material, drawings, manuals, and related documents for their equipment, both electronically and hard copy?

• Purchasing’s role in the reliability based design effort? Do we have supplier partners who provide high reliability? Supplier alliances?

• Requirement for suppliers or contractors to pack, ship, and store equipment to retain its reliability during the construction phase (e.g. no hold down straps on motor shafts); and stores capability for continuing support thereafter?
Reliability Based Design Requirements (cont.)

• Requirement for stores participation in the design or installation effort?
• A process for disposition of “excess” equipment at the end of a project, e.g., return to supplier, put into stores, etc.
• Requirement for contractors to have specific validation criteria and explicit commissioning standards for their work? Will they “deliver an effect” (reliability), or simply install equipment? (See Table 3); Note that some 67% of failures are infant mortality
Reliability Based Design Requirements (cont.)

• Requirement for operators and skilled trades to participate in the startup and commissioning process of major projects? Define the process.

• Process for post installation support, e.g.: *The Project Engineer as the maintenance engineer for one year after start up?*

• Process for “project warranty coverage”, e.g., back-charging the project for poor quality work and errors
Reliability Based Design Requirements (cont.)

• A post project review as to: What was done well? Poorly? Lessons learned?
• Process for validating the project’s analysis as to return on investment, and reliability goals, five years hence?
• A policy or methodology for resolving conflict regarding lowest installed cost or lowest life cycle cost?
• Anticipation of higher design engineering costs for a longer, yet more comprehensive design process, and reduced life cycle costs?
The Way Forward

- Assessment of our current design/project practices
- Development of a draft policy for capital projects requirements
- Development of our next steps:
  - Policy review and finalization
  - Action plan to address shortfalls
  - Implementation
### Assessment of Current Practices

On a scale of 0-10, provide an honest assessment of your score on the practices and issues indicated below. A score of zero indicates no system is in place or the practice is non-existent; a 10 indicates perfection or no room for improvement. Most people will be somewhere in between. When completed, add each category to get a total score out of 100 possible.

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Score (10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Do project engineers and designers use specific life cycle cost models, vs. lowest installed cost, in a disciplined way?</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Are specific reliability requirements, e.g., availability of 99%, uptime/OEE of 85%+, MTBF, MTTR, etc., converted into actual design requirements?</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Are there minimum specific Asset Utilization/OEE or other performance requirements for existing equipment that must be met before authorizing new capital for increased capacity or capability?</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Are there specific maintainability standards that we apply, e.g., access, lifting, monitoring, laydown space, etc., in the project management process?</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Do we use explicit standards for commissioning the process, and for verifying the quality of equipment installation, including contractor efforts?</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Do we have and use a process for a thorough review of the preliminary design by the shop floor, before project or subsystem authorization?</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Do we require our suppliers to perform a RCM or FMEA analysis on critical equipment to improve its reliability, as appropriate?</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Do we use RCM /FMEA for determining PM and spare parts needs using operational experience, equipment histories, etc., as part of the design?</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Do we use processes for validating the project analysis as to return on investment, reliability goals, etc., some 2-5 years after start up?</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Do we use a definitive process for post installation support; for example, project engineer as maintenance engineer for one year after startup? Or, for chargeback to the project for design/installation errors corrected by the operating plant?</td>
<td></td>
</tr>
</tbody>
</table>

Name: ____________________________  Plant: ____________________________  Total Score: ______ (100)
Using your response to the questions above as a guide, as well as other experience and requirements, define clearly your capital projects policy as it relates to reliability requirements, and your measures of success:

1. Select the top few (3-5) areas where policies need to be established, or reinforced.
2. Identify any other areas where related policies need to be established in support of these, e.g., your asset management strategy or policy.
3. Identify any corporate support necessary for these or other policies.
4. Any other issues which must be addressed or integrated, e.g., purchasing, stores, in-line spares policy, etc?
5. Describe the process for policy implementation.
6. Define your measures of success for the implementation of these policies.

The thrust of this exercise is to complete the following statement:

As a matter of policy, our capital projects must assure that we...
1. Think about the material covered on reliability and capital project principles.

2. What are the “Top 3” actions you’re going to take as a result of this workshop? You might: Make one something you can get done in one week; or one month; or three months; or less than one year; Make one something that requires teamwork between projects, operations, and maintenance.

3. If you’re here with associates at your plant or business, share with them your actions and work with them to develop an action plan or set of key next steps you can take on returning to your business.

4. List the three actions you’re going to take:
   A. Action: ____________________________ by when: ____________
   B. Action: ____________________________ by when: ____________
   C. Action: ____________________________ by when: ____________