Root Cause Analysis (RCA)

An essential element of Asset Integrity Management and Reliability Centered Maintenance Procedures

Dr Jens P. Tronskar
Root Cause Analysis (RCA) is a structured process that uncovers the physical, human, and latent causes of any undesirable event in the workplace.

Can be:
- Single or multidiscipline cases
- Small or large cases
Some other definitions

Failure Cause –

• The physical or chemical processes, design defects, quality defects, part misapplication, or other processes that are the basic reason for failure or that initiate the physical process by which deterioration proceeds to failure.

• The circumstances during design, manufacture, or operation that have led to a failure.

Failure Effect – The consequence(s) a failure mode has on the operation, function, or status of an item.

Failure – The termination of its ability to perform a required function.

Failure Mode – The effect by which a failure is observed on the failed item.
Root Cause (RCA)

- Indispensable component of proactive and reliability centred maintenance
- Uses advanced investigative techniques
- Apply correctives
- Eliminates early life failures
- Extends equipment lifetime
- Minimizes maintenance
Traditional maintenance strategies tend to neglect something important:

*Identification and correction of the underlying problem.*
A Root Cause Analysis will disclose:

- Why the incident, failure or breakdown occurred
- How future failures can be eliminated by:
  - changes to procedures
  - changes to operation
  - training of staff
  - design modifications
  - verification that new or rebuilt equipment is free of defects which may shorten life
  - repair and reinstallation is performed to acceptance standards
  - identification of any factors adversely affecting service life and implementation of mitigating actions
Improved availability “up-time” and increased production
Reactive maintenance

• Run the equipment until breakdown
• Overhaul and repair
• Extensive unplanned downtime and recurrent repair
Periodic maintenance

- Scheduled calendar or interval-based maintenance
- Expensive components exchanged even without signs of wear or degradation
- Unexpected failures with incorrect schedules and component change-out
Predictive maintenance by condition monitoring

- Apply technologies to measure the condition of machines
- Predict when corrective action should be performed before extensive damage to the machinery occurs
Short and long-term benefits of Proactive Maintenance Strategies involving RCFA:

Optimization of service conditions:

- Increased production
- Reduced downtime
- Reduced cost of maintenance
- Increased safety
Experience and statistical data

MMS DATABASE
- Information on equipment design and service conditions
- Failure statistics i.e. MTBF
- Description of service failures, approach and methods for failure investigation
- Consequences of failure:
  - Downtime/pollution and spillage/secondary damages
- Causes of failures
- Recommendations and remedial actions
Methods and analytical tools to identify the causes of failure or breakdown

- Review background data
- Loss Causation Model and RCA methods and working process

Detailed analyses of failed parts/components:
- Analyse service conditions
- Utilise experience data from data bases or other sources
- Laboratory investigation
The Loss Causation Model

© Det Norske Veritas

The main causes…

Something is done wrong or gone wrong

A failure

Here the losses occur

MANAGING RISK
Data Collection

- Interviews
- Documents (paper) evidence
- Parts/component evidence
Interviewing Considerations

- Where to interview
- Who to interview
- Condition of people at the scene
- How to handle multiple witnesses
- How to handle after the incident
- How to work with teams
Investigation techniques

- A number of named techniques that are commonly used within RCA:
  - Step-method
  - FMEA
  - Bow-tie
  - Event Tree
  - Failure Tree
  - Interview
  - Fish Bone
  - Why-Why

- The techniques have strength and weaknesses depending on the situation.
Methods for RCA; Content

• Data Collection
  – Interviews
  – Paper and technical evidence

• Methods for RCA
  – STEP
  – FMEA
  – FTA
STEP 1: Register Equipment Incidents

Purpose: Register Off-spec. Operation / performance, Survey & Condition Monitoring data
Start: Triggered by off-spec. operation/performance, Survey & Condition Monitoring data
Stop: Incident logged in Maximo

Register Equipment Incidents

Input to Process
- Off-spec operation / performance:
  - Equipment failure
  - Trips
  - Abnormalities
- Survey/Inspections/ Audits/Reviews and Condition Monitoring by Maintenance

Process control
- Issue Run-Log or Work Request in Maximo
- Assess cause of failure
- Perform short-term Corrective action
- Failure report in Maximo

Expected output from Process
- Off-spec operation/ performance logged in Maximo:
  - Equipment failures
  - Trips
  - Abnormalities
- History of Condition Monitoring, Surveys, and Recommended Maintenance Action in Maximo

Resources
- Operation department
- Maintenance department
- Maximo

Managing Risk
STEP 2: Trigger Mechanism for RCA

**Purpose:** Evaluate need for RCA

**Start:** Registered HSE issues or off-spec operation/performance incidents

**Stop:** Start RCA

**Input to process:**
- Off-spec operation/performance: Equipment failures
  - Trips
  - Abnormalities
- Surveys, Audits, Inspection, Reviews and Condition monitoring by Maintenance

**Process control:**
- Single incidents with high production loss or repair cost
- Prepare monthly report per site
- Prepare quarterly report for HQ
- Do Preliminary LCC; Actual Loss/Cost vs Investment (Replacement)

**Expected output from process:**
- Incidents above trigger level
  - Single operation incidents with production loss/repair cost > X
  - Off-spec operation vis-à-vis (KPI)
  - Multiple operating incidents per Tag no./Equipment type
  - High risk findings from survey/CM

**Recommended RCA Case:**
- Incidents below trigger level, and mitigation not cost effective
- No Action

**Resources:**
- Plant Reliability Engineer/Senior Planning Engineer
- HQ Senior Reliability Engineer
- Reliability Engineer (Plant/HQ)

**MANAGING RISK**
STEP 3: Appoint the RCA Team

- **Minor RCAs:**
  - Run within a department, using the procedure

- **Larger RCAs:**
  - Leader – appointed by the Plant manager
  - Facilitator – reliability engineer.
  - Discipline(s) or specialists at specific plant

- **Optional to involve:**
  - Disciplines from other sister plants
  - HQ-Engineering support and technical staff
  - Vendor
  - Failure laboratories
  - Other 3rd parties
  - Specialist
STEP 4: The Root Cause Analysis

RCA method steps

MANAGING RISK
The main RCA report

1 Description of the Incident(s)
An incident is the event that precedes the loss or potential loss. This section should include a description of what happened. Include all aspects related to the incidents, like outage time, cost of repair, people involved, tools in use, operational status, weather conditions etc.

2 Immediate Cause(s)
The immediate causes of an incident are the circumstances that immediately preceded the contact and can usually be seen or sensed. For example if the incident is an oil spill, the immediate cause could be a broken sealing. The Immediate Causes often are the same as the failure codes registered in Maximo.

3 Basic Cause(s)
Basic Causes are the real causes behind the immediate causes: the reasons why the substandard acts and conditions occurred, the factors that, when identified, permit meaningful management control. In case of an oil spill caused by a broken sealing, the Basic Causes could be that the sealing used was of wrong type, it had a design failure or it might be installed wrong.

4 Lack of Control
Lack of Control means insufficient oversight of the activities from design to planning and operation. Control is achieved through standards and procedures for operation, maintenance and acquisition, and follow-up of these. If an oil spill has occurred because of wrong installation of a sealing, the Lack of Control could be related to inadequate procedures for checking after maintenance.
<table>
<thead>
<tr>
<th>Loss: Description of the Incident</th>
</tr>
</thead>
</table>

**Immediate Causes**

<table>
<thead>
<tr>
<th>Sub-Standard Condition (A):</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Detect Equipment &amp; Tools</td>
</tr>
<tr>
<td>2. Working Environment</td>
</tr>
<tr>
<td>3. External Weather</td>
</tr>
<tr>
<td>4. Control / Operation</td>
</tr>
<tr>
<td>5. Production Profile</td>
</tr>
<tr>
<td>6. Mobilization of equipment</td>
</tr>
<tr>
<td>7. Modification of equipment</td>
</tr>
<tr>
<td>8. Deterioration / Corrosion</td>
</tr>
</tbody>
</table>

**Basic Causes**

<table>
<thead>
<tr>
<th>Personal Factors (B):</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Inadequate knowledge of the working process</td>
</tr>
<tr>
<td>2. Inadequate Competence</td>
</tr>
<tr>
<td>3. Motivation</td>
</tr>
<tr>
<td>4. Physical and psychological load during work</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Causes related to the work (B):</th>
</tr>
</thead>
<tbody>
<tr>
<td>10. Inadequate management and control of work</td>
</tr>
<tr>
<td>11. Design Failure (or lack of design)</td>
</tr>
<tr>
<td>12. Purchasing</td>
</tr>
<tr>
<td>13. Maintenance</td>
</tr>
<tr>
<td>14. Ageing / Obsolescence</td>
</tr>
</tbody>
</table>

**Lack of Control**

<table>
<thead>
<tr>
<th>Lack of Control (C):</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Inadequate Management System</td>
</tr>
<tr>
<td>2. Inadequate system standards</td>
</tr>
<tr>
<td>3. Inadequate compliance with routines</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Causes related to the work (C):</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. Inadequate Maintenance Procedures</td>
</tr>
<tr>
<td>5. Inadequate Operational Procedures</td>
</tr>
<tr>
<td>6. Inadequate Design Procedures</td>
</tr>
</tbody>
</table>
### RCA reporting system

#### RCA TEMPLATE

**RCA TEMPLATE**

**Title:** Root Cause Reporting Form  
**RCA No.:**  
**Incident Date:**  
**System/Component/Fail:**  

**Loss Description of the Incident:**

- **Feature Code:**  
- **Problem Code:**  
- **Cause Code:**  

**Risk Assessment Matrix - RAV (Potential Consequence):**

- **Assets:**  
- **Production Loss:**

#### Sub-Category

- **Sub-Category (A):**
  - 1. Defect equipment and tools  
  - 2. Working environment  
  - 3. Control/Operation  
  - 4. Production Practice  
  - 5. Instability of equipment  
  - 6. Modification of equipment  
  - 7. Determination/Correction

#### Personal Factors (B)

- **Personal Factors (A):**
  - 1. Inadequate knowledge of the working process  
  - 2. Inadequate management and control of work  
  - 3. Motivation  
  - 4. Physical and psychological load during work

**Sub Category:**

- **Sub-Category:**
- 10. Maintenance  
- 11. Operation of equipment outside design boundaries  
- 12. Wrong use of equipment  
- 13. Failure in maintenance and operation

#### Basic Causes

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inadequate design and control of design</td>
<td></td>
</tr>
<tr>
<td>Inadequate training and qualification of personnel</td>
<td></td>
</tr>
<tr>
<td>Inadequate operation of the equipment</td>
<td></td>
</tr>
<tr>
<td>Inadequate planning and preparation of equipment</td>
<td></td>
</tr>
<tr>
<td>Inadequate maintenance and operation of equipment</td>
<td></td>
</tr>
<tr>
<td>Inadequate planning and operation of the equipment</td>
<td></td>
</tr>
</tbody>
</table>

**Identify Causes**

- **A1:** Defect equipment and tools
  - A1.1: Defect in design or use of the equipment for this service  
  - A1.2: Defect in material used in test and equipment

- **A2:** Working environment
  - A2.1: Inadequate knowledge of the working process
  - A2.2: Inadequate training and qualification of personnel

- **A3:** Control/Operation
  - A3.1: Inadequate design and control of design
  - A3.2: Inadequate planning and preparation of equipment

- **A4:** Instability of equipment
  - A4.1: Inadequate operation of the equipment

**Identify Issues**

- B1.1: Lack of experience
- B1.2: Lack of knowledge
- B1.3: Lack of training
- B2.1: Lack of information
- B2.2: Lack of knowledge of the working process
- B3.1: Lack of attention to the equipment's use

**Identify Problems**

- B4.1: Inadequate training
- B4.2: Inadequate planning and preparation of equipment
- B4.3: Inadequate operation of the equipment
Methods for RCA

• STEP; Sequential Time Event Plotting
• FMEA; Failure Mode Effect Analysis
• FTA; Fault Tree

• + common sense, engineering/operational experience
1. Identify actors
2. Identify events
3. Link 1&2
4. Mark Substandard acts/deviations

...all links are AND gates
# FMEA; Failure Mode and Effect Analysis

**Loss/Consequence:**

Pump not started

<table>
<thead>
<tr>
<th>Function/Object</th>
<th>Failure Mode</th>
<th>Failure Cause</th>
<th>Consequence System/Component</th>
<th>Detection</th>
<th>Likelihood (low – possible– high)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump</td>
<td>Broken axel</td>
<td>Fatigue</td>
<td></td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Impeller</td>
<td>Corrosion/Wear</td>
<td>Loss of Pressure</td>
<td>Pressure Indicator</td>
<td></td>
<td></td>
</tr>
<tr>
<td>El. Motor</td>
<td>Winding</td>
<td></td>
<td></td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft-starter</td>
<td>Fail to Operate</td>
<td>Unknown</td>
<td></td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Switch</td>
<td>In off position</td>
<td></td>
<td></td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal</td>
<td></td>
<td></td>
<td></td>
<td>Alarm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor</td>
<td>Fail to operate</td>
<td></td>
<td>Wrong signal to control unit</td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Temp. Protection</td>
<td>Fail to operate</td>
<td></td>
<td>No detection of failure and larger damage</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fault Tree

What is a Fault Tree?

- Identifies causes for an assumed failure (top event)
- A logical structure linking causes and effects
- *Deductive* method
- Suitable for potential risks
- Suitable for failure events
Which one to use?

• **STEP:**
  – For complex events with many actors
  – When time sequence is important

• **FMEA:**
  – Getting overview of all potential failure
  – Easy to use

• **FTA:**
  – Identifies structure between many different failure causes
  – Non-homogenous case (different disciplines)
Detailed analyzes of failed parts/components
Typical examples of systems/equipment that can be analyzed:

- Electrical generators
- Heat exchangers
- Subsea equipment
- Valves
- Control systems
- Pumps
- Fire and gas-detectors
- Sensors and measuring devices
- Components of gasturbines
- Compressors
- Cranes and lifting equipment
- Well and down hole drilling equipment
Proactive maintenance through Root Cause Failure Analysis (RCFA)

Maintenance strategy based on systematic and detailed knowledge of the causes of failure and breakdown

- Systematic removal of failure sources
- Prevent repetitive problems
- Minimise maintenance down-time
- Extend equipment life
RCFA evaluates factors affecting service performance such as:

- Materials/corrosion/environment
- Changes in operational conditions
- Stresses and strains
- Presence of defects and their origin, nature and consequences
- Design
- Welding procedures and material weldability
The most common causes of service failures or breakdown:

- Incorrect operation
- Poorly performed or inadequate maintenance
- Incorrect installation and bad workmanship
- Incorrect repair introducing new defects
- Poor quality manufacture leading to sub-standard components
- Poor design
Examples of problems disclosed by the laboratory investigation as part of the RCFA:

GEARS

- Incorrect material
- Incorrect heat treatment
- Incorrect design
- Incorrect assembly
- Corrosion
- Lubricating problems
- Vibration
- Incorrect surface treatment
- Geometric imperfections
- Incorrect operation
- Fatigue or overloading
Examples of problems disclosed by the laboratory investigation as part of the RCFA:

BOLTS

- Indoor material
- Poor design
- Manufacturing defects
- Incorrect assembly
- Corrosion
- Vibration

- Poor or incorrect surface treatment
- Geometric imperfections
- Incorrect application
- Incorrect torque or overloading
Examples of problems disclosed by the laboratory investigation as part of the RCFA:

BALL-/ROLLER BEARING

- Poor design
- Manufacturing defects
- Poor alignment and balance
- Seal failure
- Electrical discharge (arcing)

- Overload
- Inadequate lubrication
- Vibration
- Contamination
- Fretting
- Corrosion
Root Cause Failure Analysis

Disclosed Failure of:

MAIN BEARING

- Heavily worn raceway, cracking of casehardened surface, plastic deformation of sealing groove
- The main cause of failure was overloading of the bearing.

Actions/recommendation:
- Reanalysis by FEM and redesign
Root Cause Failure Analysis Disclosed

Failure of:

O-RING

- Four gas leaks on TLP platform equipment in HP & IP service
- Caused by explosive decompression (ED) of O-Ring
- Actions/recommendation: Change to another O-Ring type with other elastomer
Examples of problems disclosed by the laboratory investigation as part of the RCFA:

DRIVE SHAFTS

- Incorrect material quality
- Incorrect design
- Poor quality manufacture
- Geometric imperfections
- Incorrect operation

- Surface defects
- Corrosion
- Incorrect balance and alignment
- Incorrect assembly
- Fatigue or overloading
ROOT CAUSE FAILURE ANALYSIS

DISCLOSED:

Bearing Breakdown

- Axial overloading
- Thrust washers fitted in both bearing housings
- Incorrect assembly

Actions/recommendation:
Remove thrust washers from one bearing housings
ROOT CAUSE FAILURE ANALYSIS
DISCLOSED:

Gear Breakdown

• Broken gear tooth. Fatigue initiated from quench cracks.
• Fabrication induced defects (Basis for discussion of liability and subsequent claims against manufacturer)

Actions/recommendation:
Fitting of new gears where heat treatment and case hardening procedure had been verified to be correct
ROOT CAUSE FAILURE ANALYSIS
DISCLOSED:

**Damaged pinion and gear wheel**

- Severe surface deformation on one side of teeth
- No surface hardening
- Incorrect lubrication

**Actions/recommendations:**
Renew gear wheel and pinion with components that have been verified to have correct surface hardening. Change lubricant and revise lubrication procedure.
Typical components that can be analysed

- Gears
- Bearings
- Bolted connections
- Shafts
- Impellers
- Pistons/cylinders
- Motor rotors/stators
- Pressurized components and pressure vessels
- Steel wire ropes
- Hydraulic components
- Welded joints
Reliability assessment

… considering total system reliability!
STEP

(Sequentially Time Event Plotting)
STEP Method

(Sequentially Time Event Plotting)

- Capturing of the sequential events leading up to an accident.
- Can be a simple timeline
- Investigation of larger incidents/accidents where the time sequence is important
- Handles complex events with:
  - several actors
  - several events in parallel
  - a longer time horizon
- Should include both equipment, control and human actions
STEP; Sequentially Time Event Plotting

1. Identify actors
2. Identify events
3. Link 1 & 2
4. Mark Substandard acts/deviations

…all links are AND gates
Example of a simple STEP diagram

**Actors**
- Engineer
- Sealing
- Valve
- Operator

**Timeline**
- January
- May
- June

**Case: Manual valve oil leakage**

1. Deviation 1

**Missed annular inspection of valve sealing**

**Sealing becomes dry and brittle**

**Inadequate tightening**

**Oil leakage**

**Manually Moving the valve**

**MANAGING RISK**
FMEA
Failure Mode and Effect Analysis

FMECA
Failure Mode and Effect Criticality Analysis
FMEA (Cause-Consequence)

(Failure Mode and Effects Analysis)

- Overview of failure mode and effect for a complex machinery/operation
- Getting an overview of all potential failure causes and effects at an initial stage of an investigation
- Requires detailed knowledge of the problem in question
- Easy to use for both events and for potential losses where risk is included
- Not good at handling time series
Technique/Working Process

Analysis Goal

System definition
- System boundaries
- Operational state
- Limitations, assumptions

System description
- Documentation
- Division into sub-systems (e.g. functional decomposition)

Analysis planning
- Find expert team
- Plan expert sessions (when, what, who?)
- Make documentation available

Expert sessions
- Guided brainstorming to collect information
- Fill in forms

Likely Causes

Evidence Finding
- Inspections
- Failure Analysis
- Interview

Exclusion

Final Causes
Cases/Examples
Offshore Gas production
Statistics from 320 incidents/ “RCA” cases

Total Losses; Ca. 100 mill$/yr

- Design 33%
- Personal related 26%
- Lack of management of work 15%
- Preventive Maintenance 8%
- Other 18%

Total Losses; Ca. 100 mill$/yr
Immediate causes

Immediate Causes - Substandard Conditions

- A1.3: Failure during service
- A1.4: Failure during startup
- A1.5: Failure during maintenance

Immediate Causes - Substandard Acts

- A14.1: Operator initiated failure
- A10.1: Error during maintenance/repair
- A13.1: Violation of operation procedures
- A13.4: Failure during preparation for maintenance
- A13.3: Violation of working procedures
- A11.1: Operator overlooking control signals
- A10.3: Equipment damaged during construction
- Too slow operator reaction
- Error during testing
- Work without workpermit
Basic Causes

**Basic Causes - work related**

- Bad design
- Insufficient PM
- Insufficient planning QA after
- Insufficient CM
- Insufficient QA of work
- Operational response
- QA of maintenance
- QA at delivery
- Change in SW/design ...
- Procedure/work descri...

**Basic Causes - Personal Factors**

- Lack of experience
- Lack of job related ...
- Lack of info/drawings
- Stressful work situ...
- Lack of support
- Job related training
- Lack of knowledge
Explosion and fire at refinery
Refinery Explosion & Fire

Localised Corrosion in overhead Piping

Debutanizer Column

Debutanizer Overhead Receiver
Longford Gasplant
Rich oil de-ethanizer reboiler

Figure 6.18 Finite element model for GP905 thermal stress calculations
BRITTLE FRACTURE IN CHANNEL TO TUBESHEET WELD

- Low temperature due to process upset
- caused brittle fracture initiation from root
- of weld containing lack of fusion defect

**Actions/recommendations:**
- Reconstruct using low temperature steel grade, carry out proper UT. Modify operation procedure and controls to prevent future process upsets.

DISCLOSED:

Damage mechanism: Brittle fracture
RCFA of LNG Plant Failure
RCFA of LNG Plant Failure
RCFA of WHRU

- Regen heater P
- V91303 regen separator P
- Regen Flow in balance

- Starting to depressurise Regeneration system
- Imbalance increases sharply at time of incident
- Regeneration gas heater flow imbalance starts to increase
- Inlet valve to regeneration gas heater closed
- External fires extinguished

Pressure (barg): 0, 10, 20, 30, 40, 50, 60, 800, 900
Flow (T/D): 0, 100, 200, 300, 400, 500, 600, 700, 800, 900

Dates: 16-Aug-03, 16-Aug-03, 16-Aug-03, 16-Aug-03, 16-Aug-03, 16-Aug-03, 16-Aug-03
Metallurgical investigation
Findings

• Explosion caused by trip of turbine and leak from WHRU gas coil to header weld
• Following gas leak, auto-ignition of air/gas mixture occurred. The auto-ignition temperature was equal to the surface temperature of the equipment based on instrument readings
• Weld failure due to creep/fatigue and time dependent embrittlement of weld HAZ
• Damage was caused by air/gas mixture explosion equivalent to 68 kg TNT
Failure of 24” OD subsea clad pipeline

Figure 1: Schematic representation of the pipeline and riser system
Corrosion in 24” OD clad pipeline