Topic 3

MAINTENANCE OF UNRELIABLE SYSTEMS

RELIABILITY RESEARCH

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MAINTENANCE OF UNRELIABLE SYSTEMS

NEED FOR EQUIPMENT

- Businesses use a variety of equipment to produce output and services
- Equipment unreliable – failure due to failure of one or more components
- Most equipment are complex systems (a truck has more than 15,000 components, an aircraft has 4.5 million components)

CONSEQUENCE OF FAILURE

- Failure of equipment results in availability
- This in turn results in loss of revenue
  - Aircraft: 0.5 million dollars per day
- Other indirect costs: Delays to production, Loss of good will, Dissatisfied customers etc

EQUIPMENT FAILURE

- Equipment failures depend on inherent reliability which is determined by the decisions made during design and manufacture
- Equipment degrade with age and usage
- The rate of degradation depends on usage intensity, operating environment, and maintenance actions

RELIABILITY THEORY

- Reliability theory deals with the study of equipment degradation and failures
- It includes Reliability Science, Reliability Engineering, Reliability Management and Reliability Mathematics
- Maintenance is also part of reliability theory

MAINTENANCE

- Maintenance are actions (or activities) needed to (i) control equipment degradation and failures and (ii) to restore a failed equipment to operational state.
- The former is termed Preventive Maintenance (PM) and the latter as Corrective Maintenance (CM)

APPROACHES TO MAINTENANCE

- Changed significantly over the last fifty years.
- Pre 1950: Maintenance was regarded simply as an unavoidable cost
- Post 1950: Scientific approach to maintenance (mainly OR models - dealing with operational and economic issues)

APPROACHES TO MAINTENANCE

- Post 1970: Maintenance management
  - Integral to business performance
  - Part of strategic management
  - More integrated and pro-active approach
  - Many approaches (e.g., TPM, RCM, Tero-technology, ILS) have evolved

IMPACT OF TECHNOLOGY

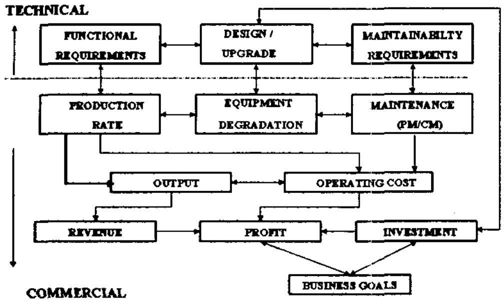
- Systems are getting more complex
- Maintenance requires specialist skills and equipment
- It is not often not economical for businesses to carry out in-house maintenance.
- Out-sourcing of maintenance is an option

IMPLICATIONS

- Maintenance needs to be managed from an overall business viewpoint
- Several options

1. Own and maintain equipment
2. Own but outsource maintenance (Service contract)
3. Lease of equipment (Lease contract)

Strategic Maintenance Management



CHALLENGES

- Need to model the different elements (technical, commercial, operational)
- Need to understand the underlying degradation processes involved (Reliability science)
- Adequate data to build and validate models
- Application in different industry sectors

CASE STUDY: DRAGLINE

- Townson, P. Murthy, D.N.P. and Gurgenci, H. (2002), Optimisation of Dragline Load, in *Case Studies in Reliability and Maintenance*, WR Blischke and DNP Murthy [Editors], Wiley, New York.

NEW CASE: RAIL TRACK

- Increase in traffic (goods and passenger)
- How to cope? Several options -- More frequent operations; More wagons; Greater axle load; Faster speeds etc
- Implications: More load on the track and faster degradation
- What should be the optimal strategy?

NEW CASE: RAIL TRACK

- Need to integrate operation (commercial decision) with maintenance (technical decision)
- Increase load? Short term gain but long term loss!
- Upgrade track? Costly
- Design better rolling stock?

OTHER NEW CASES

- Networks: Water pipe, Gas pipe, Oil pipe, Road
- Power plant: Overload to meet increased demand
- Manufacturing: Higher production rate to meet increased demand

Out-Sourcing of Maintenance

IMPORTANT FEATURES

- Two different parties
  - Service agent (providing the maintenance service)
  - Owner (of the system and recipient of the maintenance service) is the customer
- Different objectives or goals
- Decision problems for both parties

GAME THEORETIC APPROACH

- Service agent offers several options (A_1, A_2, ..A_k)
- The owner chooses the optimal option
- The parameters (decision variables) of each option to be selected optimally by the service agent
- The service agent needs to take into account the optimal response of customer

TWO OPTIONS

Option A_1

For a fixed price P, the agent carries out all repairs over the life L. If a repair is not completed within a period τ after failure, the agent incurs a penalty α per unit time.

The cost to the customer is certain.

TWO OPTIONS

Option A_2

The agent charges Cs for each repair and there is no penalty if the repair time exceeds τ

The cost to the customer is uncertain as the number of failures over L is uncertain.

THIRD OPTION

If P and C_s are large, the buyer might prefer the following option since the customer incurs loss as opposed to making profit in an expected sense.

Option A_0

Not to purchase the system.

CUSTOMER'S OPTIMAL ACTION

The customer (risk averse) chooses the optimal decision A* from the set {A_0, A_1, A_2} to maximise the expected utility.

The choice is influenced by P, C_s and τ, the decision parameters of the agent.

Has information regarding equipment reliability

AGENT'S OPTIMAL DECISION

Agent is risk neutral.

Decision variables under the agent's control are P, C_s and τ

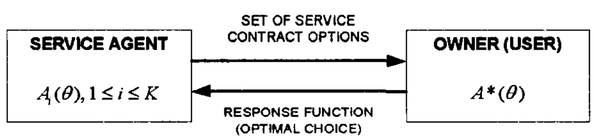
The agent chooses these optimally to maximises the expected profit.

GAME THEORETIC FORMULATION

The agent needs to take into account the optimal actions of the buyer in the optimal choice of P, C_s and τ.

STACKELBERG game situation with the agent as the leader and the customer as the follower.

STACKELBERG GAME



θ: Decision variable of the service agent

OTHER ISSUES

- **How many customers should the service agent have?**
- **How many repair facilities (servers) should the customer have?**
- **Customers differ in their attitude to risk**
- **Equipment are different (age, usage intensity etc)**

SPECIAL CASE

1. **Identical customers (attitude to risk)**
2. **Equipment failures: Occur according to Poisson process**
3. **Repair times exponential**
4. **Single agent and several customers**
5. **Complete information (for both parties)**

SPECIAL CASE

- **The special case has been studied in detail. See, D.N.P. Murthy and E. Ashgarizadeh, Optimal decision making in a maintenance service operation, *Euro. Jr. Operational Res.*, 116 (1999) 259- 273**

NEW RESEARCH

- **Nash game formulation**
- **Several service agents (competition)**
- **Limited information**
- **Moral hazard (when the owner cannot assess the maintenance effort) – link to Agency theory**

Maintenance of Leased Equipment

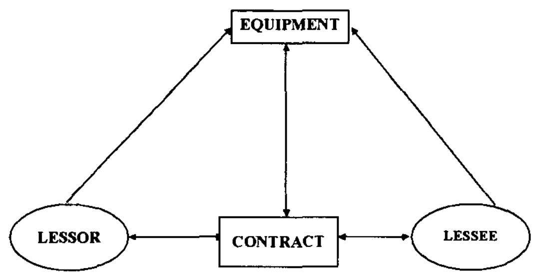
REASONS FOR LEASING

- The rapid technological changes makes equipment obsolete in a short period.
- Also the cost of owning and maintaining an equipment is increasing due to increased sophistication with each new generation.
- Hence, leasing is a better option.

TERMINOLOGY

- Lessor: Owns and leases the equipment
- Lessee: Leases the equipment for a specified period (L)
- Equipment: Unreliable and prone to failure over the lease period
- Contract: Which defines the conditions for lease

MAIN ELEMENTS



AN IMPORTANT FEATURE

- The advantage of leasing is that the lessor provides the maintenance. As such, the equipment (a physical item) is bundled with maintenance (a service) and offered as a package to the lessee. This raises several new issues for both the lessor and the lessee.

LEASE CONTRACT

- There are three main issues in a lease contract.
- Issue 1: This deals with the contract terms and conditions -- the period of the lease, the performance requirements that the leased equipment should meet and the actions and the obligations of each party (lessor and lessee).

LEASE CONTRACT

- Issue 2: This deals with the economic aspect of leasing. These include the amount that the lessee must pay the lessor (or also called the price) for the lease on equipment and the terms of payment.
- Issue 3: Drafting of the contract

MODEL FORMULATION

- Let L denote the period of lease and the number of failures over the lease period. Two different reliability requirements and the associated penalties are as follows:

  (1) Repair time penalty

  (2) Penalty for failures over [0,L)

REPAIR TIME PENALTY

- Each repair to be completed within a specified time τ. Failure to do so results in a penalty which is function of the repair time Y (a random variable from a distribution, G(y), called the repair time distribution)
- The penalty function is given by

  $C_t \; max\{0, Y - \tau\}$, with $C_t > 0$

REPAIR TIME PENALTY

- Let N(L), denote the total number of failures over the lease period, then the total penalty resulting repairs not completed within the specified time τ is given by

$$\phi_1(N(L), Y_i, \tau) = C_t \left\{ \sum_{i=1}^{N(L)} \max[0, Y_i - \tau] \right\}$$

PENALTY FOR FAILURES

- If the number of failures over the lease period exceeds a specified number η (≥ 0) then the lessor incurs a penalty which is given by the following function:

$$\phi_2(N(L), \eta) = C_n \{\max[0, N(L) - \eta]\}$$

with $C_n > 0$

CORRECTIVE MAINTENANCE

- All failures over the lease period are rectified through repair and that the cost of each corrective maintenance action (CM) is C_f
- The total cost of CM actions is given by N(L) C_f

PREVENTIVE MAINTENANCE

- Preventive Maintenance (PM) actions are used to reduce the number of failures over the lease period and as a result the two penalty costs.
- PM actions involve extra cost and is worthwhile only if the reduction in penalty costs is greater then the PM cost

OPTIMAL PM ACTION

- Several different PM policies - with parameters to be selected optimally to minimise the total cost (PM + CM + Penalty).
- See Jaturnnatee, J., Murthy, D.N.P. and Boodiskulchok, R. "Optimal preventive maintenance of leased equipment" submitted for publication