DESIGN FAILURE MODE AND EFFECT ANALYSIS – CASE STUDY

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Abstract. Design-Failure mode and effect analysis (D-FMEA) is very important tool used in industries to detect failure during design stage. D-FMEA is a technique to find out causes of failure and their effects on the performance of a system(parts) during design phase. In this paper, the D-FMEA of critical components of designed automatic tilting mechanism trolley is carried out. The critical components of automatic tilting mechanism trolley are identified and analyzed by the D-FMEA tool. This paper provides risk priority number of components of trolley. The component with higher risk priority number has higher chances of failure. The risk priority number of critical components is reduced by incorporating corrective actions. This paper provides probable causes of failure, effects of failure and corrective actions to be undertaken during design phase of Automatic tilting mechanism trolley. The D-FMEA tools helps in reducing accidents.

Keywords. Design failure mode and effect analysis, Risk priority number, Severity, Occurrence, Detection.

1. INTRODUCTION

There are various operational and safety issues concerning with material handling trolleys due to which the operator faces various health disorders like musculoskeletal disorder (MSD) that is why study of the material handling trolleys is essential. In this paper burr material handling trolley is considered. In industries normally, the burr handling trolleys are transferred manually from one place to other. Manual pushing and pulling of trolleys causes fatigue to operator. Normally 800-1000 kg of burr is transferred over long distance by manual pushing. In manufacturing industries burr material handling is transferred manually over long distance. In this paper a better design of material handling trolley is prepared to reduce load carried per unit off human efforts. The transferring of trolley is not done by pushing or pulling but it is transferred through forklift and hence due to which entire manual movement of trolley is eliminated.

Hence a trolley with automatic tilting mechanism is designed named as automatic tilting mechanism trolley as shown in Fig. 1. Trolley with tilting mechanism is designed to reduce human efforts and
increase safety in material handling. In this paper, D-FMEA of critical component of automatic tilting mechanism trolley is carried out.

![Fig. 1 Trolley image](image-url)

**2. AUTOMATIC TILTING MECHANISM TROLLEY DESIGN**

In this new design of trolley automatic tilting mechanism is incorporated. The centroid of trolley is calculated by using Creo software for full load and no-load conditions. Figure 2 shows center of gravity of empty and full bin. The approx. value are given below.

- Center of gravity of empty bin (CS0)
  - Xcs0=407mm
  - Ycs0=438mm
- Center of gravity of full bin (CS1)
  - Xcs1=437mm
  - Ycs1=439mm

![Fig. 2 Center of gravity of trolley](image-url)

Centroid of trolley is shifted by 180mm (as shown in Fig. 3) so that the trolley will get automatically tilted. At this shifted centroid point Plummer block ball bearing are provided. The trolley rotates about this point. Helical extension springs are used to avoid the sudden jerk which the trolley will undergo while tilting. It acts as a shock absorber. By sitting in the forklift, the lever oflocking system can be pulled by using rope. When the latch is disengaged the trolley will unload automatically. Fig. 4 shows...
the tilted trolley image. The manual movement of trolley is eliminated, and trolleys are taken to unloading area by means of forklift.

Fig. 3 Shifted centroid

2.1. Design of shaft: Material Selection - Mild steel is used as shaft material due to its properties like high tensile strength, Shear strength, Good modulus of elasticity and rigidity, High toughness and less cost compared to other steel materials.  
Total load inside the trolley - 800kg  
One bearing load carrying capacity - 400kg  
Weight - 400 X 9.81 N  
The shaft diameter is calculated from above data by bending stress equation and is 35 mm.

2.2. Design of bearing  
Since the radial load acts on the shaft, ball bearings are used for this trolley with automatic tilting mechanism.

For 35 mm shaft diameter the bearing selected from bearing catalogue is, 6007.

2.3. Design of Spring  
The helical extension spring is used as a shock absorber. The material of spring used is standard.

Spring material: En747 (Quench and temper 32-36 Rc)

For the given application, estimated maximum spring force (P) and the corresponding required deflection (δ) of the spring.

P - 40kg
δ - 180mm - Deflection of spring
k - Spring stiffness
Shear stress - 525 N/mm²
Wire diameter - d - 3.5 mm
Coil diameter - D - k X d = 3.5 x 7 = 24.5 mm
Number of coils - N = 62
Spring length - L - 217mm
The Fig. 4 shows the tilted trolley image or tilted position of trolley.

3. **D-FMEA**

D-FMEA is a technique to find out causes of failure and their effects on the performance of a system (parts). It helps in analysing for possible failure modes and to prevent them from occurring by incorporating corrective actions. D-FMEA is a analysing technique of new design prior to implementation. This will help to reduce the chances of failure after implementation. D-FMEA is one of the most efficient analysis techniques.

“Severity (S) is the fact or condition being severe to the individual component or system as a whole. Rating from 1 to 10 is given, with 1 means no effect to the system and 10 for very hazardous effect on the system. The severity rating criteria along with its description is given in table no. 1” (Pattnaik, 2015).

“Occurrence (O) means how frequently a failure or incident will happen. The rating of 1 to 10 is given where, 1 means “very unlikely to happen” and 10 means “failure is inevitable”. The occurrence rating criteria along with its description is given in table no. 2” (Pattnaik, 2015).

“Detection (D) means chances of failure detection. Similar to severity and occurrence, a numeral rating of 1 to 10 is given where 1 means “the failure will be detected very easily” and 10 means “the failure is not possible to detect with current controls”. The detection rating criteria along with its description is given in table no. 3” (Pattnaik, 2015).

Risk Priority Number (RPN) is multiplication of the Severity, Occurrence and Detection. RPN is given below [4,5],

\[
RPN = (\text{Severity Rating}) \times (\text{Occurrence rating}) \times (\text{Detection rating})
\]

\[
RPN = S \times O \times D
\]

| SR. NO. | EFFECTS               | RANKING | DESCRIPTION                                                                 |
|--------|-----------------------|---------|-----------------------------------------------------------------------------|
| 1      | Hazardous without warning | 10      | Failure occurs without warning. Machines cannot be repaired, and they are inoperable. Affects safe operation without warning. |
| 2      | Hazardous with warning   | 9       | Failure with warning. Affects safe operation with warning.                   |
| 3      | Very High               | 8       | Loss of primary function and system is inoperable. It involves major repair and rework. It makes product inoperable. |
| 4      | High                    | 7       | Makes product operable at reduced performance (customer dissatisfaction).     |

*Table 1. Severity Rating Criteria*
5 Moderate 6 No loss of primary function. Only a part of a system is failed and that part can be made operable by rework.
6 Low 5 Components is working but at reduced comfort. The working of system is affected. Efficiency of operation is reduced.
7 Very Low 4 By minor changes failures can be avoided. System or components are not affected majorly.
8 Minor 3 There is no performance loss but cause little disturbance. By minor rework it can be reworked.
9 Very Minor 2 Components is operable with minor loss or no loss. Rework or repair is not required.
10 None 1 No effect.

**Table 2. Occurrence Rating criteria**

| SR. NO. | EFFECTS                     | RANKING | DESCRIPTION                                      |
|---------|-----------------------------|---------|--------------------------------------------------|
| 1       | Very High: Inevitable failures | 10      | Failure in every third component (1:3)           |
| 2       | High: Failures occur almost as often as not. | 9       | Failure in every sixth component (1:6)          |
| 3       | High: Repeated failures     | 8       | Failure in every ninth component (1:9)          |
| 4       | High: Failures occurs often | 7       | Failure in every 50 components (1:50)           |
| 5       | Moderately High: Frequent failures | 6   | Failure in every 150 components (1:150)         |
| 6       | Moderate: Occasional failures | 5       | Failure in every 800 components (1:800)         |
| 7       | Moderately Low: non-frequent failures | 4 | Failure in every 4500 components (1:4500)       |
| 8       | Low: Relatively low failures | 3       | Failure in every 30000 components (1:30000)     |
| 9       | Very Low: Failures are few and far between | 2 | Failure in every 150000 components (1:150000) |
| 10      | Remote: Failure is unlikely | 1       | Failure in every 1.5 million components (1:1.5million) |

**Table 3. Detection Rating criteria**

| SR. NO. | EFFECTS             | RANKING | DESCRIPTION                                      |
|---------|---------------------|---------|--------------------------------------------------|
| 1       | Uncertainty         | 10      | Unable to detect a cause of failure by controls. |
| 2       | Very Remote         | 9       | Very low chances.                                |
| 3       | Remote              | 8       | Poor chance of detection of failures by controls.|
| 4       | Very Low            | 7       | Very low chances of detection.                   |
| 5       | Low                 | 6       | Possibility of detection of failure mode by controls. |
| 6       | Moderate            | 5       | Moderate chances of detection.                   |
| 7       | Moderately High     | 4       | Failures have good chances of detection.        |
| 8       | High                | 3       | High chances of detection i.e. automatic detection. |
| 9       | Very High           | 2       | Very high chances of detection.                 |
| 10      | Almost certain      | 1       | Controls certain to detect. Error proofed by product design. |

4. D-FMEA COMPONENTS:

The D-FMEA was applied on different components of the Automatic tilting mechanism trolley.

Components of D-FMEA:

- **Failure of bearing shaft**: The total load in the trolley bin acts on the shaft hence it is the most important component of D-FMEA. The load acting on trolley is carried by bearing shaft. Hence failure of bearing shaft may result in loss of primary function i.e. tilting.
- **Failure of wheels**: The wheels are used for manual movement of trolley which is important to locate trolley in any area of shop floor.
- **Failure of bearing resting frame:** The load is transferred from shaft to bearing and from bearing to resting frame. Hence failure of resting frame may result in loss of primary function (tilting).

- **Failure of pin:** The overall trolley rotating torque is taken by locking pin. Hence failure of pin may result in loss of primary function (tilting). Also sudden failure of pin can lead to accident.

- **Failure of helical extension spring:** It is used as a shock absorber to avoid sudden jerk on trolley bin.

- **Failure of forklift Square section:** The trolley is taken to unloading area by means of forklift and forklift is engaged in forklift square section. The total lifting load is acting on the section. Hence failure of forklift square section can damage entire trolley.

5. **D-FMEA IMPLEMENTATION:**

5.1. **Failure of bearing shaft** If shaft failure is caused by first two cases, then the severity rating is 10 since the trolley is inoperative. Also, sudden failure causes damage to whole trolley and hence the repair is almost impossible. It may result in safety incidents. By carrying out analysis of shaft for given load, the severity rating is reduced to 8 from 10 [10]. The detection rating is 7 in first two cases, since controls have poor chance of detection. But it is reduced to 6 by time to time inspection.

In third case, welding failure the severity rating is 10. By providing flange at the end of shaft (as shown in Fig. 5) the severity rating is reduced to 4. The detection rating is 6 since controls have good chance of detection. By providing flange the welding failure is reduced. Hence, here detection rating is reduced from 6 to 4. The occurrence rating given here is 3 in all cases. By assuming failure in every 30000 components. Occurrence rating is reduced to 3 from 2.

| Sr. No. | Components | Potential failure mode | Effects of failure | S | Cause of failure | O | Current process control | D | P | N | Recommended action(s) |
|---------|------------|------------------------|--------------------|---|-----------------|---|-------------------------|---|---|---|-----------------------|
| 1       | Bearing shaft | Breaking of shaft, Fatigue failure | May damage bearing, Entire mechanism failure may occur. | 10 | Stress exceeds yield stress of material due to excess radial load and impact load, Fatigue failure of shaft due to cyclic loading. | 3 | NA | 7 | 20 | 6 | 90 | Design shaft with proper specification, Analysis of shaft is carried out to find maximum permissible stress it can carry, Time to time preventive maintenance and inspection. |
|         | Under size shaft diameter | Failure of shaft, Wrong bearing selection, Bearing failure, Entire mechanism failure may occur. | 10 | Shaft not designed with proper specification, Wrong inputs regarding load carried by shaft | 3 | NA | 7 | 210 | 6 | 98 | Design shaft with proper specification, Analysis of shaft is carried out to find maximum permissible stress, Time to time preventive maintenance and inspection. |
|         | Welding failure between shaft and bin | Mechanism failure, Failure of bearing and trolley parts | 10 | Less welding surface area of shaft, Also, difficulty in welding of shaft with thin sheet of bin | 3 | NA | 6 | 180 | 4 | 32 | Flange is provided at the end of shaft were weld is to be made to increase surface area of welding. |

The analysis of shaft is carried out, allowable and von-mises stresses are compared [10].
Material used: Mild steel
Yield strength of material: 250MPa Assume FOS: 2
Allowable stress: 125MPa
Load on shaft: 400 kg
Von-mises stress: 93.52MPa (from analysis as shown in Fig.4)
Maximum principal stress: 100.079MPa (from analysis)

5.2 Failure of wheels
If wheel failure is caused by wheel undersize, then the severity rating is 6 since the trolley is operable and manual movement of trolley cannot be performed. By replacing wheel, the trolley can be used same as before.

The detection rating is 7, since controls have poor chance of detection. Due to use of preventive maintenance of wheels the detection rating is reduced to 4.

The occurrence rating given here is 3 in all cases. By assuming failure in every 30000 components. Occurrence rating is reduced to 3 from 2 by performing time to time preventive maintenance.

| Sr. No. | Components | Potential failure mode | Effects of failure | S | Cause of failure | O | Current process control | D | R | P | N | Recommended action(s) |
|---------|------------|------------------------|--------------------|---|------------------|---|------------------------|---|---|---|---|----------------------|
| 2       | Wheels     | Wheel undersize         | • Failure of wheels • Failure of caster • More force required for pushing/pulling. | 6 | Wheels not selected properly from the catalogue. • Less load carrying capacity of wheels. | 5 | NA | 7 | 126 | • Analysis of wheel for given radial load is carried out. • Also, wheels having high material yield strength is selected. • Preventive maintenance of wheels to be carried out. |

5.3. Failure of bearing resting frame
If failure of bearing resting frame is caused by buckling, then the
severity rating is 10 since the trolley is inoperable. Also, sudden failure causes damage to bearing and other trolley parts and hence the repair is almost impossible. By carrying out analysis of bearing resting frame for given load, the severity rating is reduced to 8 from 10[10]. The detection rating is 7 in first case, since controls have poor chance of detection.

In second case too, severity rating is 10 since the trolley is inoperable. Also, sudden failure causes damage to bearing and other trolley parts and hence the repair is almost impossible. And detection rating in this case is 6 since by visual inspection controls have moderate chance of detection. Since bending has chances of detection by visual inspection.

The occurrence rating given here is 3 in all cases. By assuming failure in every 30000 components. Occurrence rating is reduced to 3 from 2. This can be reduced by providing rib to the resting frame.

If locking pin failure is caused by shear or bending, then severity rating given is 8. Here primary function failure, trolley will remain in tilted position due to which automatic tilting mechanism will not be performed. By designing pin properly by considering proper design standard the severity rating can be reduced and alternate lock is provided to bin for support. Due to which the severity rating is reduced to 5, alternate lock will perform the function of pin in case of failure of pin. The detection rating is 7, since controls have poor chance of detection.

Table.6: D-FMEA of Bearing resting frame and Pin

| Sr. No. | Component | Potential failure mode | Effects of failure | S | Cause of failure | O | Current process control | D | P | N | Recommended action(s) | S | O | D | P | N |
|---------|-----------|------------------------|-------------------|---|-----------------|---|------------------------|---|---|---|-------------------------|---|---|---|---|---|
| 3       | Bearing resting frame | • Buckling | • Automatic tilting mechanism failure. • May damage bearing shaft. | 10 | • Aspect ratio not defined properly. • Less thickness of column. | 3 | NA | 7 | 210 | Rib provided to avoid buckling. • Analysis is carried out. • Thickness is high enough to sustain the load. | 6 | 2 | 7 | 84 |
|         |           | • Bending and structural failure. | • Automatic tilting mechanism failure. • Bearing and shaft failure. | 10 | • Repeated high cyclic loading. • Stress exceeds yield stress of material due to excess radial load and impact load. | 3 | NA | 6 | 180 | Rib provided to avoid buckling. • Analysis is carried out. | 6 | 2 | 6 | 72 |
| 4       | Pin       | • Pin failure | • Trolley will remain in tilted position i.e., mechanism will not work. | 8 | • Pin not designed according to specification. • More load acting on pin. • High torque since all rotating load acts on pin. • Stress exceeds yield stress of material due to excess radial load and impact load. | 3 | NA | 7 | 180 | Design pin properly. • Alternate lock is provided. • Analysis of pin is carried out. | 5 | 2 | 4 | 40 |

5.4 Failure of helical extension spring In all the cases of failure of helical extension spring, the severity rating is 6 since the trolley is operable and primary function can be performed. Spring corrosion can be eliminated by providing anti corrosive coating. Hence life of spring can be increased. The severity rating is reduced to 1 from 6 due to coating.

The detection rating is 7 in first two cases, since controls have poor chance of detection. In first case detection rating is reduced to 4, this is be done by carrying out analysis and time to time inspection of spring. In second case too detection rating is reduced to 4, this is done by providing mark on trolley above which no material should be filled in trolley. The detection rating is 4 in third case,
since corrosion can be easily detected by eyes.

The occurrence rating given here is 3 in all cases. By assuming failure in every 30000 components. Occurrence rating is reduced to 3 from 2.

| Sr. No. | Components | Potential failure mode | Effects of failure | S | Cause of failure | O | Current process control | D | E | P | N | Recommended action(s) | S | O | D | R | P | N |
|---------|------------|------------------------|-------------------|---|------------------|---|------------------------|---|---|---|---|-----------------------|---|---|---|---|---|---|
| 5       | Helical extension spring | Fringe failure of spring | Sudden rack on trolley, Unbalance of load | 6 | Due to faulty choice of springs, Spring fails due to loads exceeding the yield stress of the spring material, During tilting spring most extend and compress. Hence it is a cyclic phenomenon which may result in fatigue failure. | 3 | NA | 7 | 126 | • Choose springs according to trolley loads and other specification. | 6 | 2 | 4 | 48 |
|         |            | Spring relaxation       | Spring mechanism failure | 6 | When load carried more than specified limit of spring. | 3 | NA | 7 | 126 | • Mark given on trolley above which no material should be filled. | 6 | 2 | 4 | 48 |
|         |            | Spring corrosion         | Less life, Sudden failure of spring | 6 | Material selection not properly done. | 3 | NA | 4 | 72  | • Material selection should be done properly. | 1 | 2 | 4 | 8  |

5.5. Failure of forklift Square section In all the cases of failure of forklift square section by bending, the severity rating is 10 since the trolley is inoperable and primary function cannot be performed i.e. tilting of trolley. It is reduced to 8 by carrying out analysis and designing the part properly. If failure is by improper welding the severity rating is 6 it is reduced to 4 by efficient welding and time to time inspection. If failure is by corrosion the severity rating is 6 it is reduced to 3 by time to time painting of trolley.

The detection rating is 6 in first two cases, since controls have good chance of detection. In third case detection rating is reduced to 3, since this can be easily detected by eyes. The detection rating is 4 in third case, since corrosion can be easily detected by eyes.

The occurrence rating given here is 3 in all cases. By assuming failure in every 30000 components. Occurrence rating is reduced to 3 from 2.
### Table 8: D-FMEA of Forklift square section

| Sr. No. | Components | Potential failure mode | Effects of failure | S | Cause of failure | O | Recommended action(s) | D | R P N |
|---------|------------|------------------------|--------------------|---|-----------------|---|-----------------------|---|-------|
| 6       | Forklift square section | Bending | Primary function degradation and movement of trolley by forklift will not be possible. Sheet bending due to more load. | 10 | More lifting load than specified. Less strength of material. | 3 | NA | 6 | 100 |
|         |            | Broken welds | Bending and weakening of frame. All mounting parts gets weakened. | 6 | Fatigue Defects | 3 | NA | 6 | 108 |
|         |            | Corrosion | Less life of part. Sudden failure of part due to weakening. | 6 | Paint removal. Used in high moisture environment. | 3 | NA | 4 | 72 |

6. **STRESSES COMPARISON:**

The Table 9 shows the allowable and von-mises stress comparison.

### Table 9: Stress comparison

| Components       | Material                                      | Load acting(kg) | Yield strength(MPa) | Allowable stress(MPa) | Vonmises stress(MPa) | Max Principal stress(MPa) |
|------------------|-----------------------------------------------|-----------------|---------------------|-----------------------|----------------------|---------------------------|
| Bearing shaft    | Mild steel                                    | 400             | 250                 | 125                   | 93.52                | 100.079                   |
| Wheels           | Ultra-high molecular weight polyethylene (UHMW-PE) | 200             | 39.98               | 19.98                 | 3.79                 | 3.86                      |
| Bearing resting  | Mild steel                                    | 400             | 250                 | 125                   | 36.95                | 40.12                     |
|                |        |      |      |      |      |
|----------------|--------|------|------|------|------|
| frame          |        |      |      |      |      |
| Pin            | Mild steel | 600  | 250  | 125  | 21.2 | 24.85 |
| Helical extension spring | En747 steel | 400  | 280  | 140  | 35.11 | 38.22 |
| Forklift square section | Mild steel | 800  | 250  | 125  | 25.64 | 41.67 |

7. PRIORITY GRAPH:

Priority Graph is a representation of risk priority numbers of the system/components on the graph. From the above evaluation, the graph is shown below with RPN on Y axis and parts of trolley on X axis. The Fig 6 shows components of trolley with higher and lower RPNs. The recommended corrective/preventive measures are undertaken for critical components of trolley to reduce chances of failure. Fig.6 shows the priority graph.

![Priority Graph of Components](image)

Fig 6 Priority graph of components

CONCLUSION

The D-FMEA technique was successfully applied to the automatic tilting mechanism trolley components. The analysis helped us to find the critical components of the mechanism. The critical components of trolley are shaft, frame, pin and square section which has highest risk priority number. The RPN rating is reduced for critical components by incorporating the corrective actions. Required preventive measures were undertaken as mentioned in above respective tables and incorporated during design and fabrication stage of the automatic tilting mechanism trolley.
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