TO SELECT BEST MAINTENANCE STRATEGY FOR THE CONSTRUCTION EQUIPMENTS

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

WATER RESOURCES DEVELOPMENT

By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled, **"TO SELECT BEST MAINTENANCE STRATEGY FOR THE CONSTRUCTION EQUIPMENTS"** in partial fulfillment of the requirement for the award of degree of MASTER OF TECHNOLOGY in WATER RESOURCES DEVELOPMENT and submitted in the Department of Water Resources Development and Management of Indian Institute of Technology Roorkee is a record of my own work carried out during a period from July 2006 up to June 2007 under the supervision of **Prof. Gopal Chauhan**, Professor of Water Resources Development and Management and **Dr. Dinesh Kumar**, Professor of Mechanical & Industrial Engineering, Indian Institute of Technology Roorkee, India .

The matter embodied in this dissertation has not been submitted by me for the award of any other degree.

Dated : June 13 , 2007

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This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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SYNOPSIS

Present day Construction projects are capital intensive where deployment of large and heavy equipments & machinery so as to ensure earlier accrual of benefits, is ubiquitous.

High mechanization entails heavy initial investment on the construction equipment which may be as high as 25 to 30 percent of the cost of the project. However, in the long run, if the equipment is operated, maintained and managed efficiently, then the investment will pay more than what it costs Therefore, it is important to maintain the equipment because idle equipment due to lack of maintenance not only can add to losses, but also the equipment is likely to be rendered unserviceable due to lying unused. Their periodic maintenance, brings the equipments near to its original condition. Hence maintenance of these equipments is of vital importance to ensure that these are in the perfect condition for use on the works.

The Objective of this study is to identify procedures, by which the maintenance of equipment can be carried out efficiently and effectively in order to achieve maximum economical production from the equipment, with minimum breakdowns. Hence, the procedures and models in maintenance of equipment are discussed for achieving the overall economy of maintenance. The essential requirements for an efficient maintenance programme like scheduled maintenance, inspections and repair or overhaul with minimum waiting are also covered.

This topic includes discussion of some of system models for maintenance to achieve the objective of efficient maintenance programme. The application of waiting line model, sequencing model, assignment model, replacement model are of great use in achieving the maximum profit and least downtime of equipment and their use has been illustrated.

Equipment and machines rarely incur uniform wear and tear. Some elements or components are likely to deteriorate faster than others. Under these conditions it is often economical to repair the equipment to the extent of its useful life. Some repairs follow a periodic pattern and can be planned; while some repairs follow unpredictable pattern. The equipment becomes a candidate for replacement when it is anticipated that it will require an additional and extensive repair frequently. Accordingly a chapter an replacement model in this dissertation on best maintenance strategy which may look out of place initially, but a second thought would reveal that when equipment or a component of equipment is no longer economical to maintain it may be a better alternative to replace it by a new component or equipment, is included in this dissertation.

CHAPTER - I

INTRODUCTION

1.1. MAINTENANCE

Present day Construction projects are capital intensive where deployment of large and heavy equipments & machinery so as to ensure earlier accrual of benefits, is ubiquitous.

Maintenance is the function of keeping an equipment an integrated assembly/component in its original form, so that its functional properties do not deteriorate to a point where it may involve hazards due to its growing unsafe or result in loss in productive capability there of, if it is used for production.[1]

Construction equipment, besides being expensive, has often to work under rough job conditions. The timely and economical completion of a work essentially depends upon a satisfactory performance of the equipment. Through maintenance the equipments are kept available for work. Maintenance includes servicing (lubrication, greasing), inspection, preventive maintenance, small repair in the field, major repair and overhauls in the workshop and upkeep of laid-up machines.

Maintenance is common for all the equipments working on projects irrespective of their application.

1.2. TYPES OF MAINTENANCE[1]

Basically maintenance can be classified under the following three categories.

1. Scheduled maintenance
2. Preventive maintenance
3. Breakdown maintenance

1.2.1. Scheduled Maintenance

This is a maintenance programme prescribed by the manufacturers laying down a schedule for greasing, lubricating, changing oil and filters, cleaning of machines etc.

The scheduled maintenance implies a prescribed maintenance drill laid down in the form of a programme, a chart and specification. It has to be followed, in respect of the particular grades, of oils and greases to be used, the point of lubrication to be attended, the period of intervals at which repetitive greasing or lubrication or oil changes have to be carried out, or replacement of filters is to be made.

1.2.2. Preventive Maintenance

This is a maintenance undertaken a little before the possible or anticipated breakdown.

When the equipment is put into operational use, it will be subject to wear and tear. Unless personal attention is given for protecting the equipment and for ensuring its systematic maintenance, adjustments and repairs, its components are liable to undergo wear and consequently fail, however perfect may be its original design. The process of systematic inspection and attending to periodic adjustments and repairs on a rigid time schedule in order to retain the machinery in as good a condition as is economically feasible for working is called Preventive Maintenance.

Preventive maintenance includes all types of planned maintenance works carried out to reduce the frequency of breakdown maintenance to minimum.

1.2.3. Breakdown Maintenance

Breakdown maintenance implies the repairs arising out of deterioration suffered by an equipment, or its component, in the course of its use, accidents, improper adjustments etc. and when it can not perform its function any longer.

Equipment sick for breakdown maintenance gives lower overall machine utilization and causes disruption in production.

1.3. NEED FOR MAINTENANCE PLANNING[1]

Maintenance is an expensive process and there is generally an economic limit up to which it can be planned after considering the value of equipment and the loss and inconvenience that may be caused by any breakdown. Planning is a technique enabling adoption of a systematic approach to attend to a breakdown and keep up of the equipment to make it available for work most of the time.

Maintenance planning helps in preparation of workable schedules for breakdown, preventive and scheduled maintenance based on their frequencies. All operations can be sequenced and a schedule showing the starting and finishing dates of each operation prepared. Several plans must be considered before the best feasible plan is selected. Optimization studies are, thus, integral with planning.

Planning for maintenance begins with an assessment of scheduled maintenance of every machine from daily to yearly maintenance requirements. Based on this assessment the requirements of men, material, tools and spare part are worked out so that these can be arranged in time. Workshop and stores facilities are an essential requisite in the planning for maintenance.

An efficient maintenance programme should be well planned and organized. It should be systematic and thorough, and adherence to it should be ensured through proper supervision. The personnel employed on this programme should be skilled. All necessary material and tools, including spare parts should be available as also the maintenance manuals, charts etc. supplied by manufacturers. Adequate workshop facilities and mobile servicing units should be arranged.

Organization for carrying out the systematic inspections should also be planned to minimize the breakdowns of equipment and in turn increase the production.

1.4. THE PRINCIPLE ASPECTS AND METHODS OF MAINTENANCE[14]

The three principal aspects of maintenance are: Servicing, repairs and inspection. As far as possible, inspection should be independent of the servicing and repairing agencies.

Servicing includes the operations of supplying the requirements of fuel, lubricants, cooling water, air etc., and are performed by the machine operator as well as by the servicing staff. Field repairs are attended to by another crew upon advice of the servicing party or of the inspection personnel. Inspection is performed on the equipment in operation to detect obvious defects which may prove the potential causes of breakdown. Faulty maintenance (servicing and field repairs) is also uncovered by periodical inspection.

The principal methods of maintenance of field machines are:

1. Maintenance in a central depot
2. Maintenance at the site of work by mobile servicing units.

On small projects where distances are not long, machines may be brought to the central maintenance depot and serviced there. The servicing is usually done during non operating shift to save time during the working shift. For large works where the machines are distributed over a wide area it is desirable to bring maintenance facility to the machine. The servicing can be done during recess in a working shift or after the working hours. A skilled crew with a well equipped servicing trailer may take only about 10 minutes to service a machine so that it can be quickly fed back to work after being serviced.

Like servicing, field repairs can be performed either in a field repair workshop or through a mobile workshop truck. As in the case of mobile servicing units the mobile workshop leads to economy by saving the time of movement of the machine to the field workshop.

For vehicles which are usually serviced at the depot, a specific day should be fixed for each machine and painted on the vehicle to avoid any omission in servicing.

The central workshop which caters to major repairs and overhauling is not generally considered a part of the maintenance organization.

1.5. SCOPE OF STUDY

High mechanization entails heavy initial investment on the construction equipment which may be as high as 25 to 30 percent of the cost of the project. However, in the long run, if the equipment is operated, maintained and managed efficiently, then the investment will pay more than what it costs Therefore, it is important to maintain the equipment because idle equipment due to lack of maintenance not only can add to losses, but also the equipment is likely to be rendered unserviceable due to lying unused. Their periodic maintenance, brings the equipments near to its original condition. Hence maintenance of these equipments is of vital importance to ensure that these are in the perfect condition for use on the works, thus, in Chapter II the procedure for different kinds of maintenance are discussed. By observing these procedures, the maintenance of equipment can be carried out to suit specific needs.

Maintenance of equipment involves the inspection, preventive maintenance, major overhaul etc. The best plan for maintenance is one which ensures maximum machine availability at minimum cost of maintenance. These problems essentially involve decision making which is usually quite difficult in view of the large number of alternatives that baffle the judgement of decision maker. The methods of Operations Research provide a powerful tool to the management for taking decision. Hence, Chapter III describes system models applicable to maintenance planning and include Waiting line models, sequencing models, assignment models and simulation models. These help in making the decision for minimization of maintenance cost.

Chapter IV covers replacement model which in this dissertation on best maintenance strategy may look out of place but a second thought would reveal that when equipment or a component of equipment is no longer economical to maintain it may be a better alternative to replace it by a new component or equipment. Hence a chapter on replacement models is included in this dissertation.

Chapter V gives based conclusions based on the study.

CHAPTER – II

PROCEDURES FOR EQUIPMENT MAINTENANCE

2.1. PROCEDURE FOR SCHEDULLED MAINTENANCE

Scheduled maintenance includes the regular care of equipment viz lubrication, cleaning and change of filters etc.

The areas of responsibility are:[3]

1. Periodic lubrication
2. Cleaning mud and debris from critical areas
3. Recording fuel usage, service meter hours and observed service needs by machine

2.1.1. Periodic Lubrication

Equipment manufacturers normally provide detailed lubrication and maintenance instructions with machines or through the dealer. These instructions are based on actual field tests and extensive research, and they should be followed closely.

Correct lubricants are essential to equipment maintenance. Suppliers must be instructed to provide the lubricants specified by the equipment manufacturer.

Adherence to recommended lubrication change periods is equally important. Greasing and oil changes must be performed within recommended time intervals. Failure to do so will increase operating costs.

Use only clean lubricants. Contaminants in lubricants, or dirt which has entered the system during oil changes, often account for early breakdown of engine or power trains.

Only a complete job of lubrication assures component service life. A grease job cannot prevent a machine breakdown if one fitting is regularly forgotten.

2.1.2. Cleaning Mud and Debris from Critical Areas

Cleaning mud and debris is very important for keeping the machine in smooth running condition. For example, all concreting equipment should be cleaned and washed after the days operation so that concrete may not set on the surfaces of the equipment components.

2.1.3. Recording Fuel Usage, Service Meter Hours and Observed Service Needs by Machine

Records of fuels and lubricants issued and used on individual equipment maintained in order to arrive at average fuel and lubricant consumption. A typical form for maintenance of fuel and lubricant record is given in appendix 2.

2.1.4. Facilities[3]

Requirements for field maintenance equipment will vary greatly with the size and location of the site, the type of heavy machinery used, and the work schedule of the operation.

On small jobs, a contractor may use a single truck for fuel, lubricants, tools, filters, water, and all supplies. The expense of on site service facilities is warranted only when the project is of sufficient size and/or duration, or is too remotely located to be serviced from a home base.

The lubrication truck should be equipped to provide all oils and greases and other expendable items, such as filter elements, required for routine maintenance of the equipment fleet. Lubricants required in large quantities, such as engine and hydraulic oil and cooling water or antifreeze solutions, should be carried in built in tanks of suitable size.

Dispensing equipment may be mounted on the drums of gear oil, chassis grease, and other lubricant which are normally dispensed in small quantities. Individual air powered pumps are normally used to dispense these lubricants. Proper pumps are needed to provide high volume, low pressure flow for low viscosity oils, and the low volume, high pressure delivery to dispense heavy greases. Meters for recording consumption can be attached to the pumps. They permit keeping detailed maintenance records on each machine serviced.

The trucks air compressor provides power for the delivery pumps. It may also be used to inflate tires, run impact wrenches, and blow dirt off machines. For night operations, an electric generator can be installed to power floodlights. An air or electric powered, small capacity, high pressure pump, attached to a 50 or 75 gallon reservoir of water and detergent, will provide spot cleaning for lubrication or for inspection of highly stressed areas such as scraper goosenecks. The truck should have storage space for engine and hydraulic oil filters, air cleaner elements, and similar expandable parts.

Whenever on site service facilities are planned, they must be located a safe distance from other structures – away from the job traffic to avoid dust and congestion, yet easily accessible. Such stations may include fuel storage tanks, wash racks, grease pits, tire change equipment, and welding facilities. Such a maintenance facility may reduce the need for such mobile equipment as fueling and lubrication trucks.

On large earth moving jobs, and especially on around the clock operations, mobile maintenance equipment is the best solution.

2.2. PROCEDURE FOR PREVENTIVE MAINTENANCE

Preventive maintenance is the term applied to all phases of field maintenance when they are properly performed, and properly recorded. Only with a well organized program is a machine owner able to monitor the condition of equipment, to predict production based on machine availability, and to schedule repairs and overhauls in advance. Analysis of accurately compiled maintenance records supplies him virtually all information needed for performance evaluation, repair or replacement decisions, and cost of operations reviews.[3]

2.2.1. Inspection of Equipment[8]

Regular inspection of the equipment is an importance aspect of preventive maintenance program. These regular inspections enable the detection of faults which can be rectified in time avoiding costly breakdowns of the equipment. These inspection programmes should be independent of the operation and field repair work. The inspecting personnel should be technically skilled and competent for the job. Depending upon the type, size and duty of the equipment, the inspection frequency and nature should be decided.

Four basic types of inspection need to be planned and effectively carried out within an organization's equipment maintenance system. Each type of inspection has its own specific objectives and provides necessary information to specific individuals in the management group of the organization. The four types are referred below as A, B, C, and D types.

A-Type Inspections might also be termed spot check inspection carried out by top management personnel. Such inspections are to determine the adequacy and effectiveness of maintenance at various levels within the organization's structure.

The scope of these inspections includes a systematic inspection of the administrative procedures of the facilities, tools, equipment and personnel provided, and a technical inspection (type D inspection) of at least 10% of each type of equipment assigned for use by each unit, section of group within the organization. Generally, A inspections are scheduled by top management staff at least twice annually and therefore include each year in all a technical inspection (type D) on 20% of the using unit's equipment. The equipment inspected is selected at random by the inspection team.

B-Type Inspections are formal inspections at regular periodic intervals conducted by the immediate manager or supervisor of a mechanical equipment using unit or section. Type B inspection are also held by the intermediary management charged with mechanical equipment use and maintenance within the area of responsibility. The frequency of such inspections is generally determined by a general top management policy and is dependent largely on:

a. The type of equipment
b. Its maintenance requirements
c. Results maintenance

Organizations may schedule type-B inspection of motor vehicles, construction equipment and other similar types of motorized equipment on a monthly basis. In many respects the B- inspection is a formalized system of periodically taking a good look at your own operations as far as equipment preventive maintenance is concerned.

C-Type inspection is similar in nature to type B except that it is informal in nature. It is conducted only by the equipment using unit as a check on itself and means of determining by an immediate supervisor that the operating and maintenance personnel immediately under him are effectively performing their assigned preventive maintenance responsibilities on daily, weekly, monthly or other assigned frequencies. Organizations, particularly that operate sizeable vehicle fleets should have well developed C-type inspection procedure.

D-Type inspection is a technical inspection. The purpose of this inspection is to assess serviceability and anticipate future maintenance and exchange requirements. Deficiencies noted during these inspections serve as a means of detecting failure in early stages, preventing major breakdowns, overhauls and the overloading of the maintenance and repair shop and services.

Inspections during equipment operation :

Inspections can be carried out while the equipment is in operation for following observations:

1. Engine sound
2. Power Output
3. Colour of exhaust
4. Oil pressure
5. Temperature of the oil
6. Temperature of the water
7. Brake and clutches

Inspection during equipment shut down:

For equipment inspection, during their shutdown following observations should be made for determining the wear and general condition of equipment.

1. Thorough scrutiny for obvious defects, e.g. oil dripping, loose bolts etc.
2. Checking the amount of wear on common bearing parts.
3. Checking the tightness of all securing devices which are difficult to access while the machine is operating.
4. Effecting minor repairs
5. Checking tyres, wire ropes and batteries etc.

As regards frequency of inspection, it should be balanced. If frequency of inspection is more, it will cost more and results in loss production. At the same time, if inspection frequency is low, more breakdowns may result, causing an increase in cost of operation. The frequency of inspections depends on the nature of facilities and the items being checked, their importance to the continuity of operations, the safety of plant and employees, and the time interval between the first indication of trouble and actual failure.

2.2.2. Factors Affecting the Effective Preventive Maintenance Program[1]

The main factors that affecting the effective preventive maintenance program are

1. Selection of equipment
2. Availability of spare parts
3. Training of personnel and incentives
4. Scheduling of preventive maintenance

Selection of equipment plays an important role in its proper maintenance. In making the selection of equipment initially, one should look for the built in maintenance features in the equipment and should also ensure that the rated production and other specifications aptly suit the job requirements. The design features should also be compatible with the overall concept of economy in running, maintenance and repairs to equipment. The machines which give overall economy in operation considering the repair and maintenance aspects should normally be preferred.

While selecting a machine preference is also given for having good design features to withstand the severity of work on which it is to be employed and quality of components and parts of the machine which do not tend to breakdown frequently.

Preventive maintenance programme can not be successful if adequate spare parts are not procured in advance. The procurement department of the project is responsible for speedy procurement of spare parts from within the country or from outside the country, planning for procurement of spare parts can be done best through the application of inventory models. Previous experience also helps in the matter of keeping the inventory levels minimum for consumables items and for fast moving parts.

The training of personnel is highly essential for making them familiar with the service manual and operational instructions. This training to supervisory maintenance and operating staff should be given with the consultation of the manufacturers and should be given by a specialist. Also, besides training attractive incentive programme should be implemented from time to time to give encouragement to the staff involved.

Lastly the scheduling of the preventive maintenance should also be well planned in consultations with experienced personnel, specialists and manufacturers.

2.2.3. Record Keeping For Preventive Maintenance[14]

The records of operation and maintenance are most essential to analyse the various aspect regarding the availability, productive capacity and cost of operation and maintenance of the machine. Record keeping is the best tool for controlling all the maintenance operations by a Project Manager, which enable him to obtain all information regarding the maintenance operation carried out by the servicing section of the maintenance organization. Different operation which constitute the daily servicing and maintenance of the equipment including field repairs, are recorded in the predefined formats. Besides helping in the control of preventive maintenance programmes these records make it possible to trace the cause and fix responsibility for failure of an equipment. The workshop records include the entire repair history of the machine including the period and extent of overhauling and replacement of parts or assemblies done during each overhaul. The following important records regarding the equipment are prescribed to be maintained.

The machine Record book (or log book) includes information about day to day consumption of stores, repairs and replacements, and working hours, idle hours and breakdown hours. Besides locating faulty operation or potential trouble spots, this record enables proper cost accounting of the machine and is an invaluable record during its disposal stage. It contains all original data about a machine, and should be carefully maintained and safeguarded against loss or abuse. A typical record book form is given in appendix 3.

The history book of machine gives its technical and cost data, history of repairs and alterations and abstract of utilization in terms of machine hours and depreciation. It helps in evaluating the general condition of a machine at any time to decide the nature and extent of future repairs and to assess its book value. A typical history book form is given in appendix 4

Special records for costly items, such as tyres and tubes, batteries, steel wire rope, etc. are also kept on some projects.

2.2.4. Facilities

The facilities for preventive maintenance include the mobile units, the field repair shop and the base workshop. Minor replacements and adjustments of easily accessible components are done by mobile units. Replacement of major assemblies and servicing is carried out in the field repair shop. The base workshop is responsible for close and direct field support under taking all major repairs and overhaul operations in the shop which are beyond the capacity of field units.

1. Mobile Workshop[8]

The tools required for maintenance are installed on a suitable trucks chasis and the important ones are listed below –

a. Power take off for transmitting power to the welding generator from the truck engine.
b. Air compresors 0.28 to 0.42 cum/minute capacity.
c. Drill press
d. Hydraulic press
e. Anvil
f. Work benches with vices
g. Tool grinder
h. Hydraulic jacks
i. Grease pump and container
j. Oxy – acetylene welding and cutting apparatus.
k. Tools like hammer, punches, spanners, tool kit and puller etc.

2. Field Repair shop

This shop is normally located near the work area and should satisfy the following requirements –

a. The workshop floor space should preferably be concreted and covered with provision for light and power.
b. The field fitting shop should contain vices, benches, racks, portable electric drills, grinders, jacks and tool kits.
c. The hoisting equipment will include lifting tackle, gantry crane or mobile crane of large capacity.
d. For welding and cutting operations portable electric welding equipment, oxy acetylene gas cylinders with cutting and welding torches are provided.

e. It should also contain field stores items which include sufficient tools.

3. Base Workshop

A well planned base workshop, is the most important and essential requirement for the successful implementation of a preventive maintenance programme. Details about base workshop are covered subsequently under procedure for breakdown maintenance.

2.3. PROCEDURE FOR BREAKDOWN MAINTENANCE

The breakdown maintenance, calls for a bigger task force for maintenance, then is available. Any such situations can be tackled by apportioning additional staff on manpower to meet this requirement. However, one of the main requisites for meeting the breakdown maintenance work is to provide tools, handling equipment, welding sets etc, so that least time is lost in carrying out the necessary repairs. Planning a head of time for manpower and tools and equipment for meeting requirements of breakdown maintenance, commensurate with the size of fleet of equipment, pays great dividends, as this would reduce the loss in production time and make it possible for the required targets of production to be fulfilled.

Breakdown maintenance can be carried out in two places depending upon nature of breakdown.

1. Field workshop
2. Base workshop

2.3.1. Field Workshop

Field workshop have covered space for repair of machines in addition to uncovered floor area with concrete floor.

The maintenance shop should have a small store for keeping day to day, fast moving spare parts and other hardware items, including filters required for the machine. The field repair shop should be furnished with working benches, racks, hand tools, lifting tackles, mobile crane, portable welding equipment etc. for executing the repairs and maintenance work with speed and efficiency. These shops are necessitated where the base facility is far off from the normal work area.

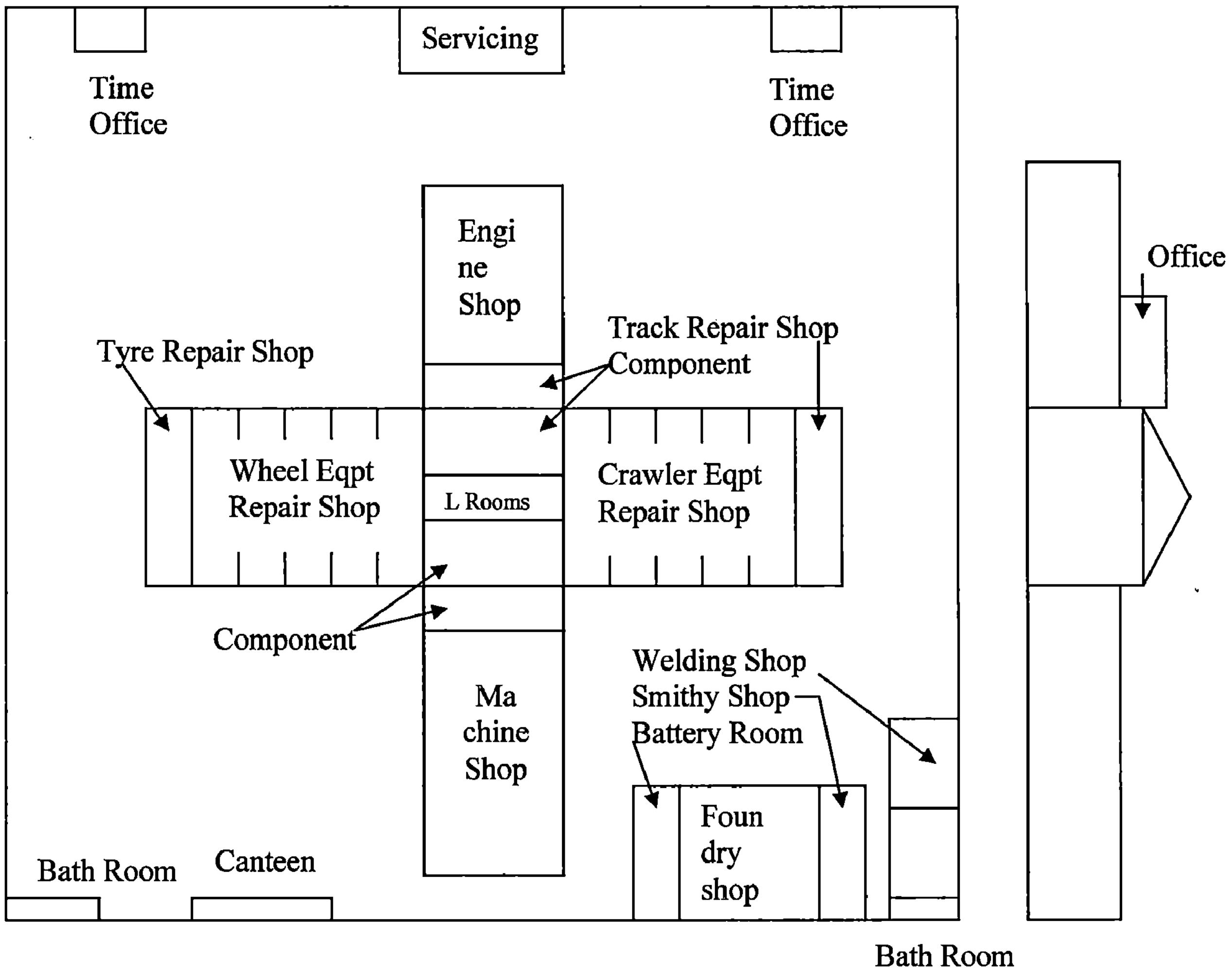
2.3.2. Base Workshop

The base workshop on a project is essential for a successful maintenance programme. The location, layout and construction of the workshop should be such that the repair work can be carried out efficiently and with minimum delays in placing the equipment back in operation. The workshop should be located at a place which is easily accessible to field equipment an machine can be transported to it and back from there in minimum time and cost. Arrangement for this transportation is an essential part of the service of the workshop. The workshop should be laid out in section such that sections providing related or immediately following operations are located closed to each other. Sufficient covered area and flooring space should be provided. Roof should be adequate in height, and doors and passages wide enough to permit the largest size of machine to pass through. Adequate lighting and ventilation are also necessary in the workshop building. The workshop should be furnished with necessary tools and appliances, and also with warehouse facilities, and should be adequately manned both in quality and number of workmen. Every maintenance shop should be equipped with electric overhead crane. The size of crane is to be determined by the heaviest piece to be handled.

The work in base workshop can be subdivided according to the functional requirements, keeping in view the minimum time necessary for repairs. The shops which may be planned are as follows:[8]

1. Machine shop
2. General repair and fitting shop
3. Smithy shop
4. Foundry shop
5. Electrical shop
6. Heavy equipment repair shops – wheeled and crawler.

7. Structural shop – Steel fabrication works including sheet metal shop
8. Servicing section
9. Carpenter's shop including upholstery work
10. Paint shop
11. Tyre retreading shop
12. Welding shop
13. Rigging shop
14. Transport and light vehicle repair shop
15. Pump repair shop
16. Inspection, progress department and other offices



Total Area 37350.61M
Covered Area 9878.04M
Uncovered Area 27439.02M

Shop Areas
1. 18.29Mx6.09M
2. 30.48Mx18.29M
3. 30.48Mx18.29M
4. 18.29Mx6.09M
5. 24.38Mx12.20M
6. 12.20Mx6.09M
7. 12.20Mx6.09M
8. 12.20Mx6.09M
9. 12.20Mx6.09M
10. 24.38Mx12.20M
11. 15.23Mx0.09M
12. 18.29Mx15.23M
13. 15.23Mx6.09M
14. 21.32Mx6.09M

Fig.2.1. Typical Workshop Layout for Repair Facilities for 200 Machines[2]

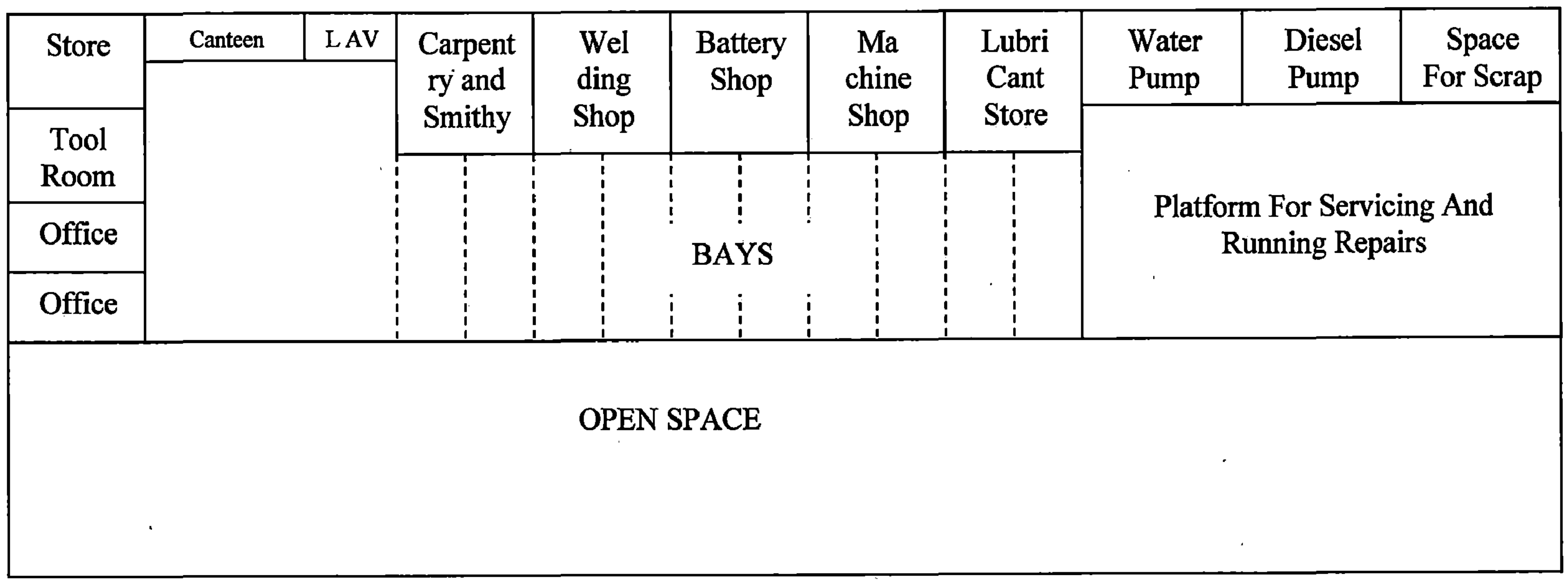


Fig.2.2. Layout Plan Of Field Workshop[1]

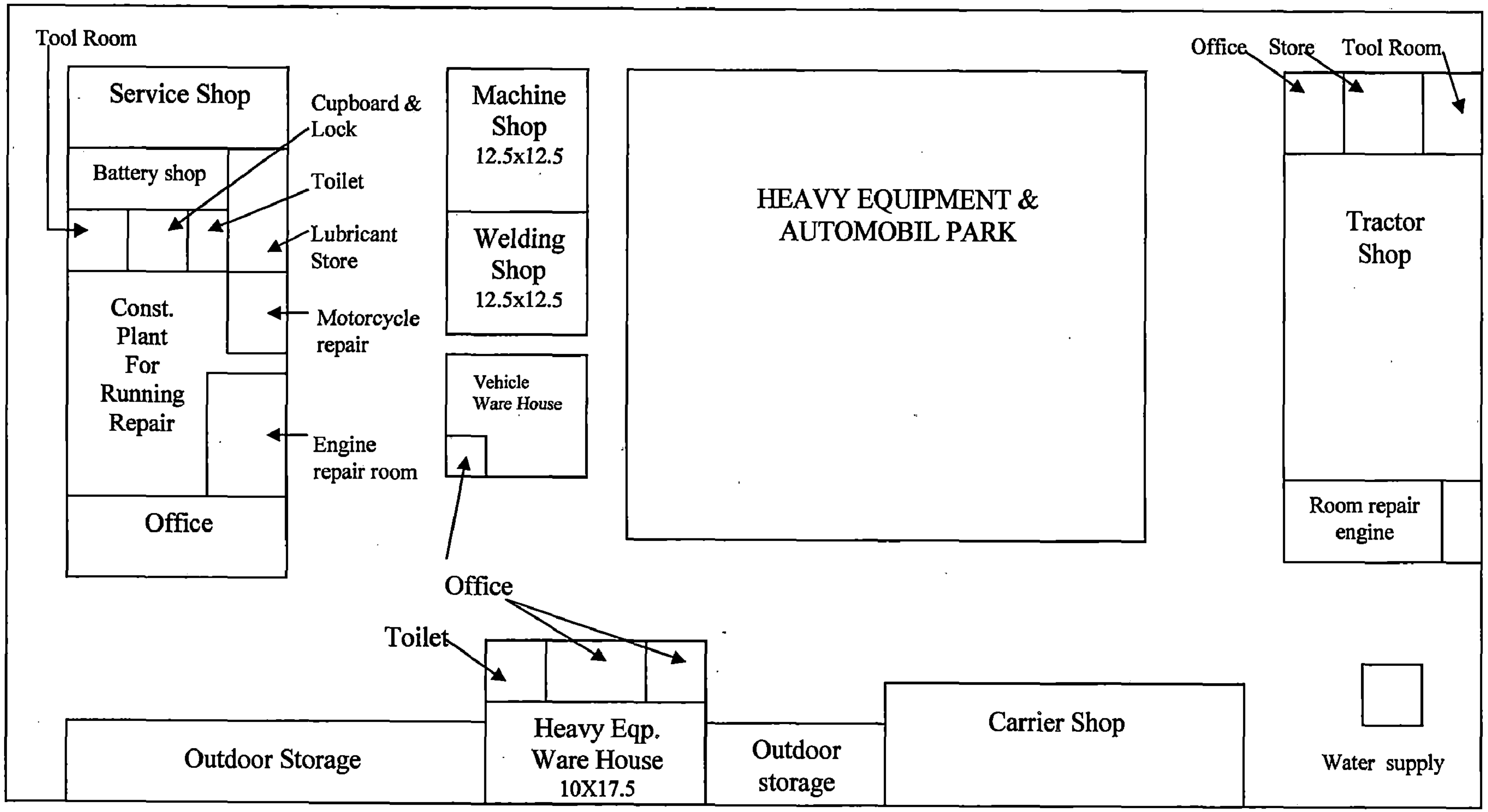


Fig.2.3. Layout Of Workshop Of Jratunseluna Project (Indonesia)[6]

CHAPTER - III

SYSTEM MODELS IN EQUIPMENT MAINTENANCE

3.1. INTRODUCTION

Modern construction projects are marked for their size, complexity in design, and speed of execution. Mechanization has become synonymous with speed of execution. With large scale mechanization the need for the operational availability of equipment is more exacting and this calls for an elaborate programme for operation and maintenance of equipment. Besides, the effective planning and management of operation and maintenance of construction equipments could best be achieved through the use of system models.

The primary function of maintenance is to control the condition of equipment. Some of the problems associated with this include determination of

- Inspection frequencies
- Depth of inspection
- Overhaul intervals, i.e. part of preventive maintenance policy
- Whether or not to do repairs, i.e. a breakdown maintenance policy or not.
- Whether or not an equipment modification should be made
- Replacement rules for component
- Reliability considerations
- Maintenance crew sizes
- Composition of machines in workshop
- Space provisioning rules
- Sequence rules for jobs requiring some form of maintenance effort
- Scheduling start times for constituent jobs of maintenance project.

Problems within these areas can be classed as being deterministic or probabilistic. Deterministic ones are those where the consequences of a maintenance action are assumed to be non-random. For example, after an overhaul the future trend in operating cost is expected to be known. A probabilistic problem is one where the outcome of the maintenance action is random. For example, after equipment repair, the time to next failure is probabilistic.

To solve any of the above problems there are often a large number of alternative decisions that can be taken. For example, for component subject to sudden failure we may have to decide whether to replace it while it is in an operating state, or only on its failure; whether to replace similar components in groups when one perhaps has failed etc.

Thus it is seen that the function of the maintenance department is to a large extent concerned with identifying the appropriateness of various decisions to control the condition of equipment to be in line with the objectives of organization.

In its simplest form the arrival of construction equipment for preventive maintenance crew may be analyzed as follows;

Different types of preventive maintenance checks / services can be grouped according to time interval between them so as to facilitate scheduling of preventive maintenance consider for example, the grouping of PM checks/service into four groups, say A,B,C and D. as indicated in Table 3.1.

TABLE 3.1

Grouping Of Preventive Maintenance Checks / Service[5]

Type	P.M. Checks / Service	Interval of P.M.	
		Vehicles	Heavy Equipment
1	2	3	4
A	Checking of - Oil, Water and Fuel Level - Battery, Ampere Meter, Air Pressure, Oil Pressure Gauges - Tyre Inflation - Daily Greasing etc.	Daily	Daily

B	Engine Oil Change / Replacement of - Fuel Filter, Engine Oil Filter - Corrosion Resistor Cleaning of - Air Filter, Radiator Core Adjustment Of - Clutch / Brake Clearance - Track Tension etc. - Monthly Greasing Including Type A Services	3000 kms Or 1 month	100 hours Or 1 month
C	Cleaning Of - Hydraulic Oil Filter - Transmission Oil Filter Checking Of Wear on - Tyres, rollers, Chain Sprockets - Cutting edge etc. and including Type B Services	15000 kms Or 6 months	500 hours Or 6 months
D	Checking of - Engine Compression, Injectors - Transmission Oil Change - Hydraulic Oil Change Replacement Of - Transmission Oil Filter - Hydraulic Oil Filter, etc. and including Type C Services	30000 kms Or 12 months	1000 hours Or 12 months

This grouping helps in scheduling of preventive maintenance or in computing the frequency of PM. Checks / service pertaining to any group. As an example, suppose a crane is required to operate for 1,500 hours per year and assuming 5 working days per week, we get total working days per year as 252. Then frequency of PMG for type B service can be calculated by using the equation[4]

$$PMG = \frac{252SI}{AW}$$

Where : PMG = PM group

SI = Service interval in operating hours (equipment) or miles (vehicles)

AW = annual work in operating hours or miles.

So

$$PMG = \frac{252 \times 100}{1500} = 16.8 = \text{say } 17$$

This crane would be listed as PMG = 17, or type B service would be required every 17 working days. Again, if the total number 'N' of cranes on a project be 18, then days 'D' between services for machines in each group will be calculated next from

$$D = \frac{PMG}{N} = \frac{17}{18} = 0.9$$

Where ; D = days between services for machines in PMG

PMG = PM group

N = number of machines in group

This means that we will have to schedule 10 cranes every 9 days for type B service or arrival rate of cranes is 10 cranes in 9 days. For construction project operating 175 pieces of equipment, the computation would be as in table 3.2.

TABLE 3.2

Scheduling Of Equipment For Preventive Maintenance[4]

PMG	N	D		Arrival Rate or Service Rate
17	18	17/18	=	0.9 or 10 in 9 days
126	62	126/62	=	2.0 or 1 every 2 days
105	12	105/12	=	8.8 or 5 in 44 days
92	8	92/8	=	11.5 or alternating 11 and 12
63	35	63/35	=	1.8 0r 5 in 9 days
42	4	42/4	=	10.5 or alternating 10 and 11 days
28	36	28/36	=	0.8 0r 5 in 4 days

3.2. OPTIMUM NUMBER OF REPAIRMAN[5,15]

One of vexed problem for maintenance management organization concerns the work force or requirement of crew in the maintenance department. Due to inherent variability in the maintenance systems and corresponding uncertainty of breakdown and repairs, the problem of manpower planning for breakdown maintenance is far more difficult than manpower estimation for production departments. Many maintenance organizations used to engage staff more or less as the need arose. Due to difficult nature of manpower planning, any manpower level could be justified for maintenance task in the absence of scientific analysis.

When several machines, of different types deployed on a major construction project are to be maintained, the problem resembles the usual waiting line model, and the repair crew is the serving station. If the crew is already working on a maintenance of other equipment, successive equipment that breakdown must wait for service and the cost associated with downtime will grow with the delay. This situation of downtime of equipment can be reduced by increasing the size of crew, but this solution too costs money since it will increase the idle cost of crew when there is no work for them in case of no breakdown situation. Therefore, a balance between the downtime costs of the machine and cost of the maintenance crew has to be struck.

Consider the case of a repair workshop where the maintenance crew are paid on results so that it is considered essential that each crew is allocated a fixed number of machines. In order to give every crew an equal allocation of machines to every crew is necessary. Hence, the maintenance repair system can be considered as consisting of a number of parallel single server systems.

In order to avoid any resentment among the production workmen ie equipment operators who may be working with incentive the maintenance personnel are instructed to attend to the machines on a first come first served basis.

A statistical investigation of the breakdown and repair time of machines reveals that the rate of breakdown found to have a poisson distribution and the repair time exponentially distributed. Therefore, the appropriate waiting line model available in most management science/operational research is applied too the problem.

The problem of determining optimum number of repairmen is one of the most common problems faced by maintenance managers. In providing the maintenance service to a given production system, essentially there types of costs are incurred which are detailed as follows:

1. Cost of Idle Time of Machines

   When a machine needs maintenance then it is either operated at reduced speed (efficiency) or has to be stopped. However, due to the unavailability of a repairman at the time of machine breakdown, the machine must wait for repairs. Once the repairman starts repairing the machine, sometime is required to repair it depending on the rate at which repairs are carried out by them. The time duration over which a machine has to wait for repairs and the time the repairmen actually takes to repair it determines the idle time for a machine breakdown. Higher the idle time for a machine breakdown, higher will be the cost of idle time of machines. The total cost of machine idle time is generally indirectly proportional to the number of repairman.

2. Cost of Providing Maintenance Service

   This depends directly on the number of repairmen employed to repair the machines/equipment. This include the wages and other benefits payable to employees.

3. Cost of Stores and other Consumables

   This cost is due to the repair parts, utilities and other consumables used to repair the machines. This cost is independent of the number of repairmen employed in the production shop. For a given number of machines approximately same number of breakdowns will occur requiring a fixed amount of spare parts, utilities and consumables. Hence this cost represents the fixed cost of providing the maintenance service to the production system. Therefore, the cost of machine idle time and the cost of employing the maintenance repairmen are the two variable costs of the production maintenance interface by the production system.

According to parameters behavior optimization models can be classified as:

(i) Deterministic Model

(ii) Probabilistic Model

The deterministic model is the simplest kind of waiting line models in which the arrival and service rate can be predicted with certainty.

In Probabilistic model, the arrival rate and rate at which units after being served depart, are random in nature and takes values in accordance with a known probability distribution function.

The waiting line analysis may start with no initial queue or with a queue in existence. In the latter case there is usually a carryover of waiting unit to next cycle. We are dealing with models having no initial queue.

3.2.1. Deterministic Model[13,15]

The arrival of units for repair are assumed to occur at regular known intervals of time. Similarly, serving time is also known. Since arrival and service takes place at well defined intervals of time, if the rate of rendering service is faster than arrival rate of units no queue will form.

Let us assume

C_w = Cost of waiting of one unit for one period of time

C_f = Facility cost for servicing one unit

C_t = Total system cost

t_a = Time between two arrivals

t_s = Time to complete one service

Hence:

Number of units arriving during the period and previous unit served will be

$$= {}^{t_s}\!/_{t_a}$$

Cost of waiting per period of time = $C_w \frac{t_s}{t_a}$

Number of units served per unit time = $1/t_s$

Cost of servicing facility will be $= C_f \frac{1}{t_s}$

Therefore total cost will be

$$C_t = C_w\left(\frac{t_s}{t_a}\right) + C_f\left(\frac{1}{t_s}\right)$$

For minimum total cost $\frac{dC_t}{dt_s} = \frac{C_w}{t_a} - \frac{C_f}{t_s^2} = 0$ or $t_s = \sqrt{\frac{C_f t_a}{C_w}}$ ....(1)

Equation (1) gives the economical time period for serving a unit. The nearest feasible value of service time can be adopted which would give an economical capacity of the facility.

For M server unit

$$t_s = \sqrt{\frac{C_f t_a M}{C_w}}$$

3.2.2. Probabilistic Model[13,15]

The deterministic model is too naïve and simple for most application in the real world. In reality the arrival and the serving patterns are characterized by randomness, and the arrival and the service times have well defined probability distributions. The simplest and the most commonly used model assumes the inter arrival and service times as exponentially distributed.

The system cost in the probabilistic model is a random variable, the two elements of this cost having their individual independent, probability distributions.

Let

C_{wm} = Mean cost of waiting of one unit for one time period

C_{fm} = Mean cost of serving one unit, and

C_{tm} = Mean cost of the system

The mean cost of waiting per period of time is equal to the mean cost of waiting of one unit for one unit time period (C_{wm}) multiplied by the mean number of units waiting in the system during a period (L_q). Similarly, the mean cost of serving per period of time is the product of the cost of serving one unit (C_{fm}) and the number of units served in the period i.e. x

Therefore, the total mean cost C_{tm} is given by

$$C_{tm} = C_{wm} L_q + C_{fm} x \qquad ....(1)$$

Substituting the value of L_q as $\left(\frac{\lambda}{\mu - \lambda}\right)$, we get

$$C_{tm} = C_{wm}\left(\frac{\lambda}{(\mu-\lambda)}\right) + C_{fm}(x) \qquad \text{....(2)}$$

For finding the minimum cost, the total cost C_{tm} is differentiated with respect to μ and equated to zero, viz

$$\frac{dC_{tm}}{dx} = -\frac{C_{wm}\lambda}{(\mu-\lambda)^2} + C_{fm} = 0$$

And system minimum average total cost will be

$$= C_{fm}\lambda + 2\sqrt{\lambda C_{wm} C_{fm}} \qquad \text{....(3)}$$

For minimum total system cost equation (3) gives the capacity of the serving facility. Therefore, the capacity of the serving facility (x_o) corresponding to minimum cost is

$$x_o = \lambda + \sqrt{\frac{\lambda C_{wm}}{C_{fm}}}$$

So that the number of gangs M is simply the ratio of x_o to x.

3.3. WAITING LINE MODELS[13]

Waiting line model deals with problems of congestion, where customers arrive at a service facility, perhaps with in a queue, are served by 'server' and then leave the service facility.

In maintenance problems customers may take the form of construction equipment arriving at a workshop from various sites and the servers in these cases could be the repair crew in the workshop and the service crews available to look after machine breakdowns and servicing.

The essential features or characteristics of a queuing system shown below :

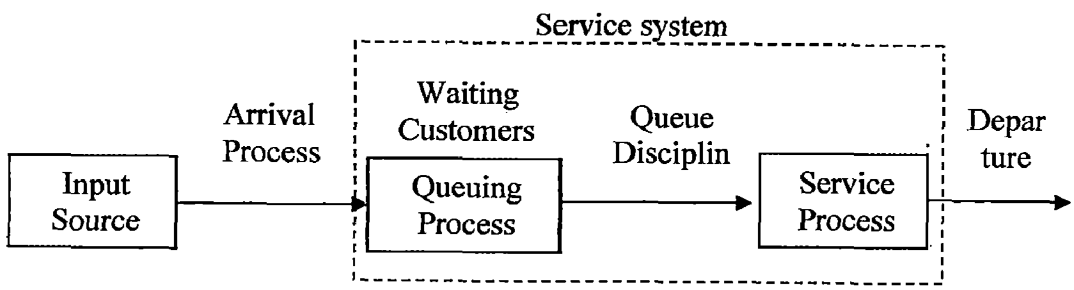


Fig.3.1. Queuing System

Customers requiring service are generated at different times by an input source, commonly known as population. The rate (constant or random) at which customer's arrive at the service facility is determined by the arrival process. The customer's entry into the service system depends upon the queue conditions. If at the time of customer's arrival, the server is idle, then the customer is served immediately. Otherwise the customer is asked to join the queue, which can have several configurations.

Customers from the queue are selected for service according to certain rules known as queue discipline. The service facility may consist of no server (self service), one or more servers (arranged in series or parallel).

The rate (constant or random) at which service is rendered is known as the service process. After the service is rendered, the customer's leaves the system.

All these essential features (or component) have certain characteristic which need to be examined before developing mathematical queuing models.

The actual arrival and service patterns for preventive maintenance, or for that matter the unscheduled or breakdown maintenance are probabilistic and waiting line theory considers this.

The results of queuing theory enable questions such as the following to be answered :

1. For a given service facility (e.g. workshop size, maintenance crew size) what is the time that a job has to wait in queue?
2. For a given service facility what is the average number of jobs in the system at any one time?
3. For a given service facility and given pattern of work load, what is the average idle time of the facility?
4. For a given service facility, what is the probability of waiting time greater than t?
5. For a given service facility what is the probability of one of the servicers in the facility being idle?

Once information such as the above is obtained it may then be possible to identify the optimal size of the service facility to minimize the total cost of the service facility and down time incurred due to jobs waiting in queue for sevice. These basic conflicts are illustrated in Fig.3.2.

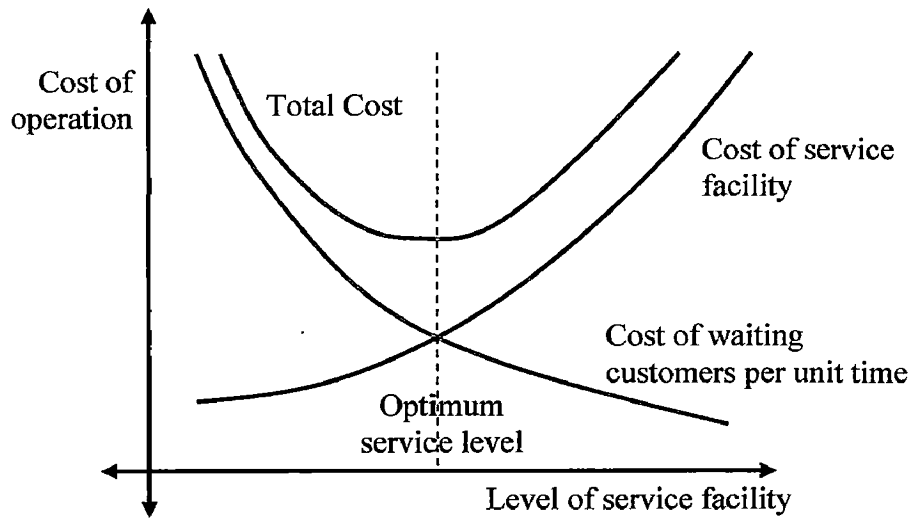


Fig.3.2. Queuing Costs Vs Level of Service Facility

Obviously, an increase in the existing service facilities would reduce the customer's waiting time. Conversely, decreasing the level of service should results in long queue(s). This means an increase or decrease in the level of service increases or decreases the cost of operating service facilities but decreases or increases the cost of waiting. The optimum service level is one that minimizes the sum of the two costs.

3.3.1. The Arrival Population

The size of calling population whether it is homogeneous or consist of several sub populations is considered either to be finite or infinite. When the number of potential arrivals is dependent on the number of customers already in the system (those being serviced plus those in queue), the calling population is finite or limited. An example of a finite calling population is a factory having only four machines which often require repair / service and two of them (say) are in working condition. Then at any point in time, there are only two machines which could possibly require service. Most of the situation for maintenance of construction equipment fall in this class (finite).

Alternately, if a new customers arrival is independent of the number of customers already in the system, the calling population is considered unlimited or infinite. Examples of infinite population include customers arriving at a bank or supermarket, cars arriving at a highway petrol pump, etc.

The arrival population for maintenance of construction equipment, although always finite in size, may be considered infinite under certain conditions. If the departure rate is small relative to the size of population, the number of units that potentially may require service will not be seriously depleted. Under this condition, the population may be considered infinite.

In some cases the proportion of the population requiring service may be fairly large when compared with the population itself. In these cases, the population is seriously depleted by the departure f individuals to the extent that the departure rate will not remain stable.

Since model used to explain waiting line systems depend upon the stability of the arrival rate, finite cases must be given special treatment. Example of waiting line operation that might be classified as finite are production machines that may require repair and hence automatic production facilities that require operator attention.

In general problems involving infinite populations are easier to solve than those which involve finite populations of customers.

3.3.2. The Service Facility[13]

The capacity of the service mechanism is measured in terms of customers that can be served simultaneously and/or effectively. Service may be thought of as the process of providing the activities required by the units in the waiting line. It may consist of collecting spares from store, filling a repair order, providing a necessary repair, or completing a manufacturing operation.

The service mechanism, like the arrival mechanism, is discrete, since items are processed on a unit basis. The arrival of customers at the facility result in the formation of the waiting line. A unit being served or waiting its turn for service is considered to be in the waiting line. This formation of waiting line is discrete process and the number of units waiting at any instant of time is integer value. The size of waiting line depends upon the relative value of arrival rate of customers and serving rate of facility. The order in which customers are served by the facility is important and is called waiting line (or queue) discipline. The common arrangement is of first come, first served type.

The service facility may consist of a single channel, or it may consist of several channels in parallel as in Fig.3.3. and Fig.3.4.

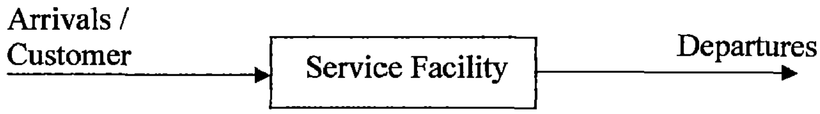


Fig. 3.3. Single Channel

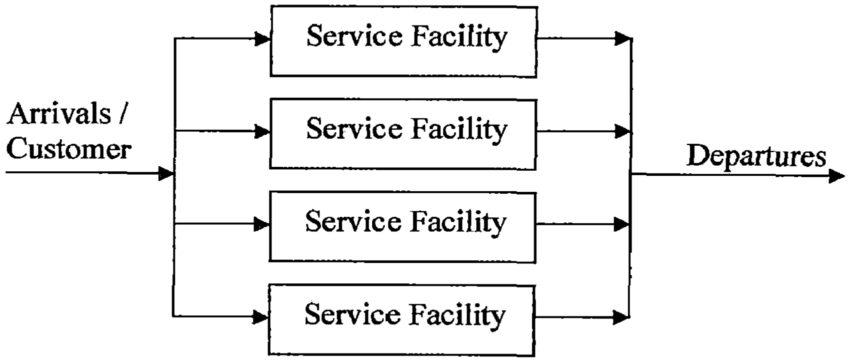


Fig. 3.4. Multiple Channel

If it consist of only a single channel, all arrivals must eventually pass trough it. If several channels are provided, arrivals may join the queue of his choice in front of service facilities or he may be served by any service facility.

3.3.3. Arrival and Service Pattern

The arrival and serving patterns are assumed to be random, i.e. the interval between arrival of jobs at service facility will be negative exponentially distributed. Thus dealing with a poisson process where the arrival rate per unit time is distributed according to poisson distribution which is

$$P \{n \text{ arrivals in Time } t\} = \frac{(\lambda t)^n e^{-\lambda t}}{n!}$$

Where : n = Number of arrivals in time t

λ = arrival rate (number of units arriving) per unit of time

t = time interval

f(t) = density function for time interval t between two arrivals

Mean time between arrivals, $1/\lambda = \int_0^\infty t f(t)dt$

The arrivals are assumed completely random ie independent of time, queue length and any other property of waiting line system.

The service distribution is assumed to be negative exponential i.e. the time taken to repair a job in the service facility is negative exponentially distributed.

$$P \{n \text{ services in Time } t\} = \frac{(\mu t)^n e^{-\mu t}}{n!}$$

Where μ = number of service rendered by facility in a unit time.

The priority rules is first come, first served i.e customers are served in the order of their arrival.

State of the system is steady i.e. the probability that n items are in queue at any time remains the same with the passage of time.

3.3.4. Type of Waiting Line Models[13]

Waiting line model can be classified according to number of service facility :

According to service facilities there are two types

(i). Waiting line situation where there is a single server facility (i.e. single server facility) and only one customer can be served at any time. All incoming jobs join a queue, unless the service facility is idle, and eventually depart from the system, as shown in fig. 3.3.

(ii). Waiting line situations where multi –channel servicing system exists, customers join a queue and then go from the queue to the first facility that becomes vacant as shown in Fig 3.4.

In maintenance operations both types of these systems could be existent. Further, both single channel and multi channel systems could be either with infinite population, or with finite population on the face of it the word infinite population appears to be out of context for repair / maintenance of equipment but the population may be considered as infinite when breakdown is low.

3.3.5. Single Channel Waiting Line Model For Infinite Population

Considering the inter arrival times and service time, as exponentially distributed (i.e. number of arrivals per period and number of services per period are poisson distributed). The probability P_n of n units being in the queue at any time t in terms of arrival and service rate of system is given by

$$P_n = \left[1 - \frac{\lambda}{\mu}\right]\left[\frac{\lambda}{\mu}\right]^n$$

Where : λ = arrival rate

μ = service rate

n = 0,1,2,3,....

Expected number of units in system (L_s)

$$L_s = \frac{\lambda}{\mu - \lambda}$$

Expected waiting time per arrival (in queue + in service) (W_s)

$$W_s = \frac{L_s}{\lambda} = \frac{1}{\mu - \lambda}$$

Expected queue length (L_q)

$$L_q = L_s - \frac{\lambda}{\mu} = \frac{\lambda^2}{\mu(\mu - \lambda)}$$

Expected waiting time in queue/unit (Wq)

$$W_q = W_s - \frac{1}{\mu} = \frac{\lambda}{\mu(\mu - \lambda)}$$

Example 3.3.5.1:

As an example to illustrate these formula, let us consider the case of a large construction project having many identical heavy dump truck. A study is made of the time between the arrival of machines for routine servicing and of the time required for servicing. The average time between arrival was found to be one dump truck after 200 hours and each repair on the average took 10 hours of the repair crew. Determine the following:[5]

a. The probability that no dump trucks are available waiting for repair at repair shops.
b. The average number of dump trucks in the queue
c. The average waiting time for a dump truck in the queue

Solution :

It is given that:

Mean arrival rate, $\lambda = 1/200$ per hour

Mean service rate $\mu = 1/10$ per hour.

Therefore, utilization factor, $\rho = \lambda/\mu = 10/200 = 5\%$

For simple queue (ie. Only one repair gang)

a. The probability that no dump trucks are available waiting for repair at repair shops.

$$P_n = \left[1 - \frac{1}{20}\right]\left[\frac{1}{20}\right]^n \quad \text{for } n = 0 \qquad P_o = 0.95$$

b. The average number of dump trucks in the queue

$$L_q = \frac{\lambda}{(\mu - \lambda)} = \frac{1/200}{(1/10 - 1/200)} = 0.053$$

c. The average waiting time for a dump truck in the queue

$$W_q = \frac{\lambda}{\mu(\mu - \lambda)} = \frac{L_q}{\lambda} = \frac{0.053}{1/200} = 10.6 \text{ hours}$$

Example 3.3.5.2:

A large construction project has over 25 power shovels working in different locations. These are attended to, increase of breakdowns, by a mobile crew of repairmen. It is found that these machines have a breakdown rate of one machine after every 3 days, and each repair on the average, take 2 days of the crew. The breakdowns are poisson distributed and the service times can be considered as exponentially distributed. Find the probability that there will be no breakdown on any day and the repair crew rendered idle. Also find the probability that there will be two or fewer machines under breakdown needing repairs (or under repair) on any day.

Since the number of machines is large as compared to the breakdown rate, the population may be considered as infinite in this problem.[5]

Solution:

It is given that: $\lambda = 1/3$ and $\mu = ½$

Therefore, $\lambda/\mu = 2/3 = 0.67$

The probability that there will be no breakdown on any day and the repair crew rendered idle

$$P_0 = (1 - 0.67)\,(0.67)^0 = 0.33$$

a. The probability that there will be two or fewer machines under breakdown.

$$P_n = \left[1 - \frac{\lambda}{\mu}\right]\left[\frac{\lambda}{\mu}\right]^n$$

$$P_1 = (1 - 0.67)\,(0.67)^1 = 0.2211$$

$$P_2 = (1 - 0.67)\,(0.67)^2 = 0.1481$$

b. For the system the mean number of breakdown in the queue

$$L_s = \frac{\lambda}{\mu - \lambda} = \frac{0.3334}{0.5 - 0.3334} = 2$$

c. Mean time spent by an machine in waiting

$$W_s = \frac{L_s}{\lambda} = \frac{1}{\mu - \lambda} = \frac{1}{0.5 - 0.3334} = 6 \text{ days}$$

3.3.6. Multiple Channel Waiting Line Model For Infinite Population[13]

In this case instead of single service channel, there are multiple servers in parallel equal to s. For this queuing system it is assumed that customers arrive according to a poison process at an average rate of λ customers per unit of time and are served on a first come, first served basis at any of the servers. These servers are identical, each serving customers according to an exponential distribution with an average of μ customers per unit of time. It is further assumed that only one queue is formed. The overall service rate of servers is obtained in two situations, when n customers are in system :

i. If $n < s$, (number of customers in the system is less than the number of servers), then there will be no queue. However, $(s - n)$ number of servers are not busy. The combined service rate will then be

$$\mu n = n\,\mu \quad ; \quad n < s$$

ii. If $n \geq s$, (number of customers in the system is more than or equal to the number of servers) then all servers will be busy and the maximum number of customers in the queue will be $(n - s)$. The combined service rate will be

$$\mu n = s\,\mu \quad ; \quad n \geq s$$

Thus to derive the results for this model we have

$$\lambda_n = \lambda \text{ for all } n \geq 0$$

$$\mu_n = \begin{cases} n\mu & ; \quad n < s \\ s\mu & ; \quad n \geq s \end{cases}$$

The Probability of n units being in the queue (P_n)

$$P_n = \begin{cases} \dfrac{\rho^n}{n!} P_o & ; \quad 1 \leq n < s \\ \dfrac{\rho^n}{s!\,s^{n-s}} P_o & ; \quad n \geq s \quad ; \quad \rho = \dfrac{\lambda}{\mu} \end{cases}$$

The probability that no equipment in the queue (P_o)

$$P_o = \left[\sum_{n=0}^{s-1} \frac{(s\rho)^n}{n!} + \frac{1(s\rho)^s}{s!(1-\rho)} \right]^{-1} \quad ; \quad \rho = \frac{\lambda}{s\mu}$$

Expected queue length (L_q)

$$L_q = \left[\frac{1}{(s-1)!} \left(\frac{\lambda}{\mu} \right)^s \frac{\lambda\mu}{(s\mu - \lambda)^2} \right] P_o$$

Expected number of units in system (L_s)

$$L_s = L_q + \frac{\lambda}{\mu}$$

Expected waiting time per arrival (W_q)

$$W_q = \frac{L_q}{\lambda}$$

Expected queue length (Ws)

$$W_s = W_q + \frac{1}{\lambda}$$

Example 3.3.6.1:

As an example, consider a three channel system with poisson arrivals at mean rate of 0.50 units per period and exponential service at each channel with a mean service rate of 0.25 units per period.[11]

Under this condition ρ is equal to $\frac{\lambda}{s\mu}$

$$\rho = \frac{0.5}{3 \times 0.25} = 2/3$$

The probability that no equipment in the queue (P_o)

$$P_o = \left[\sum_{n=0}^{s-1} \frac{(s\rho)^n}{n!} + \frac{1(s\rho)^s}{s!(1-\rho)} \right]^{-1} = \left[\sum_{n=0}^{3-1} \frac{(2)^n}{n!} + \frac{(2)^3}{3!(1/3)} \right]^{-1}$$

$$P_o = \frac{1}{5+6+6} = 1/17 = 0.06$$

Average length of the queue

$$L_q = \left[\frac{1}{(3-1)!} \left(\frac{0.5}{0.25} \right)^3 \frac{0.5 \times 0.25}{(3 \times 0.25 - 0.5)^2} \right] 0.06 = 2.67 \times 0.06 = 0.16 \text{ Units}$$

Average number of units in the system

$L_s = L_q + \rho = 0.16 + (0.5/0.25) = 2.16$ units

Expected waiting time per arrival (W_q)

$$W_q = \frac{L_q}{\lambda} = \frac{0.16}{0.5} = 0.32 \text{ periods}$$

Expected queue length (Ws)

$$W_s = W_q + \frac{1}{\lambda} = 0.32 + 2 = 2.32 \text{ periods}$$

3.3.7. Single Channel Waiting Line Model For Finite Population[13]

This model is similar to the Single Channel Waiting Line Model For Infinite Population except that the calling population (input source) of potential customers is limited, say M. Thus arrival of additional customers is not allowed to join the system when the system becomes busy in serving the existing customers in the queue. For example: A maintenance staff provides repair to M machines in a workshop. Here the M machines are customers and the repair staff members are the servers.

When there are n customers in the system, then system left with the capacity to accommodate M – n more customers. Thus, further arrival rate of customers to the system will be λ (M – n). That is, for s =1, the arrival rate and service rate is stated as follows:

$$\lambda = \begin{cases} \lambda(M-n) & ; \quad n = 1,2,\ldots M \\ 0 & ; \quad n > N \end{cases}$$

$$\mu_n = \mu \qquad ; \quad \text{n=1,2,}\ldots M$$

The Probability of n units being in the queue (P_n)

$$P_n = \frac{M!}{(M-n)!}\left(\frac{\lambda}{\mu}\right)^n P_o \quad ; \quad \text{n = 1,2,.....M}$$

The probability that no equipment in the queue (P_o)

$$P_o = \left[\sum_{n=0}^{M} \frac{M!}{(M-n)!}\left(\frac{\lambda}{\mu}\right)^n\right]^{-1}$$

Expected queue length (L_q)

$$L_q = \sum_{n=1}^{M}(n-1)P_n = M - \left(\frac{\lambda+\mu}{\lambda}\right)(1-P_o)$$

Expected number of units in system (L_s)

$$L_s = \sum_{n=0}^{M} nP_n = L_q + (1 - P_o) = M - \frac{\mu}{\lambda}(1 - P_o)$$

Expected waiting time per arrival (W_q)

$$W_q = \frac{L_q}{\lambda(M - L_s)}$$

Expected queue length (W_s)

$$(W_s) = W_q + \frac{1}{\mu} \quad \text{or} \quad \frac{L_s}{\lambda(M - L_s)}$$

Example 3.3.7.1:

A mechanic repairs four machines. The mean time between service requirements is 5 hours for each machine and forms an exponential distribution The mean repair time is one hour and also follows the same distribution pattern. Determine the following:[13]

a. Probability that the service facility will be idle
b. Probability of various number of machines (0 through 4) to be out of order and being repaired
c. Expected number of machines waiting to be repaired, and being repaired

Solution:

It is given that

$\lambda = 1/5 = 0.2$ machine/hour $\mu = 1$ machine/hour

$M = 4$ machines $\rho = \lambda/\mu = 0.2$

a. The probability that the system shall be idle (or empty) is

$$P_o = \left[\sum_{n=0}^{M} \frac{M!}{(M-n)!}\left(\frac{\lambda}{\mu}\right)^n\right]^{-1} = \left[\sum_{n=0}^{4} \frac{4!}{(4-n)!}(0.2)^n\right]^{-1}$$

$$= \left[1 + \frac{4!}{3!}(0.2) + \frac{4!}{2!}(0.2)^2 + \frac{4!}{1!}(0.2)^3 + \frac{4!}{0!}(0.2)^4\right]^{-1}$$

$$= [1 + 4(0.2) + 4\times3(0.04) + (4\times3\times2)(0.0008) + (4\times3\times2\times1)(0.00016)]^{-1}$$

$$= [1 + 0.8 + 0.48 + 0.192 + 0.000384]^{-1}$$

$$= 0.4030$$

b. Probability that there shall be various number of machines (0 through 4) in the system

n	$\frac{M!}{(M-n)!}\left(\frac{\lambda}{\mu}\right)^n$	Probability
(1)	(2)	(3) = (2) x P_o
0	1.00	0.4030
1	0.80	0.3224
2	0.48	0.1934
3	0.19	0.0765
4	0.00	0.0000

c. The expected number of machines to be out of order and being repaired

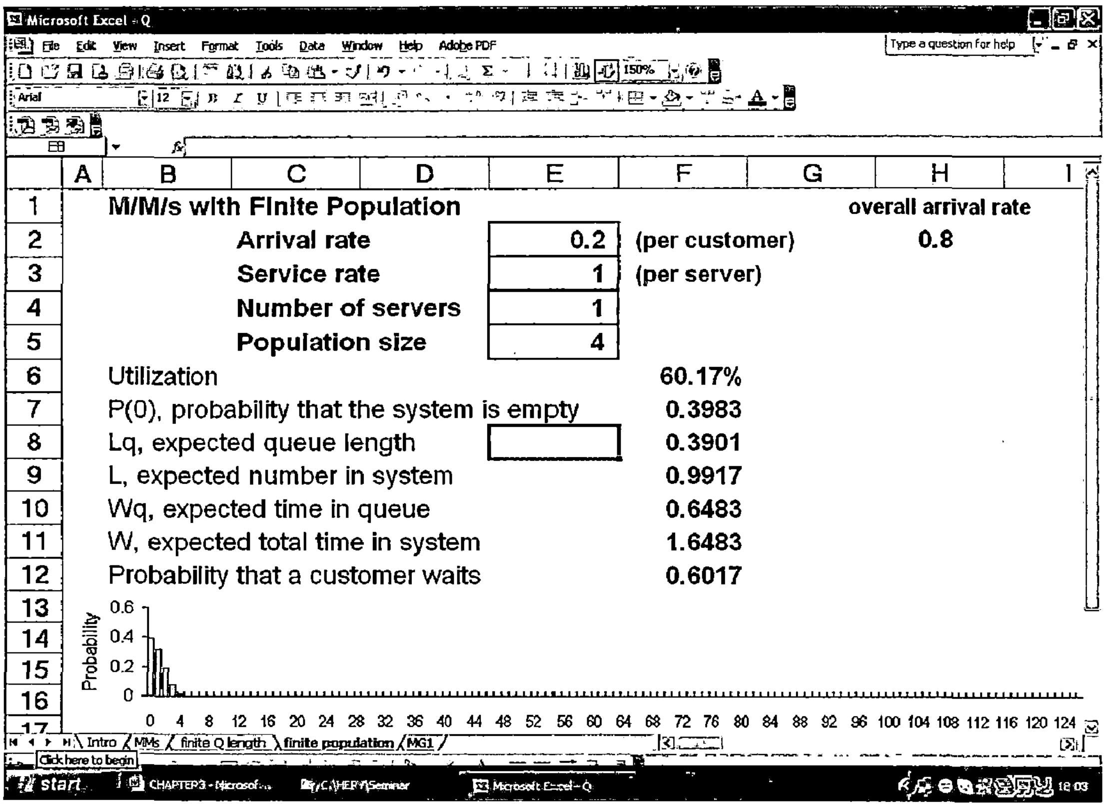
$$L_s = M - \frac{\mu}{\lambda}(1-P_o) = 4 - \frac{1}{0.2}(1-0.403) = 1.015 \text{ machines}$$

d. Expected time a machine will wait in queue to be repaired

$$W_q = \frac{L_q}{\lambda(M-L_s)} = \frac{1}{\mu}\left[\frac{M}{1-P_o} - \frac{\lambda+\mu}{\lambda}\right] = \left[\frac{4}{1-0.403} - \frac{0.2+1}{0.2}\right]$$

$$= \frac{4}{0.597} - 6 = 0.70 \text{ hours or 42 minutes}$$

Using the workbook called Q.xls for performing these calculations.



3.3.8. Multiple Channel Waiting Line Model For Finite Population[13]

For this model, we define λ_n and μ_n as the rate of arrival and service, respectively as follows:

$$\lambda_n = \begin{cases} (M-n)\lambda & ; \quad 0 \le n < M \\ 0 & ; \quad n \ge M \end{cases}$$

$$\mu_n = \begin{cases} n\mu & ; \quad 0 \le n < s \\ s\mu & ; \quad n \ge s \end{cases}$$

The Probability of n units being in the queue (P_n)

$$P_n = \begin{cases} \dfrac{M!}{n!(M-n)!}\left(\dfrac{\lambda}{\mu}\right)^n P_o & ; \quad 0 \le n \le s \\ \dfrac{M!}{(M-n)!s!s!^{n-s}}\left(\dfrac{\lambda}{\mu}\right)^n P_o & ; \quad s < n \le M \end{cases}$$

The probability that no equipment in the queue (P_o)

$$P_o = \left[\sum_{n=0}^{s-1} \frac{M!}{n!(M-n)!} \left(\frac{\lambda}{\mu}\right)^n + \sum_{n=s}^{M} \frac{M!}{n!(M-n)!s!s^{n-s}} \left(\frac{\lambda}{\mu}\right)^n \right]^{-1}$$

Expected queue length (L_q)

$$L_q = \sum_{n=s+1}^{M} (n-s)P_n = \sum_{n=s+1}^{M} nP_n - s\sum_{n=s+1}^{M} P_n$$

$$= \sum_{n=0}^{M} nP_n - \sum_{n=0}^{s} nP_n - s\left\{ \sum_{n=0}^{M} P_n - \sum_{n=0}^{s} nP_n \right\}$$

$$= \sum_{n=0}^{M} nP_n - \sum_{n=0}^{s} nP_n - \left\{ 1 - \sum_{n=0}^{s} P_n \right\}$$

$$= L_s - s + \sum_{n=0}^{s} (s-n)P_n = L_s - (s - \bar{s})$$

Where : $\bar{s}$ = expected number of idle servers = $\sum_{n=0}^{s} (s-n)P_n$

Expected number of units in system (L_s)

$$L_s = L_q + (s - \bar{s}) = L_q + \frac{\lambda_{eff}}{\mu}$$

Where : $\lambda_{eff} = \mu(s - \bar{s})$

The expression for λ_{eff} represents the expected arrival rate λ (M – n) of customers (n customers are already in the system each with mean arrival rate λ) under steady-state condition. Thus

$$\lambda_{eff} = \sum_{n=0}^{M} \lambda(M-n)P_n = \lambda M \sum_{n=0}^{M} nP_o - \lambda \sum_{n=0}^{M} nP_n$$

$$= \lambda M - \lambda L_S = \lambda(M - L_S)$$

Expected waiting time per arrival (W_q)

$$W_q = \frac{L_q}{\lambda_{eff}} = \frac{L_q}{\lambda(M - L_s)}$$

Expected queue length (W_s)

$$W_s = \frac{L_s}{\lambda_{eff}} = \frac{L_s}{\lambda(M - L_s)}$$

Example 3.3.8.1:

To illustrate this model, let us consider the data of example 3.3.7.1. with 2 servicemen.

Solution:

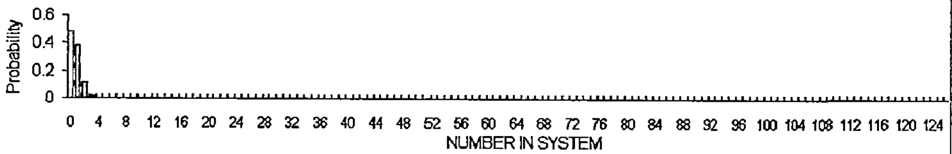
From data of the problem, we have

$\lambda = 1/5 = 0.2$ machine/hour $\qquad \mu = 1$ machine/hour

$M = 4$ machines $\qquad s = 2$ servicemen

Solve by Q.xls

	A	B	C	D	E	F	G	H
1		M/M/s with Finite Population						overall arrival rate
2			Arrival rate		0.2	(per customer)		0.8
3			Service rate		1	(per server)		
4			Number of servers		2			
5			Population size		4			
6		Utilization				33.10%		
7		P(0), probability that the system is empty				0.4778		
8		Lq, expected queue length				0.0275		
9		L, expected number in system				0.6896		
10		Wq, expected time in queue				0.0416		
11		W, expected total time in system				1.0416		
12		Probability that a customer waits				0.1399		



Intro / MMS / finite Q length / finite population / MG1

Example 3.3.8.2

Consider the data given in table 3.2.

$$\text{Arrival rate } (\lambda) = \frac{10/9 + 1/2 + 5/44 + 2/23 + 5/9 + 4/42 + 5/4}{7} = 0.53 \text{ per day}$$

Service rate for type B service (μ) = 2 machine/day

Total number of equipment (M) = 175

Total number of server (s) = 1

Mean cost of waiting of one unit for one time period (C_{wm})

$$= \frac{\text{Mean cost of waiting of one unit for one day}}{\text{Service rate for type B service}}$$

$$= \frac{1000}{2} = 500 \text{ Rupees}$$

Mean cost of serving one unit (C_{fm})

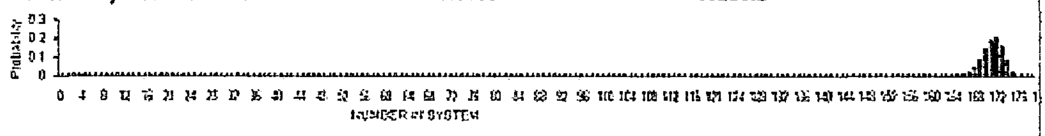
$$= \frac{\text{Cost of 1 Mechanic} + \text{Cost of 2 helpers}}{\text{Service rate for type B service } (\mu)} = \frac{150+200}{2} = 175 \text{ Rupees}$$

Mean cost of the system $(C_{tm}) = C_{wm}\, L_q + C_{fm}\, x$

Where x = the number of units served in the period = 1

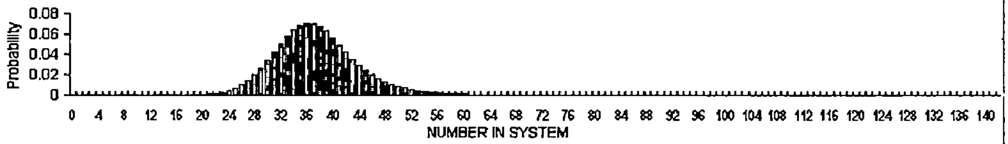
Solve by Q.xls.

	B–D	E	F	H–I
1	M/M/s with Finite Population			overall arrival rate
2	Arrival rate	0.53	(per customer)	92.75
3	Service rate	2	(per server)	Cost Of server
4	Number of servers	1		175
5	Population size	175		Total cost of server
6	Utilization		100.00%	175
7	P(0), probability that the system is empty		0.0000	Cost of idle customer
8	Lq, expected queue length		170.2264	500
9	L, expected number in system		171.2264	Total cost of idle customer
10	Wq, expected time in queue		85.1132	85113.21
11	W, expected total time in system		85.6132	Total cost
12	Probability that a customer waits		1.0000	85268.2



Calculations show that with single service facility average waiting time for a equipment to receive attention is too long (85 days) and expected number of equipment in the queue is also high (170 equipment), obviously the simplest method for reducing queue length is to increase the number of service facility. The solution by using Q.xls for different values of server is given in table 3.3. From table 3.3, it is observed after with 42 facilities the total cost of maintenance will be increased. Therefore optimum number of service facility is 42. The optimum solution for 42 service facilities is given below by using Q.xls.

M/M/s with Finite Population			overall arrival rate
Arrival rate	0.53	(per customer)	92.75
Service rate	2	(per server)	Cost Of server
Number of servers	42		175
Population size	175		Total cost of server
Utilization		86.85%	7350
P(0), probability that the system is empty		0.0000	Cost of idle customer
Lq, expected queue length		0.8699	500
L, expected number in system		37.3478	Total cost of idle customer
Wq, expected time in queue		0.0119	434.9529
W, expected total time in system		0.5119	Total cost
Probability that a customer waits		0.2244	7784.95



The graph at the bottom shows the probability distribution of the number of customers in the system.

Table 3.3.
The result of calculations up to 53 server

lo. of Server	Po	Lq	Ls	Wq	Ws	Probability	Cost of Service Facility	Cost of Idle Time	Total Cost
1	0	170.23	171.23	85.11	85.61	1.0000	175.00	85,113.00	85,288.0C
2	0	165.45	167.45	41.36	41.86	1.0000	350.00	82,725.00	83,075.0C
3	0	160.68	163.68	26.78	27.28	1.0000	525.00	80,340.00	80,865.0C
4	0	155.91	159.91	19.49	19.99	1.0000	700.00	77,955.00	78,655.0C
5	0	151.13	156.13	15.11	15.61	1.0000	875.00	75,565.00	76,440.0C
6	0	146.36	152.36	12.20	12.70	1.0000	1,050.00	73,180.00	74,230.0C
7	0	141.59	148.59	10.11	10.61	1.0000	1,225.00	70,795.00	72,020.0C
8	0	136.81	144.81	8.55	9.05	1.0000	1,400.00	68,405.00	69,805.0C
9	0	132.04	141.04	7.34	7.84	1.0000	1,575.00	66,020.00	67,595.0C
10	0	127.26	137.26	6.36	6.86	1.0000	1,750.00	63,630.00	65,380.0C
11	0	122.49	133.49	5.57	6.07	1.0000	1,925.00	61,245.00	63,170.0C
12	0	117.72	129.72	4.91	5.41	1.0000	2,100.00	58,860.00	60,960.0C
13	0	112.94	125.94	4.34	4.84	1.0000	2,275.00	56,470.00	58,745.0C
14	0	108.17	122.17	3.86	4.36	1.0000	2,450.00	54,085.00	56,535.0C
15	0	103.40	118.40	3.45	3.95	1.0000	2,625.00	51,700.00	54,325.0C
16	0	98.62	114.62	3.08	3.58	1.0000	2,800.00	49,310.00	52,110.0C
17	0	93.85	110.85	2.76	3.26	1.0000	2,975.00	46,925.00	49,900.0C
18	0	89.08	107.08	2.47	2.97	1.0000	3,150.00	44,540.00	47,690.0C
19	0	84.30	103.30	2.22	2.72	1.0000	3,325.00	42,150.00	45,475.0C
20	0	79.53	99.53	1.99	2.49	1.0000	3,500.00	39,765.00	43,265.0C
21	0	74.76	95.76	1.78	2.28	1.0000	3,675.00	37,380.00	41,055.0C
22	0	69.98	91.98	1.59	2.09	1.0000	3,850.00	34,990.00	38,840.0C
23	0	65.21	88.21	1.42	1.92	1.0000	4,025.00	32,605.00	36,630.0C
24	0	60.43	84.43	1.26	1.76	1.0000	4,200.00	30,215.00	34,415.0C
25	0	55.66	80.66	1.11	1.61	1.0000	4,375.00	27,830.00	32,205.0C
26	0	50.89	76.89	0.98	1.48	1.0000	4,550.00	25,445.00	29,995.0C
27	0	46.11	73.11	0.85	1.35	1.0000	4,725.00	23,055.00	27,780.0C
28	0	41.34	69.34	0.74	1.24	1.0000	4,900.00	20,670.00	25,570.0C
29	0	36.57	65.57	0.63	1.13	0.9997	5,075.00	18,285.00	23,360.0C
30	0	31.81	61.81	0.53	1.03	0.9986	5,250.00	15,905.00	21,155.0C
31	0	27.09	58.08	0.44	0.94	0.9949	5,425.00	13,545.00	18,970.0C
32	0	22.49	54.44	0.35	0.85	0.9845	5,600.00	11,245.00	16,845.0C
33	0	18.11	50.98	0.28	0.78	0.9614	5,775.00	9,055.00	14,830.0C
34	0	14.13	47.83	0.21	0.71	0.9194	5,950.00	7,065.00	13,015.0C
35	0	10.69	45.11	0.16	0.66	0.8554	6,125.00	5,345.00	11,470.0C
36	0	7.87	42.88	0.11	0.61	0.7714	6,300.00	3,935.00	10,235.0C
37	0	5.67	41.14	0.08	0.58	0.6738	6,475.00	2,835.00	9,310.0C
38	0	4.01	39.83	0.06	0.56	0.5707	6,650.00	2,005.00	8,655.0C
39	0	2.79	38.65	0.04	0.54	0.4698	6,825.00	1,395.00	8,220.0C
40	0	1.92	38.18	0.03	0.53	0.3765	7,000.00	960.00	7,960.0C
41	0	1.30	37.69	0.02	0.52	0.2942	7,175.00	650.00	7,825.0C
42	**0**	**0.87**	**37.35**	**0.01**	**0.51**	**0.2244**	**7,350.00**	**435.00**	**7,785.0C**
43	0	0.58	37.11	0.008	0.51	0.1672	7,525.00	290.00	7,815.0C
44	0	0.38	36.96	0.005	0.51	0.1218	7,700.00	190.00	7,890.0C
45	0	0.24	36.85	0.003	0.50	0.0867	7,875.00	120.00	7,995.0C
46	0	0.15	36.78	0.002	0.50	0.0603	8,050.00	75.00	8,125.0C
47	0	0.09	36.74	0.000	0.50	0.0400	8,225.00	45.00	8,270.0C
48	0	0.06	36.71	0.000	0.50	0.0300	8,400.00	30.00	8,430.0C
49	0	0.03	36.69	0.000	0.50	0.0200	8,575.00	15.00	8,590.0C
50	0	0.02	36.67	0.000	0.50	0.0100	8,750.00	10.00	8,760.0C
51	0	0.01	36.67	0.000	0.50	0.0000	8,925.00	5.00	8,930.0C
52	0	0.01	36.67	0.000	0.50	0.0000	9,100.00	5.00	9,105.0C

Data of table 3.3 is shown in graph given in fig. 3.5.

Fig. 3.5. Relation Between Cost and Service Facility

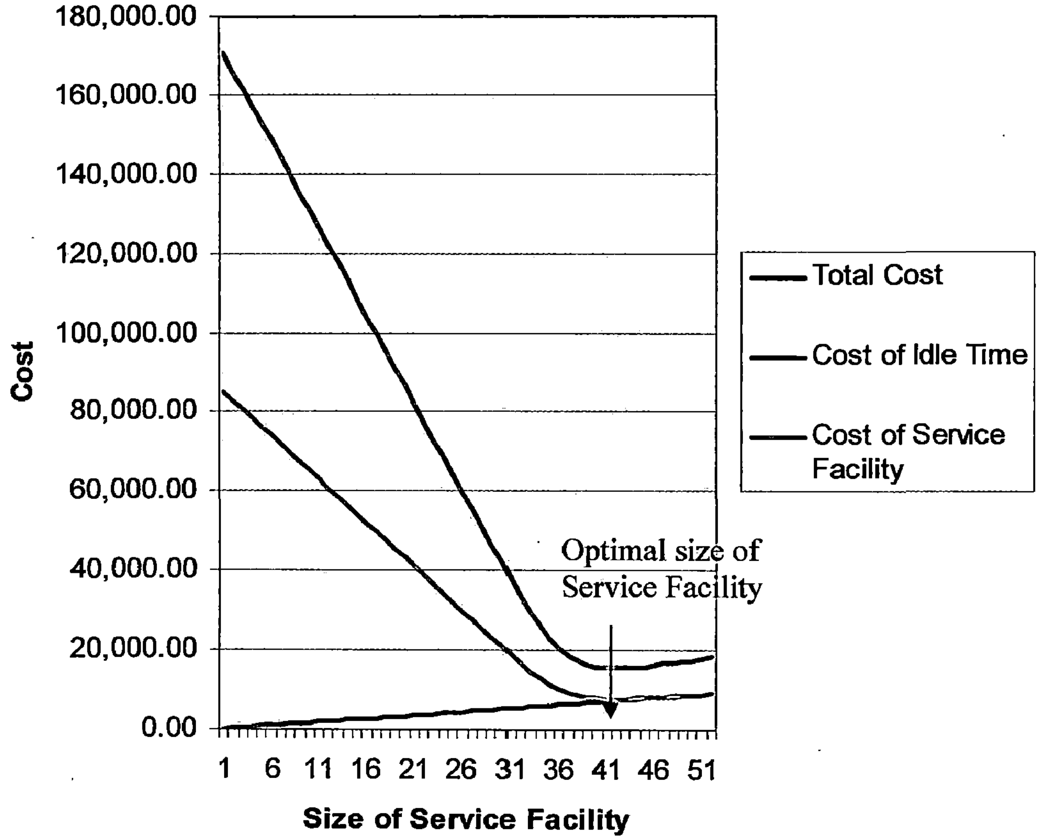


Fig.3.5. Shows that, an increase in the existing service facilities would reduce the customer's waiting time. Conversely, decreasing the level of service should results in long queue(s). This means an increase or decrease in the level of service increases or decreases the cost of operating service facilities but decreases or increases the cost of waiting. The optimum service level is one that minimizes the sum of the two costs.

3.4. SEQUENCING MODEL[15]

A sequencing model arises when a few facilities, each rendering a different kind of service, are to be assigned to a number of jobs in such a way that the order of rendering service by the facilities on each job is maintained unaltered. The order of rendering service is predefined. Maintenance scheduling problems conforms exactly to such situations.

The sequence problem can be stated as follows :

A number of jobs (say n) have to be completed, each of which needs the application of facilities (say m) in the order of 1, 2, 3,...m. The time for which application of each facility to each job needed is different. It is required to service the job in an optimal order so that each job is serviced by the facilities such that all jobs are completed in the shortest time and idle time of facilities is minimized.

FACILITIES	JOBS					
	1	2	---	J	---	N
1	a11	a12	---	a1j	---	a1n
2	a21	a22	---	a2j	---	a1n
---	---	---	---	---	---	---
I	ai1	Ai2	---	Aij	---	ain
---	---	---	---	---	---	---
M	am1	Am2	---	Amj	---	amn

Fig. 3.6. Data Matrix for Sequencing Problem

In fig. 3.6. in matrix form the order of facilities are predefined i.e. 1 to m. The figure a_{11}, a_{12} etc. indicates the time required to be served by facility 1 on job 1 and 2 respectively. It is required to determine the sequence to be observed so that all jobs are served with facilities in minimum time and facility may also remain idle for minimum time.

Solution for 2 facilities, which can be extended to problems of three facilities under certain conditions is found as follows (for 2 row matrix).

1. From an examination of the matrix mark the smallest value.

2. If this small value is in the first row, the job related to it will be serviced first by facility 1. If this value is in the second row, the job will be serviced last by facility 1.
3. Eliminate the column of job which has been sequenced in step 2, and from the remaining matrix mark the smallest value, repeat step 2.
4. Continue the above procedure till all jobs have been sequenced.
5. In case, of tie existing between two allocations, choose any one. The second smallest value would be considered during the following allocation.

When three facilities exist, the problem can be reduced to a 2 facility case by forming a new matrix with two rows, the first row has totals of values for 1 and 2, and the second row has of rows for facilities 2 and 3. Once this conversion is made from a 3 to 2 row matrix, the procedure discussed above can be applied. It is necessary that the maximum of the middle row is lesser than the minimum of at least on of the other two rows.

Example 3.4.1.:

The application of the model is demonstrated through an example. Consider five jobs, each or which is to be processed on both the machines A and B in the order AB. Processing times in hours are given in the table below :

Jobs	I	II	III	IV	V
Machine A	5	1	9	3	10
Machine B	2	6	7	8	4

Determine a sequence for the five jobs that will minimize the elapsed time T.[13]

Solution :

The smallest processing time between the two machines is 1 which corresponds to job II on machine A. Thus, Job II will be processed first as shown below:

Jobs	II				

After The job II has been set for processing first, we are left with 4 jobs and their processing times as given below:

Jobs	I	III	IV	V
Machine A	5	9	3	10
Machine B	2	7	8	4

The minimum processing time in this reduced problem is 2 which corresponds to job I on machine B. Thus, Job I will be processed last as shown below:

Jobs	II				I

The set of processing times now gets reduced to:

Jobs	III	IV	V
Machine A	9	3	10
Machine B	7	8	4

The smallest processing time in this reduced problem is 3, which corresponds to Job IV on machine A. Thus job IV will be placed in the second sequence cell and job III in the third sequence cell and job V in the fourth sequence cell. Thus, it indicates an alternative optimal sequence. The optimal sequences are, therefore, given below:

Machine A	II	IV	III	V	I
Machine B	II	IV	III	V	I

The minimum elapsed time for machines A and B is calculated as shown in table below:

Job Sequence	Machine A		Machine B	
	Time in	Time Out	Time in	Time Out
II	0	1	1	7
IV	1	4	7	15
III	4	13	15	22
V	13	23	23	27
I	23	28	28	30

From table above, the minimum elapsed time, i.e. time from start of job II to completion of last job I is 30 hours. During this time the machine A remains idle for 30 – 28 = 2 hours. The idle time for machine B is equal to the time at which the job II, job V and job I in the sequence finishes on machine I, i.e. 1+1+1= 3 hours.

Example 3.4.2.

A plant repair shop is overhauling engines of construction machines. Among the engines awaiting repairs are the engines of tractors, trucks and light vehicles. Tractor engines and truck engines burn diesel oil while light vehicle engines run on gasoline. Engines have different sizes and also different principles (4-stroke, 2-stroke). The engines have been grouped into 4 classes on the basis of repair effort needed.

The workshop has two crews, one for dismantling and repairing the engines, and the second for fitting and testing them. The work of one crew must precede the work of the second crew. In view of the assortment of sizes and types of engines, the time taken on each of the two operations by the two crews is different for different engines. Estimates of this time in working hours are shown below:

Engine Type	I	II	III	IV
Crew A (Dismantle & Repair)	16	24	36	20
Crew B (Reassemble & Test	20	20	30	12

It is required to sequence the repair of the engines in such a way that the idle time of crews is minimized.[15]

Solution :

The smallest processing time between the two crew is 12 which corresponds to engine type IV on Crew B. Thus, engine type IV will be processed last as shown below:

Engine Type				IV

After The engine type IV has been set for processing last, we are left with 3 jobs and their processing times as given below :

Engine Type	I	II	III
Crew A	16	24	36
Crew B	20	20	30

The minimum processing time in this reduced problem is 16 which corresponds to Engine type I on crew A. Thus, Engine type I will be processed first as shown below:

Engine Type	I			IV

The set of processing times now gets reduced to:

Engine Type	II	III
Crew A	24	36
Crew B	20	30

The smallest processing time in this reduced problem is 20, which corresponds to Engine type II on Crew B. Thus Engine type II will be placed in the second sequence cell and Engine type III in the second sequence cell. Thus, it indicates an alternative optimal sequence. The optimal sequences are, therefore, given below:

Crew A	I	III	II	IV
Crew B	I	III	II	IV

The minimum elapsed time for Crew A and B is calculated as shown in table below:

Job Sequence	Machine A		Machine B	
	Time in	Time Out	Time in	Time Out
I	0	16	16	36
III	16	52	52	82
II	52	76	82	102
IV	76	96	102	114

From table above, the minimum elapsed time, i.e. time from start of engine type I to completion of last Engine type IV is 114 hours. The idle time for Crew B is equal to the time at which the engine type I, engine type III in the sequence finishes on crew A, i.e. 16+16= 32 hours.

3.5. ASSIGNMENT MODEL[15]

The model can be described as follows: There exist n requirement together with n means of satisfying them, Associated with the allocation of the i^{th} means to the j^{th} requirement, there is a certain effectiveness coefficient, C_{ij}. It is assumed that the i^{th} means is fully allocated to the j^{th} demand. The problem is of maximizing (in case of profit) or minimizing (in case of cost) the effectiveness function subject to certain constraints and non negative value of allocations (x_{ij}) made. The model can be expressed mathematically as below:

Effectiveness function: $Z = \sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij}x_{ij}$

Constraint equation: $\sum_{i=1}^{n} x_{ij} = 1$ for j = 1, 2, 3 ….. n and

$\sum_{j=1}^{n} x_{ij} = 1$ for i = 1, 2, 3 ……n

Non negative condition: $x_{ij} \geq 0$.

The popular method of solving the assignment matrix is the Hungarian Method developed by the mathematician named Konig. In this method the reduced matrix of cost may be used for purpose of minimization of the measure of effectiveness. This approach is effective in view of matrix property that an assignment that minimizes the total for the original matrix of effectiveness. The effectiveness matrix is reduced by subtracting from each row the smallest element of the row, and then by subtracting the smallest element of each column from the other elements of the column, for every column. If an allocation with zero total cost can be made for the reduced matrix, the same allocation will hold for the original matrix also, for minimum total cost. If the allocation can not be made as a result of the simple reduction technique described above, other method of further reduction must be used.

Example 3.5.1.

A superintendent of a field workshop has four crews and four jobs to be completed. Determine the cost and optimal assignment of crews if the cost of each job for each crew is as given in the following matrix:

	Crews			
Type A Service	1	2	3	4
Dump Truck (A)	9	7	8	5
Excavator (B)	5	6	7	8
Bulldozer (C)	4	9	5	6
Scraper (D)	8	7	6	7

Use *the assignment model*[15]

Solution:

The Hungarian method is used to obtain an optimal solution.

Step 1. The minimum cost element in row A, B, C and D is 1, 5, 5 and 6, respectively. Subtract these elements from all elements from all elements in their respective row. The reduced cost matrix is shown below:

	Crews			
Type A Service	1	2	3	4
Dump Truck (A)	4	2	3	0
Excavator (B)	0	1	2	3
Bulldozer (C)	0	5	1	2
Scraper (D)	2	1	0	1

Step 2. In reduced table above, the minimum cost element in columns 1, 2, 3 and 4 is 0, 1, 0 and 0 respectively. Subtract these elements from all elements from all elements in their respective column to get the reduced cost matrix as shown below:

	Crews			
Type A Service	1	2	3	4
Dump Truck (A)	4	1	3	0
Excavator (B)	0	0	2	3
Bulldozer (C)	0	4	1	2
Scraper (D)	2	0	0	1

Step 3. Examine all the rows starting from first one by one until a row containing only single zero element is located. Here rows A and C have only one zero in the cells (A,4) and (C,1), respectively. We assigned these zeros. All zero in the assigned column are crossed off as shown in table below. Examine all the columns starting from first one by one until a column containing only single zero element is located.

	Crews			
Type A Service	1	2	3	4
Dump Truck (A)	4	1	3	0
Excavator (B)	0̶	0	2	3
Bulldozer (C)	0	4	1	2
Scraper (D)	2	0̶	0	1

Since the number of assignment (= 4) equals the numbers of rows (= 4), the optimal solution is obtained.

The pattern of assignments among crews and jobs with their respective cost is given below:

Crew	Type A Service	Cost
1	Dump Truck (A)	4
2	Excavator (B)	6
3	Bulldozer (C)	6
4	Scraper (D)	5
	Total	21

3.6. SIMULATION MODELS[13]

Simulation is a quantitative procedure which describes a process by developing a model of that process and then conducting a series of organized trial and error experiments to predict the behaviour of the process over time. Observing the experiments is very much like observing the process in operation. To find out how the real process would react to certain changes, we can produce these changes in our model simulate the reaction of the real process to them. In Simulation, we build mathematical models and run them in trial and error and data to simulate the behaviour of the system.

Steps on the simulation process:

1. Define the problem to simulate.
2. Formulate the model to use
3. Test the model; compare its behaviour with the behaviour of the actual problem environment.
4. Identify and collect the data needed to test the model.
5. Run the simulation.
6. Analyze the results of the simulation. If desired, change the solution.
7. Re run the simulation to test the new solution.
8. Validate the simulation; that it, increase that any inferences we draw about the real situations from running the simulation will valid.

In maintenance of construction equipment, the problem of balancing the cost of waiting against the cost of idle time of service facilities in the system arises due to the probabilistic (stochastic) nature of the inter arrival times of customers (equipments) and the time taken to complete the service to the customer. Thus instead of trying out in actual manually with data to design a queuing system, we process the data on the computers and obtain the expected value of various characteristics of the queuing system such as idle time of servers, average waiting time, queue length etc.

In simulation, probabilistic distributions are used to define numerically in a sample space by assigning a probability to each of possible outcomes. Each outcome can occur with some probability, reflecting the element of change. A random variable assigns a number to this element of change. In statistics, these numbers are estimated to assess the uncertainty inherent in the model, but in simulation these variables are controlled numerically and used to mimic these elements of uncertainty which are defined in a model. This is done by generating outcomes with the same frequency as those encountered in the process being mimicked (simulated). In this manner many experiments (also called simulation runs) can be performed, and leading to a collection of outcomes that have a frequency (probability) distribution similar to that of the model of construction equipment maintenance.

The most elementary and important type of process is the random process, which requires for its simulation the selection of samples (or event) draw from given distribution so that repetition of this selection process will yield a frequency distribution of samples values that faithfully matches the original distribution. Random number between 00 and 99 are used to obtain values of random variables that have a known discrete probability distribution in which the random variable of interest can assume of a finite number of different values.

3.6.1. Monte Carlo Simulation

The principle behind the Monte Carlo simulation technique is representative of the given system under analysis by a system described by some known probability distribution and then drawing random samples from probability distribution by means of random numbers. In case it is not possible to describe a system in terms of standard probability distribution such as normal, poisson, exponential, gamma, etc., an empirical probability distribution can be constructed.

The Monte Carlo simulation technique consist of following steps:

(i) Setting up a probability distribution for variables to be analysed.

(ii) Building a cumulative probability distribution for each random variable.

(iii) Generate random numbers. Assign an appropriate set of random numbers to represent value or range (interval) of values for each random variable.

(iv) Conduct the simulation experiment by means of random sampling.

(v) Design and implement a course of action and maintain control.

Monte Carlo approach has many distinct advantages over an algebraic approach, such as:

a. Disciplines other than first come first served are readily investigated.

b. Service and arrivals distributions are not restricted to poisson and exponential types respectively.
c. Simulation is easier to explain to the non quantitative executive since he may visually trace the element through the system rather than handle it abstractly.
d. There is flexibility to experiment with various ideas for improving the system.

Example 3.6.1.1.

A large project has 30 machines. A sample of 73 breakdowns of machines is according to the following distribution:[13]

Time between breakdowns (hrs)	:	10	11	12	13	14	15	16	17	18	19
Frequency	:	4	10	14	16	12	6	4	3	3	1

Total of frequency = 73

A study of time required to repair the machines by one mechanic yields the following distribution:

Repair Time (hrs)	:	8	9	10	11	12	13	14	15	16	17	18
Frequency	:	2	3	8	16	14	12	8	5	3	1	1

Total of frequency = 73

(i) Convert the distribution to cumulative probability distributions.
(ii) Using a simulated sample of 20, estimate the average machine waiting time and the average idle time of the mechanic.

Solution:

Random Number For Breakdowns

Time between Breaksdowns (hours)	Frequency	Probability	Cumulative Probability	Random Number Range
10	4	0.05	0.05	00 – 04
11	10	0.14	0.19	05 – 18
12	14	0.19	0.38	19 – 37
13	16	0.22	0.60	38 – 59
14	12	0.17	0.77	60 – 76
15	6	0.09	0.86	77 – 85
16	4	0.05	0.91	86 – 89
17	3	0.04	0.95	90 – 94
18	3	0.04	0.99	95 – 98
19	1	0.01	1.00	99 – 99
	73	1.00		

Random Number For Repairs

Repair time Requird (hours)	Frequency	Probability	Cumulative Probability	Random Number Range
8	2	0.03	0.03	00 – 02
9	3	0.04	0.07	03 – 06
10	8	0.11	0.18	07 – 17
11	16	0.22	0.40	18 – 39
12	14	0.19	0.59	40 – 58
13	12	0.17	0.76	59 – 75
14	8	0.11	0.87	76 – 86
15	5	0.07	0.94	87 – 93
16	3	0.04	0.98	94 – 97
17	1	0.01	0.99	98 – 98
18	1	0.01	1.00	99 – 99
	73	1.00		

The simulation worksheet is shown in table below. It is assumed that the first day begins at midnight (00:00 hours) and also the repairmen begin work at 00:00 hours. The first breakdown occurred at 14:00 and the second occurred after 15 hours at clock time of 05:00.

Simulation Worksheet

Breakdown Number	Random Number for break-downs	Time Between break-downs	Time of break-downs	Repair Work Begins at	Random Number for Repair Time	Repair Time Required	Repair Work Ends at	Total Idle Time (hours)	Waiting Time (hours)
1	2	3	4	5	6	7	8	9	10
1	61	14	14:00	14:00	87	15	05:00	15	0
2	85	15	05:00	05:00	39	11	16:00	11	0
3	16	11	16:00	16:00	28	11	03:00	11	0
4	46	13	05:00	05:00	97	16	21:00	16	0
5	88	16	21:00	21:00	69	13	10:00	13	0
6	8	11	08:00	10:00	87	15	01:00	17	2
7	82	15	23:00	01:00	52	12	13:00	14	2
8	56	13	12:00	13:00	52	12	01:00	13	1
9	22	12	24:00	01:00	15	10	11:00	11	1
10	49	13	13:00	13:00	85	14	03:00	14	0
11	44	13	02:00	03:00	41	12	15:00	13	1
12	33	12	14:00	15:00	82	14	05:00	15	1
13	77	15	05:00	05:00	98	17	22:00	17	0
14	87	16	21:00	22:00	99	18	16:00	19	1
15	54	13	10:00	16:00	23	11	03:00	17	6
16	43	13	23:00	03:00	45	12	15:00	16	4
17	20	12	11:00	15:00	63	13	04:00	17	4

1	2	3	4	5	6	7	8	9	10
18	78	15	02:00	04:00	48	12	16:00	14	2
19	96	18	20:00	20:00	22	11	07:00	11	0
20	25	12	08:00	08:00	12	10	18:00	10	0
				253		259		284	25

The average machine waiting time = (284/20) = 14.2 hours

The average idle time of the mechanic = (25/20) = 1.25 hours

CHAPTER – IV
REPLACEMENT MODELS

4.1. GENERAL[10]

At the outset a chapter an replacement model in this dissertation on best maintenance strategy may look out of place but a second thought would reveal that when equipment or a component of equipment is no longer economical to maintain it may be a better alternative to replace it by a new component or equipment. Hence a chapter on replacement models is included in this dissertation.

The Problem of replacement is felt when the job performing machines or equipments become less effective or useless due to either sudden or gradual deterioration in their efficiency, failure or breakdown.

All the equipment, machines, etc. deteriorate with age or usage unless maintenance is resorted to. Quite often it is more economical to replace the equipment completely instead of maintenance. As regards the replacement decisions (not based on any mathematical analysis) the following rules are commonly followed:

1. Replace when equipment is fully depreciated.
2. Replace when the unit cost of production is minimum.
3. Replace when equipment is worn out
4. In some cases, items are replaced not because they are not performing well any longer, but because modern equipment, the new equipment developed may perform the same operations with substantial savings or much better.

Equipment and machines rarely incur uniform wear and tear. Some elements or components are likely to deteriorate faster than others. Under these conditions it is often economical to repair the equipment to the extent of its useful life. Some repairs follow a periodic pattern and can be planned; while some repairs follow unpredictable pattern. The equipment becomes a candidate for replacement when it is anticipated that it will require an additional and extensive repair frequently.

Generally, the equipment operates at an initial peak efficiency which declines with time and use. The decrease in efficiency will require increased power consumption and longer time to accomplish the same operations. This leads to the increased cost of production which, in turn, necessitates the replacement of the existing equipment.

There are different types of replacement problems

1. Major capital equipment which can be used for a long time but with steadily increasing cost of maintenance.

   These could be replaced

   a. by an identical equipment

   b. by an alternate equipment serving the same purpose as the original one.

2. Equipment that is replaced in anticipation of complete failure, the probability of this increase with age.
3. Adoption of a preventive maintenance scheme which is designed to reduce the probability of failure.

Out of these models, the first two are of relevance to a large of number areas like construction equipment, industrial equipment, machinery etc. whereas the last has applications in defence and other areas where use of the equipment is only in case of necessity or emergency.

4.2. DEPRECIATION OF FIXED ASSETS[9]

With use of equipment its cost is written off or reduced in a rational and systematic manner. This decrease in the value of an asset with use, age or obsolescence is termed as the depreciation. This depreciation is used in calculating the use rate or the owner's rate of the equipment.

The book value or the amortized cost of an asset is the difference between the initial cost of the asset and the total depreciation charge made to date against that asset.

There are several methods of calculating the depreciation of an asset and commonly used methods for construction equipment are:

1. Straight line method
2. Sum of years digits method
3. Declining balance method

All three methods utilize a useful life (n) instead of a recovery period. Manufactures and different user organizations recommend life of equipment in years or hours. Typical values are given in columns 4 and 5 of table in appendix 1. They also require an estimated of the salvage value (F) at the end of the useful life. Under each of these methods, total depreciation taken over the useful life of the property may not exceed the cost basis less the salvage value ($P - F$).

1. Straight line method

The straight line method gives the uniform write off of the cost throughout the service life period. This method assumes that the equipment decrease in value from its original cost to the ultimate salvage value at a uniform rate. This salvage value of an equipment is the value that can be realized by disposing off the equipment at the end of its useful life. As it is very difficult to assign a salvage value to the equipment in advance, so in many cases the salvage value is neglected for the purpose of economic study. According to straight line method, the depreciation allowed at the end of each year t is equal throughout the property's useful life and is given by

$$D_t = \frac{P - F}{n}$$

The unrecovered investment at the end of year t is given by

$$S_t = P - \left(\frac{P - F}{n}\right)t$$

Example 4.2.1.

A firm has a dump truck whose purchase price (P) is Rs.1,000,000.00 with an estimated salvage value (F) of Rs.100,000.00 at the end of a projected useful life (n) of 10 years.

The straight line depreciation investment for each year would be as given in table 4.1.:

Table 4.1.
Straight line depreciation and unrecovered investment

End of Year *T*	Depreciation *Dt (Rupees)*	Unrecovered Investment *St (Rupees)*
0	-	1,000,000.00
1	90,000.00	910,000.00
2	90,000.00	820,000.00
3	90,000.00	730,000.00
4	90,000.00	640,000.00
5	90,000.00	550,000.00
6	90,000.00	460,000.00
7	90,000.00	370,000.00
8	90,000.00	280,000.00
9	90,000.00	190,000.00
10	90,000.00	100,000.00

2. ***Sum of the year's digits depreciation***

The sum of the year's digits method is known for its accelerated write off of assets. That is, it provides relatively high depreciation allowances in the early years and lower allowances throughout the rest of the property's useful life. The name sum of the year's digits comes from the fact that the sum

$$1 + 2 + \ldots\ldots + (n-1) + n = \frac{n(n+1)}{2}$$

is used directly in the calculation of depreciation. The depreciation allowance during any year t is expressed as

$$D_t = \frac{n-(t-1)}{n(n+1)/2}(P-F)$$

The unrecovered investment at the end of each year t is given by

$$S_t = P - \sum_{j=1}^{t} \frac{n-(j-1)}{n(n+1)/2}(P-F)$$

Which reduces to

$$S_t = (P-F)\frac{(n-t)(n-t+1)}{n(n+1)} + F$$

Example 4.2.2.

Let us consider data in Examples 4.1.

The Sum of the year's digits depreciation and unrecovered investment for each year would be as given in table 4.2.

Table 4.2.

Sum of the year's digits depreciation and unrecovered investment

End of Year t	Value of $\frac{n-(t-1)}{n(n+1)/2}$	Depreciation Dt (*Rupees*)	Unrecovered Investment St (*Rupees*)
0	-	-	1,000,000.00
1	0.18182	163,638.00	836,362.00
2	0.16364	147,276.00	689,086.00
3	0.14545	130,905.00	558,181.00
4	0.12727	114,543.00	443,638.00
5	0.10909	98,181.00	345,457.00
6	0.09091	81,819.00	263,638.00
7	0.07273	65,457.00	198,181.00
8	0.05455	49,095.00	149,086.00
9	0.03636	32,724.00	116,362.00
10	0.01818	16,362.00	100,000.00

3. ***Declining Balance Depreciation***

The declining balance method, like sum of the year's digits depreciation, is known for its accelerated write off of assets. In this method, the depreciation allowed at the end of each year t is a constant fraction (p) of the unrecovered investment at the end of the previous year. That is,

$$D_t = pB_{t-1} \qquad \ldots(1)$$

The unrecovered investment at the end of each year t is given by

$$S_t = P\,(1-p)^t \qquad \ldots(2)$$

Substituting Equation 2 into Equation 1 allows us to calculate the year t depreciation directly as

$$D_t = pP(1-p)^{t-1}$$

Note that in the declining balance method of depreciation, the estimated salvage value need not come into play in figuring deduction; however, the unrecovered investment must never fall below the estimated salvage value. Twice the straight line rate, or $2/n$, is the maximum constant fraction permissible under law. When $p = 2/n$, this method is known as 200% Declining Balance depreciation. For used tangible property, either 150% or 125% declining balance depreciation is the maximum permitted.

Declining balance depreciation may be used alone; however, switching from *either the* 200% or 150% declining balance method to straight line depreciation is permitted. The optimum switch takes place whenever straight line depreciation on the unrecovered portion of the asset exceeds the declining balance allowance. That is, we should switch to straight line at the first year for which

$$\frac{S_{t-1} - F}{n - (t - 1)} > pS_{t-1}$$

The estimated salvage value is used in determining the straight line depreciation component, even though it is neglected in the double declining balance method. Switching to straight line depreciation will never be desirable if the estimated salvage value F exceeds the declining balance unrecovered investment for the last year S_n, causing depreciation to be truncated.

In the case of the double declining balance method, the depreciation rate in computed as 200% of the total cost divided by the estimated life in years. This gives double the straight line rate that will be found for an equipment with zero salvage value. This method gives higher values of depreciation during early years and results in quicker return of investment than is possible by straight line method. This is more realistic and suitable, as the equipment earns more during its early life.

Example 4.2.3.

Let us again work with the dump truck of Example 4.1. The declining balance, with switch to straight line, depreciation and unrecovered investment for each year would be as given table 4.3.

Table 4.3.

200% Declining Balance depreciation and unrecovered investment

End of year ***T***	200% Declining Balance Depreciation ***Dt*** *(Rupees)*	Straight Line Depreciation on Remaining Life ***Dt*** *(Rupees)*	Unrecovered Investment ***St*** *(Rupees)*
0	-	-	1,000,000.00
1	200,000.00	90,000.00	800,000.00
2	160,000.00	77,777.78	640,000.00
3	128,000.00	67,500.00	512,000.00
4	102,400.00	58,857.14	409,600.00
5	81,920.00	51,600.00	327,680.00
6	65,536.00	45,536.00	262,144.00
7	52,428.80	40,536.00	209,715.20
8	41,943.04	36,571.73	167,772.16
9	33,554.43	33,886.08	133,886.08
10	26,843.55	33,886.08	100,000.00

4.3. REPLACEMENT OF CAPITAL EQUIPMENT[10,13]

Replacement of capital equipment becomes necessary due to deterioration of the equipment or its becoming obsolete due to use. When operational efficiency of an equipments deteriorates with time (gradual failure), it is economical to replace the same with a new one. For example, the maintenance cost of a machine increases with time and a stage is reached when it may not be economical to allow machine to continue in the system. Besides, there could be a number of alternative choices and one may like to compare available alternatives on the basis of the running cost (average maintenance and operating costs) involved.

4.3.1. Replacement policy for equipments whose running cost increases with time and value of money remains constant during a period.

The cost of maintenance of a machine is given as a function increasing with time and its scrap value is constant.

a. If time is measured continuously, then the average annual cost will be minimized by replacing the machine when the average cost to date becomes equal to the current maintenance cost.

b. If time is measured in discrete units, then the average annual cost will be minimized by replacing the machine when the next period's maintenance cost becomes greater than the current average cost.

The aim here is to determine the optimal replacement age of equipment whose running cost increases with time and the value of money remains constant (i.e. value is not counted) during that period.

Let

C = Capital or purchase cost of new equipment.

S = scrap (or salvage) value of the equipment at the end of t years

R(t) = running cost of equipment for the year t

n = replacement age of the equipment.

a. ***When time t is a continuous variable. If the equipment is used for t years, then the total cost incurred over this period is given by***

TC = Capital cost – scrap value at the end of t years + Running cost for t years

$$= C - S + \int_0^n R(t)dt$$

Therefore, the average cost per unit time incurred over the period of n years is:

$$ATC_n = \frac{1}{n}\left\{C - S + \int_0^n R(t)dt\right\} \qquad ....(1)$$

To obtain optimal value n for which ATC_n is minimum, differentiate ATC_n with respect to n, and set the first derivative equal to zero. That is, for minimum of ATC_n.

$$\frac{d}{dn}\{ATC_n\} = -\frac{1}{n^2}\{C - S\} + \frac{R(n)}{n} - \frac{1}{n^2}\int_0^n R(t) = 0$$

$$R(n) = \frac{1}{n}\left\{C - S + \int_0^n R(t)dt\right\} \; ; \qquad n \neq 0 \qquad ......(2)$$

$$R(n) = ATC_n$$

Hence, the following replacement policy can be derived with the help of Eqn. (2)

Policy : Replace the equipment when the average cost for n years becomes equal to the current/ annual running cost. That is

$$R(n) = \frac{1}{n}\left\{C - S + \int_0^n R(t)dt\right\}$$

b. ***When time 't' discrete variable. The average cost incurred over the period n is given by***

$$ATC_n = \frac{1}{n}\left\{C - S + \sum_{t=0}^{n} R(t)\right\}$$

Policy 1. If the next year, running cost, R(n+1) is more than average cost of n^{th} year, ATC_{n-1} then it is economical to replace at the end of n years. That is

$$R(n+1) > \frac{1}{n}\left\{C - S + \sum_{t=0}^{n} R(t)\right\}$$

Policy 2. If the present year's running cost is less than the previous year's average cost, ATC_{n-1}, then do not replace. That is

$$R(n) < \frac{1}{n-1}\left\{C - S + \sum_{t=0}^{n} R(t)\right\}$$

Example 4.3.1.1.

A firm has a Dump truck whose purchase price is Rs.1,000,000.00. The Maintenance & operation cost and Salvage values (consider data of result in Examples 4.3.) are as given in the following table below:

Year	:	1	2	3	4	5	6	7
Salvage Value *(Rupees)*	:	800,000.00	640,000.00	512,000.00	409,600.00	327,680.00	262,144.00	209,715.20
M & O Cost *(Rupees)*	:	80,000.00	100,000.00	130,000.00	160,000.00	190,000.00	220,000.00	250,000.00

The average annual cost of the equipment is computed for every year beginning with the first year. This will include the capital cost and the running cost and will reflect the salvage value, if any, at the end of that year.

Average annual cost at the end of year n,

$$ATC_n = \frac{1}{n}\left\{C - S + \sum_{t=0}^{n} R(t)\right\}$$

When the average annual cost is minimum when computed for different years the equipment needs to be replaced. This is on the basis that the equipment is required continuously, over an indefinite period. This can be best accomplished by preparing a table as follows

Year of Service N	M&O Cost (Rupees) R(n)	Cumulative Running Cost (Rupees) ΣR(n)	Salvage Value (Rupees) S	Depreciation Cost (Rupees) C – S	Total Cost (Rupees) ΣR(n) + C	Average Cost (Rupees) ATC_n
1	80,000.00	80,000.00	800,000.00	200,000.00	280,000.00	280,000.00
2	100,000.00	180,000.00	640,000.00	360,000.00	540,000.00	270,000.00
3	130,000.00	310,000.00	512,000.00	488,000.00	798,000.00	266,000.00
4	**160,000.00**	**470,000.00**	**409,600.00**	**590,400.00**	**1,060,400.00**	**265,100.00**
5	190,000.00	660,000.00	327,680.00	672,320.00	1,332,320.00	266,464.00
6	220,000.00	880,000.00	262,144.00	737,856.00	1,617,856.00	269,642.67
7	250,000.00	1,130,000.00	209,715.20	790,284.80	1,920,284.80	274,326.40

Thus it can be seen that strictly the equipment needs to be replaced at the end of 4th year, through the difference between this and 3th and 5th year value is very small. Thus anytime during this interval the replacement could be done.

A similar analysis can be carried out to decide the choice of the best equipment (purely from economic point of view assuming that all the equipments are equally efficient) from among several alternatives. The equipment which has the least average annual cost could be chosen.

In case the equipment is not required over an indefinite period but for a limited period. Suppose that a replacement policy is to be formulated for the truck mentioned in the problem above only for the next years assuming that presently a one year old truck is available.

4.3.2. Replacement policy for equipments whose running cost increases with time but value of money changes with constant rate during the period.

4.3.2.1. Value of money criterion

If the effect of the time value of money is t be considered, then replacement decision analysis must be based upon an equivalent annual cost. For example, if the interest rate on Rs.100 is 10 per cent per year, then value of Rs.100 to be spent after one year will be Rs.110. This is also called value of money. Also, the value of money that decreases with constant rate is known as its depreciation ratio or discounted factor. The discounted value is the amount of money required at the time of the policy decision to build up funds at compound interest large enough to pay the required cost when due. For example, if the interest rate on Rs.100 is r per cent per year, then present value (or worth) of Rs.100 to be spent after n year will be

$$d = \frac{100}{(100 + r)^n}$$

Where d is the discount rate or depreciation value. After having the idea of discounted cost, the objective should be to determine the critical age at which an item should be replaced so that the sum of all discounted cost is minimum.

4.3.2.2. Present worth factor criterion

In this case the optimal value of replacement age of an equipment can be determined under two different situations.

1. The running cost of an equipment which deteriorates over a period of time increases monotonically and the value of the money decreases with a constant rate. If r is the interest rate, then

   $$Pwf = (1 + r)^{-n}$$

   Is called the present worth factor (Pwf) or present value of one rupee spent in n years from time now onwards. But if n = 1 the Pwf is given by

   $$d = (1 + r)^{-1}$$

   where d is called the discount rate or depreciation value.
2. The money to be spent is taken on loan for a certain a period at a given rate under the condition of repayment in instalments.

The replacement of equipments on the basis of present worth factor (Pwf) includes the present worth of all future expenditure and revenues for each replacement alternatives. An equipment for which present worth factor is less is preferred. Let

C = purchase cost of an equipment

R = annual running cost

n = life of the equipment in years

r = annual interest rate

Then the present worth of the total cost during n years is given by

Total cost = C + R (Pwf for r% interest rate for n years) – S (Pwf for r% interest rate for n years)

If the running cost of the equipment is different in its different operational life, then the present worth of the total cost during n years is given by

Total cost = C + R (Pwf for r% interest rate for i years) – S (Pwf for r% interest rate for i years)

Where i = 1, 2, 3 ……, n

4.3.2.3. General cost function

The maintenance cost increases with time and the money value decreases with constant rate, i.e. depreciation value is given. Then replacement policy will be:

1. Replace if the running cost of next period is greater than the weighted average f previous cost
2. Do not replace if the running cost of the next period is less than the weighted average of the previous costs.

Suppose that the equipment is available for use over a series of time periods of equal length, say one year. Let us use the following notations:

C = purchase price of new equipment

R_n = running cost of the equipment at the beginning of n^{th} year ($R_{n+1} > R_n$)

r = annual interest rate

d = depreciation value per unit of money during a year $\{1/(1 + r)\}$

Let us assume that the equipment is replaced after every n years of service and has no resale value (or price). The replacement policy can be formulated by the calculating the total amount of money required for purchasing and running the item for n years. The period for which the total money is minimum will be considered best. The present worth (discounted value) of all future costs of purchasing and running the item with a policy of replacing it after every n years is given by

$$D_n = \{[C + R_1) + d R_2 + d^2 R_3 + \ldots + d^{n-1} R_n] \quad \text{(for 1 to n years)}$$
$$+ [d^n (C + R_1) + d^{n+1} R_2 + d^{n+2} R_3 + \ldots + d^{2n-1} R_n] \quad \text{(for n+1 to 2n years)}$$
$$+ [d^{2n} (C + R_1) + d^{2n+1} R_2 + d^{2n+2} R_3 + \ldots + d^{3n-1} R_n] \quad \text{(for 2n+1 to 3n years)}$$
$$+ \ldots\ldots$$

$= [(C + R_1)(1 + d^n + d^{2n} + \ldots) + d\, R_2\, (1 + d^n + d^{2n} + \ldots)$

$+ \ldots + d^{n-1}\, R_n\, (1 + d^n + d^{2n} + \ldots)$

$= [(C + R_1) + d\, R_2 + \ldots + d^{n-1}\, R_n][1 + d^n + d^{2n} + \ldots]$

$$= \left[C + \sum_{i=1}^{n} d^{i-1} R_i\right]\left[\frac{1}{1-d^n}\right] \quad \text{(sum of infinite G.P., D < 1)}$$

In case salvage value S, if any, corresponding to the age of an equipment after i years is to be considered, then the present worth D_n would be

$$D_n = \left[C - Sd^i + \sum_{i=1}^{n} d^{i-1} R_i\right]\left[\frac{1}{1-d^n}\right]$$

D_n would be the amount of money required to pay all the future costs of acquiring and operational the equipment when it is renewed each n years. If $D_n < D_{n+1}$, then replaining the equipment each n years is preferable to replaining each n + 1 years. Further, if the best policy is of replacement every n years, then the two inequalities

$$D_{n+1} - D_n > 0 \text{ and } D_{n-1} - D_n > 0$$

Must be true.

Example 4.3.2.1.

Let us consider the data in example 4.3.1.1 and the money is worth 10 per cent per year.

The discounted factor (or rate) over a period of one year is given by

$$d = \frac{1}{1+0.10} = 0.9091$$

Year of Service i	M&O Cost (Rupees) Ri	Salvage Value (Rupees) S	Discounted Factor $d^{(i-1)}$	$Ri\ d^{(i-1)}$	Cumulative Running Cost (Rupees) $\sum Ri\ d^{(i-1)}$	d^i	$S\ d^i$	$C - Sd^i + \sum Ri\ d^{(i-1)}$ (Rupees)	$1-d^i$	D(n) (Rupees)
1	80,000.00	800,000.00	1.00000	80,000.00	80,000.00	0.90909	727,272.73	352,727.27	0.09091	3,880,000.00
2	100,000.00	640,000.00	0.90909	90,909.09	170,909.09	0.82645	528,925.62	641,983.47	0.17355	3,699,047.62
3	130,000.00	512,000.00	0.82645	107,438.02	278,347.11	0.75131	384,673.18	893,673.93	0.24869	3,593,595.17
4	160,000.00	409,600.00	0.75131	120,210.37	398,557.48	0.68301	279,762.31	1,118,795.16	0.31699	3,529,472.10
5	190,000.00	327,680.00	0.68301	129,772.56	528,330.03	0.62092	203,463.50	1,324,866.53	0.37908	3,494,964.54
6	220,000.00	262,144.00	0.62092	136,602.69	**664,932.72**	**0.56447**	**147,973.45**	**1,516,959.27**	**0.43553**	**3,483,050.44**
7	250,000.00	209,715.20	0.56447	141,118.48	806,051.21	0.51316	107,617.06	1,698,434.15	0.48684	3,488,677.15

It is seen that discounting has slightly modified the replacement age, though as mentioned in the first case, the difference over the interval from 5th to 7th year is negligible. Generally interest affects the optimal replacement age slightly or not at all, especially for items that last only a few years. However, it affects profitability. For example, in the example discussed above, at 10% interest, the equivalent constant annual cost with six year life is $(1 - d)$ Dn = 0.0909 x 3,483,050.44 = 316.609.29 rupees, which can be compared an average annual cost of 265,100.00 rupees when no interest is charged in table 4.2. It means the truck would have to earn an annual revenue of 265,100.00 rupees to break even if no interest is charged and a revenue of 316.609.29 rupees if the funds are invested elsewhere where they can earn 10% per annum.

4.4. REPLACING THE EQUIPMENT BY SIMILAR EQUIPMENT[10]

In this case, suppose machine A can be replaced by either machine A or machine B which serves the same purpose as A but the cost patterns are different. Now, the question is to decide whether B can replace and if it can, then at what age? For this the present worth, D_{nA} and D_{nB}, of A and B are separately computed as above. If $D_{nB} < D_{nA}$, then the machine B can replace machine A, if not, replacement should be made by machine A it self. Then to decide at what age replacement should be made, present worth D_{nAB} of replacement A by B is calculated. This is done in the same manner as explained above, except for the fact that instead of taking the capital cost of the machine A, the discounted present worth of the machine B is taken into consideration for each year's computation, and the present worth to be discounted would be the minimum values which is obtained while computing the replacement costs for machine B D_{nAB} is computed by using the running cost of A, resale value of A and the optimal present worth of B discounted during the years under consideration.

4.5.REPLACEMENT IN ANTICIPATION OF FAILURE[10,13]

There are a quite large number of items that fail suddenly resulting in large cost of failure i.e. the idle time is increased and production is lost. The equipment or item itself may be so costly but the cost of failure due to loss of production, damage, accident may be considerable. In such a case replacement is made in anticipation of failure. This will require the previous history of such failures. Based on these probability of failure can be based on different degrees of use are obtained and this data can be used to decide the optimal age of replacement considering the cost of replacement of the item only and the cost of replacement considering the cost of replacement on failure including the cost of item.

When an equipment fails completely it has to be replaced. Even when the equipment is functioning it may have to be replaced if it has achieved a specific probability of failure or if an economic advantage is expected. This may lead to a consideration whether to replace it on an individual basis or on a group basis. If the replacement is to be made on the group basis then determining the minimum cost replacement interval arises. It can best be illustrated or explained with the help of an example and should be based on the analysis of failure data.

Let us consider a group of No. machines, then at the end of 't' time periods, the number of serving equipment is a function of t.

The probability of an equipment failing within each time period can be calculated as

$$P(t) = \frac{M(t-1) - M(t)}{N}$$

Where: M(t) = The number of survivors through time period t

M(t-1) = The number of survivors through time period (t-1)

N = The initial number of units in the group.

The probability that the equipment has survived to an age (t-1) and will fail during the interval (t-1) to t is defined as the condition probability of failure and is calculated as

$$P_c(t) = \frac{M(t-1) - M(t)}{M(t-1)}$$

The probability of survival to an age t is given by

$$P_s(t) = \frac{M(t)}{N}$$

Now to calculate the number of replacements required per period, it is assumed that failure occurred only at the end of the period. When the failures are replaced, the replacement them selves will eventually fail and must be replaced giving rise to the replacement of replacements.

If f_o denotes initial number of machines and f_t denotes the number of replacements made, at the end of the period 't' then the number of replacements at the end of each period will be,

$$f_o = f_o$$

$$f_1 = f_o P_1$$

$$f_2 = f_o P_2 + f_1 P_1$$

$$f_3 = f_o P_3 + f_1 P_2 + f_2 P_1$$

....

....

$$f_t = f_o P_t + f_1 P_{t-1} + f_2 P_{t-2} + \ldots\ldots\ldots\ldots + f_{t-1} P_1$$

The cost of group replacement after time period t is given by

$$C(t) = nC_1 + C_2 \sum_{x=1}^{t-1} F(x)$$

Where : n = Total number of items in the system

F(x) = Number of equipments failing during time t

C_1 = Unit cost of replacement in a group

C_2 = Unit cost of individual replacement after time t, i.e. failure

In Eqn. above, nC_1 is the cost of replacing the items as a group, and $C_2 \sum_{x=1}^{t-1} F(x)$ is the cost of replacing the individual failures at the end of each of t-1 periods before group is again replaced.

The average cost of group replacement for period

$$K = \frac{1}{t}\left(nC_1 + C_2 \sum_{x=1}^{t-1} F(x) \right)$$

The average cost of individual replacement per period

$$K_I = \frac{NC_2}{averagelife} = \frac{NC_2}{\sum_{t=0}^{\infty} tP_t}$$

Example 4.5.1.

For example, consider the failure data for trucks as given in table below on the basis of probability of failure of machine.

Analysis of truck failure data

Period	Survivors	Failures	P(t)	Pc(t)	Ps(t)
0	62	0	-	-	1.000
1	60	2	0.032	0.032	0.968
2	55	5	0.081	0.083	0.917
3	39	16	0.258	0.291	0.709
4	22	17	0.274	0.436	0.564
5	7	15	0.242	0.682	0.318
6	2	5	0.081	0.714	0.286
7	0	2	0.033	1.000	0.000

The cost of replacing Truck is Rs.1,000,000.00.

Solution :

Let f_t be the that number of trucks replaced at the end of the t^{th} year. Then

f_o = number of trucks in the system in the beginning = **62**

f_1 = number of trucks being replaced by the end of the first year

$= f_o P_1 = 62 \times 0.032 =$ **1.984**

f_2 = number of trucks being replaced by the end of the second year

$= f_o P_2 + f_1 P_1 = 62 \times 0.081 + 1.984 \times 0.032 =$ **5.08549**

$f_3 = f_o P_3 + f_1 P_2 + f_2 P_1$

$= 62 \times 0.258 + 1.984 \times 0.081 + 5.08549 \times 0.032 =$ **16.31944**

$F_4 = f_o P_4 + f_1 P_3 + f_2 P_2 + f_3 P_1$

$= 62 \times 0.274 + 1.984 \times 0.258 + 5.08549 \times 0.081 + 16.31944 \times 0.032 =$ **18.43401**

$F_5 = f_o P_5 + f_1 P_4 + f_2 P_3 + f_3 P_2 + f_4 P_1$

$= 15.00400 + 0.54362 + 1.31206 + 1.32187 + 0.58989 =$ **18.77144**

$F_6 = f_o P_6 + f_1 P_5 + f_2 P_4 + f_3 P_3 + f_4 P_2 + f_5 P_1$

$= 5.02200 + 0.48013 + 1.39342 + 4.21042 + 1.49315 + 0.60069 =$ **13.19981**

$F_7 = f_o P_7 + f_1 P_6 + f_2 P_5 + f_3 P_4 + f_4 P_3 + f_5 P_2 + f_6 P_1$

$= 2.046 + 0.1607 + 1.23069 + 4.47153 + 4.75597 + 1.52049 + 0.1607 =$ **14.34608**

From the value of f_t ($t = 0,1,2,\ldots,7$) so calculated, it can be seen that the expected number of trucks failing each year increases upto 5^{th} year and then start decreasing and later increases in the 7^{th} year. Thus f_t will oscillate till the system acquires a steady state. The expected life of each truck is given by

$$\text{Expected life} = \sum_{i=1}^{7} tP_t$$

$$= 1 \times 0.032 + 2 \times 0.081 + 3 \times 0.258 + 4 \times 0.274 + 5 \text{ x } 0.242 +$$
$$6 \times 0.081 + 7 \times 0.033$$
$$= 3.991$$

Average Number of failure per period is

$$\frac{N}{AverageLife} = \frac{62}{3.991} = 15.534953$$

Average cost of replacement on failure / period

$$K_I = \frac{NC_2}{averagelife} = \frac{62 \times 1{,}000{,}000}{3.991} = 15{,}534{,}953.00 \text{ Rupees}$$

Example 4.5.2

A new tyre costs Rs. 500 while the cost of retreading is Rs. 300. A tyre must be retreaded or replaced when it wears smooth. Retreading is possible only when the tyre walls have not deteriorated. The following table gives the probabilities of tyre failures and other data. Find the average cost per thousand kilometers, if[10]

(i) Replacement is done always by a new tyre

(ii) Retreading is done whenever possible. It is assumed that the retreading is possible only once.

Age (Thousands of Km)	7	8	9	10	11	12	13	14	15	16	17	18
Probability that tyre becomes	-	-	-	-	-	0.1	0.1	0.15	0.2	0.25	0.15	0.1
Probability that smooth tyre can be retreaded	-	-	-	-	-	0.8	0.8	0.7	0.7	0.5	0.5	0.3
Probability of failure of retreaded tyre	0.1	0.1	0.15	0.25	0.2	0.15	0.05	-	-	-	-	-

Solution:

The average age at which a new tyre becomes smooth is found by multiplying each age by the probability of smoothness and then adding. Assuming that smoothness occurs at the midpoints of the km intervals.

The average age in thousand of kilometers is

$$\begin{aligned} A &= 12.5 \times 0.1 + 13.5 \times 0.1 + 14.5 \times 0.15 + 15.5 \times 0.2 + 16.5 \times 0.2 + 17.5 \times \\ &\quad 0.15 + 18.5 \times 0.1 \\ &= 1.25 + 1.35 + 2.175 + 3.10 + 3.30 + 2.625 + 1.85 \\ &= 15.65 \end{aligned}$$

The average cost / thousand kilometers is

$$= \frac{500}{15.65} = 31.95 \text{ Rupees per thousand km}$$

Similarly, the average age at which retreading must be replaced in thousands of kilometers

$$B = 7.5\times 0.10 + 8.5\times 0.10 + 9.5\times 0.15 + 10.5\times 0.25 + 11.5\times 0.20 +$$

$$= 12.5\times 0.15 + 13.5\times 0.05$$

$$= 0.75 + 0.85 + 1.275 + 2.625 + 2.3 + 1.875 + 0.675$$

$$= 10.35$$

The cost per thousand kilometers of new tyre and retreading when possible, we must find the total average life f both. This is the average life of a new tyre plus the probability that we can use a recap, is found by multiplying the probability of smoothness of each age by the probability that the tyre can be recapped and then adding.

The probability that we can retread

= Probability of becoming smooth × Probability of retreading

$$P_s = 0.1\times 0.8 + 0.1\times 0.8 + 0.15\times 0.7 + 0.2\times 0.7 + 0.2\times 0.5 + 0.15\times 0.5 + 0.1\times 0.3$$

$$= 0.08 + 0.08 + 0.105 + 0.14 + 0.10 + 0.075 + 0.03$$

$$= 0.61$$

The total average life until we again have a new tyre

$$C = A + P_s \times B$$

$$= 15.65 + 0.61 \times 10.35$$

$$= 21.9635$$

The expected cost over the period is the cost of a new tyre plus the cost of a retreading times the probability of retreading (D).

$$D = 500 + P_s \times 300$$

$$= 500 + 0.61 \times 300 = 683$$

Average cost per thousand kilometers

$$= \frac{D}{C} = \frac{683}{21.9635} = 31.10$$

If a tyre can be retreaded, it should be retreaded instead of replacing it by a new.

CHAPTER - V

CONCLUSIONS

5.1. GENERAL

Various maintenance activities for construction equipment should be planned keeping in view the categorization of machines. Important machines like batching and mixing plant and heavy earthmoving equipment should be given utmost attention so that breakdowns are reduced to minimum, since the breakdown of any machine serving a series of other machines would result in very high down time cost as well as the loss in production. One should strictly adhere to a sound inspection schedule and other maintenance activities. Every construction project should chalk out a proper plan for providing facilities and carry out the maintenance operations depending upon the population of equipment employed on the project.

Planning for maintenance should begin with the initial stage of the project itself. It is very essential that advance planning is done to assess the requirements of men, materials, tools and spare parts. These should be properly equipped with the housing tools and other job facilities. Base workshop and field repair shop should be located at suitable places so that least distances are involved in equipment movement and minimum time is lost in getting the equipment repaired or serviced. If the distances involved are large then it is beneficial to go in for mobile workshop and mobile servicing units. Sufficient crew should be provided on these units with their defined duties.

The equipment manufacturer provides with every unit, operating and servicing manuals, lubricating charts and frequency of changing the filters. By observing the instructions of the manufacturers which are useful for scheduled and preventive maintenance planning and execution bulk of the major breakdowns can be avoided. This can be done by proper display of charts in supervisors office and with servicing unit and observing the timely compliance by the maintenance staff.

Timely repairs in the field workshop can avoid costly damages and downtime. Frequent inspection should be carried out on a planned basis with the help of check lists by maintenance staff and half yearly by management staff. Frequency of inspection can be decided after giving due consideration economic aspect.

Lubrication such as gear oil, engine oil, transmission oil, hydraulic oil and greases should be standardized to ease the preventive maintenance and avoiding the confusion of wrong adoption of lubricant by lower maintenance staff.

The objective of proper maintenance is to achieve the optimum utilization of equipment, maximum productivity, least downtime and minimum cost of production. Application of operation research techniques in maintenance planning helps in this matter. The application of waiting line model, sequencing model, assignment model, replacement model which have been illustrated through examples in this dissertation are of great use in achieving the maximum profit and least downtime of equipment.

The requirement of stores, workshop machinery and crews have to be accurately determined and these resources have to be properly allocated so as to achieve minimum cost and time in completing repairs. Due to variable nature of breakdown maintenance job and the assessment of manpower to repair the equipment is not an easy job. To achieve the minimum waiting time for equipment waiting maintenance, and least downtime with minimum cost, simulation with waiting line model should be applied to arrive at economical size of crew, which have been illustrated through examples in this dissertation.

In view the need for reliable and useful data required for planning and executing maintenance operations through system approach, record keeping of the maintenance work done, the performance of equipment in terms of hours run, type of breakdown observed, time taken for repair, cost involved and output attained are the essential requirements. This records help in analyzing the data and its performance, which helps in effective and efficient maintenance. Typical record keeping proforma have been included in appendices to this dissertation.

Equipment and machines rarely incur uniform wear and tear. Some elements or components are likely to deteriorate faster than others. Under these conditions it is often economical to repair the equipment to the extent of its useful life. Some repairs follow a periodic pattern and can be planned; while some repairs follow unpredictable pattern. The equipment becomes a candidate for replacement when it is anticipated that it will require an additional and extensive repair frequently.

Generally, the equipment operates at an initial peak efficiency which declines with time and use. The decrease in efficiency will require increased power consumption and longer time to accomplish the same operations. This leads to the increased cost of production which, in turn, necessitates the replacement of the existing equipment. Application of Replacement Model in maintenance planning helps in this matter. Application of replacement models has also been illustrated by examples in this dissertation.

5.2. SCOPE FOR FUTURE WORK

The illustrative examples for application of various models, (like waiting line model, sequencing model, assignment model, simulation model and replacement model) which otherwise do not appear to be directly applicable for best maintenance strategy, can be improved further by collecting field maintenance data for using their models there by enabling further refinement in their application for selecting best maintenance strategy for the construction equipment.

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APPENDICESS

Appendix 1

Life and Repair Provision of Equipment

Sl.No	Equipment		Life of Equipment		Repair Provision % of Cost Of Equipment	Remarks
	Category	Capacity	Years	Hours		
1	2	3	4	5	6	7
1	**Excavators**					
	Shovels and Draglines	Up to 1.5 cyd (1.15 cum)	10	12,000	150	
		1.5 to 3.0 (1.15 to 2.3 cum) (Diesel)	12	15,000	150	
		Above 3.0 cyd (2.3 cum) (Diesel)	15	25,000	150	
		2.5 to 4 (1.91 to 3.06cum) (Electric)	15	25,000	150	
		4Cyd(3.06cum) and Above (electric)	20	40,000	150	
	Walking draglines		20	30,000	150	
	Bucket wheel excavator		20	40,000	150	
	Dredger in fresh water	Hull	25	-	60	
		Machine	10	-	60	
	Barges	Hull	16	-	60	
		Machine	10	-	60	
	Tugs	Hull	16	-	60	
		Machine	10	-	60	
2	**Dumpers**					
	Bottom dumper	Upto 20 ton (18 tonne)	8	10,000	140	
		20 ton to 50 ton (18 tonne to 45.3 tonne)	10	16,000	140	
		Above 50 ton (45.35 tonne)	12	20,000	140	

1	2	3	4	5	6	7
	Rear dumpers	Upto 15 ton (13.6 tonne)	8	10,000	140	
		15 ton to 35 ton (13.6 to 31.7 tonne)	10	12,000	140	
		Above 35 ton Upto 50 ton (31.7 to 45.4 tonne)	12	15,000	140	
		Above 50 ton (45.4 tonne)	15	20,000	140	
	Highway dumpers		8	10,000	140	
3	**Scrapers**					
	A. Motorised					
	Push loaded	Upto 10 cyd (7.65 cum	8	9,000	150	
		Above 10 cyd (7.65 cum)	10	10,000	150	
	Elevating And self loading		10	10,000	150	
	B. Towed		12	15,000	75	
4	**Tractors**					
	Crawlers	Upto 100 h.p. (101 metric h.p.) (74.6 kw)	8	9,000	200	
		Above 100 and Upto 300 h.p. (101 to 305 Metric h.p.) (74.6 to 224 kw)	10	12,000	240	
		Above 300 h.p. (305 metric h.p.) (224 kw)	12	16,000	240	
	Wheeled	Upto 75 h.p. (76 metric h.p.) (56 kw)	8	12,000	150	
		Above 75 h.p. (76 metric h.p.) (56 kw)	10	15,000	150	

1	2	3	4	5	6	7
5	**Graders**		10	12,000	150	
6	**Loaders**					
	Crawler		10	12,000	200	
	Wheeled		10	15,000	150	
	Belt Loaders		16	20,000	70	
	Reclaimers and stackers		20	30,000	70	
7	**Compactors**					
	Self Propelled sheepsfoot rollers		10	12,000	80	
	Drawn Sheeps foot rollers		8	10,000	70	
	Vibratory rollers		8	8,000	150	
	Smooth drum rollers		8	10,000	80	
	Smooth drum vibratory rollers		8	8,000	150	
	Pneumatic tyred rollers		8	10,000	80	
	High speed compactors		10	16,000	100	
8	**Water sprinklers**		10	16,000	100	
9	Canal trimmer and lining equipment Above 200 Cyd/hr (153 cum/hr) capacity		16	20,000	100	

1	2	3	4	5	6	7
10	**Drills**					
	Blast hole drills		10	10,000	80	
	Core drills		8	8,000	80	
	Wagon drills		8	8,000	80	
	Tricone rotary drills		10	10,000	80	
11	**Compressors**					
	A. Diesel compressors					
	(i) Portable upto 300 cfm (8.5 cum/min)		8	10,000	100	
	(ii) Portable above 300 cfm (8.5 cum/min)		10	12,000	100	
	B. Electric compressors					
	(i) Portable upto 300 cfm (8.5 cum/min)		10	16,000	80	
	(ii) Portable above 300 cfm (8.5 cum/min)		12	20,000	80	
	(iii) Stationary		20	30,000	80	
12	**Blowers**		12		80	
13	**Cooling plants**					
	(i) Aggregate cooling plant		20	40,000	75	
	(ii) Ice plant		20	40,000	75	
14	**Batching and mixing plant**					
	(i) Cement handling, batching and mixing plant		18	30,000	75	
	(ii) Transit mixers Agitating cars		10	10,000	120	
	(iii) Portable concrete mixers		5	6,000	80	
15	**Pumps**					
	(i) Diesel engine driven, above 10h.p. (10.14 metric h.p.) (7.46 kw)		8	10,000	100	
	(ii) Electrical		12	20,000	70	

1	2	3	4	5	6	7
16	**Well points**		12	20,000	100	
17	**Cranes**					
	(i)	Mobile (pneumatic wheeled) 4 to 6 tons (3.6 to 5.4 tonnes)	10	12,000	120	
		8 to 12 tons (7.3 to 10.9 tonnes)				
		15 to 20 tons (13.6 to 18.1 tonnes)	12	15,000	120	
		26 tons (23.6 tonnes) and above				
	(ii)	Crawler mounted				
		Upto 3 tons (2.7 tonnes)	10	12,000	120	
		4 to 10 tons (3.6 to 9.1 tonnes)				
		Over 10 tons (9.1 tonnes)	12	15,000	120	
	(iii)	Tower cranes	20	30,000	120	
	(iv)	Truck mounted	10	16,000	140	
18	**Transport Equipment**					
	A. Heavy transport vehicles					
	(a) Trucks and highway dumpers					
	(i)	Diesel upto 3 ton (2.7 tonnes)	10	2,00,000 km	140	
		Diesel 3 to 5 ton (2.7 to 4.5 tonnes)				
		5 ton (4.5 tonnes) And above				
	(b) Tractor trailers		10	2,50,000 km	140	
		Upto 5 ton (4.5 tonnes)				
		5 ton to 10 ton (4.5 to 9.2 tonnes)				
		10 ton (9.1 tonnes) And above	12	20,000 Hrs	140	
	B. Light Transport Vehicles					
	(i)	Jeeps		1,60,000 km	140	
	(ii)	Station wagon				
	(iii)	Cars				
	(iv)	Ambulance cars				

1	2	3	4	5	6	7
	C. Aerial Transport					
	(i) Ropeway		20	40,000	70	
	(ii) Cableway					
	D. Rail Transport					
	Locomotive					
	Diesel		10	16,000	120	
	Electrical		22	40,000	100	
	Wagons, rail cars		20	30,000	70	
19	**Diesel Generating Sets**					
	Upto 50 kva		10	20,000	100	
	Above 50 kva		15	30,000	120	

Appendix 2

PREVENTIVE MAINTENANCE
I-DAILY SCHEDULE FOR I.H. 100 PAYHAULERS

DATE.. PAYHAULER NO. ....

TOTAL PROGRESSIVE HOURS ....

Description	Tick	Remarks,if any
STAGE - I		
(a) Wash		
(b) Clean the glass surfaces (windshield and instruments)		
STAGE - II		
(a) Fill water in radiator, check leaks and correct		
(b) Check engine oil level, add (Delvac 1330) if necessary		
(c) Check engine oil leaks and correct		
(d) Check the fluid level in the brake power cluster front and rear after cleaning the area around the filler cap. (Hydraulic Brake Fluid)		
(e) Check the transmission oil		
(f) Check the hydraulic reservoir		
(g) Clean air cleaner pan		
(h) Bleed air tank		
(i) Inspect the tyres for damage inflate pressure front 50 lbs./Sq. In rear 70 lbs./Sq.In		
STAGE - III		
(a) Drag link (front)		
(b) Drag link (rear)		
(c) Steering Cylinder anchorer		
(d) Steering Cylinder end		
(e) Kings pins		
(f) Tie rods		
(g) Hoist cylinder bearings		
STAGE - IV		
Drain fuel tank sump cock		
Drain fuel filter sump		
Fill fuel in the tank		
Special remarks, if any :		

Quantity of fuel used Lubricants used	Other materials used	Name of mechanic
1.	....	Signature
2.	....	....
3.	....	Signature of GF/Foreman/C-man
4.	....	....
		Signature of the inspecting Officer
		....

II-100 HRS. SCHEDULE FOR I.H. 100 PAYHAULERS

DATE.. PAYHAULER NO. ....

TOTAL PROGRESSIVE HOURS ....

Description	Tick	Remarks,if any
I (a) Wash		
(b) Clean the glass surfaces (windshield and instruments)		
II (a) Fill water in radiator, check leaks and correct		
(b) Check engine oil leaks and correct		
(c) Drain and refil engine oil (Delvac 1330)		
(d) Clean crank case breather		
(e) Check the fluid level in the brake power cluster front and rear after cleaning the area around the filler cap. (Hydraulic Brake Fluid)		
(f) Check Transmission Oil level with engine idling, add if necessary Mobile DTE oil Right Type Cl.		
(g) Clean Transmission breather and reoil		
(h) Check Hydraulic tank oil level, add if necessary and clean hydraulic breather Mobile DTE oil		
(i) Clean Air cleaner pan		
(j) Bleed Air tank		
(k) Check oil level in Differential		
(l) Check oil level in Drive axle		
(m) Check oil level in planetary reservoir		
(n) Check breather tube		
(o) Clean steering booster breather		
(p) Drain compressor oil and change		
(q) Change lub. Oil filter after every 200 hrs		
(r) Change transmission oil filter after every 250 hrs.		
III (a) Drain fuel tank sump cock		
(b) Drain fuel filter sump		
(c) Fill fuel in the tank		
IV GREASE THE FOLLOWING POINTS (MPG)		
(a) Drag link front		
(b) Radius rod front		
(c) Drive line front		
(d) Steering Cylinder anchorer		
(e) Steering Cylinder end		
(f) Kings pins		
(g) Tie rods		
(h) Drag link rear		
(i) Radious rod (rear)		
(j) Drive line (rear)		
(k) Hoist Cylinder bearings		
V OIL CAN POINTS (Delvac 1330)		
(a) Hinge pin & spring case		
(b) Transmission shift linkage		
(c) Hood and battery box fasteners		
(d) Wind shield wiper motor		
(e) Throttle linkage		
(f) Hoist control linkage		
(g) Emergency brake linkage		

VI (a) Check the electrolyte in battery, add distilled water if necessary (b) Check, clean and tighten battery terminals of bracket (c) Check and oil generator and self starter (d) Check lights and switches, correct, if necessary (e) Check and clean generator & self starter carbon brushes, commutator (f) Check and adjust generator belt tension, replace if necessary (g) Check and adjust fan belt replace if necessary (h) Check air pressure, water temp. & oil pressure gauges		
VII CLEAN ENGINE AIR CLEANER (a) Clean dust cap (b) Inspect tubes and clean with brush (c) Use new seal ring (d) Service filter element replace if damaged or in doubt (e) Check hoses, gasket for cracks/leaks rectify		
VIII (a) Remove mud and dirt accumulation in brake drum (b) Tighten the wheel rim clamp nuts (c) Inspect the tyres for damage presure front 50 lbs. rear 70 lbs.		

Special remarks, if any

Quantity of fuel used Lubricants used	Other materials used	Name of mechanic
1.	....	Signature
2.	....	....
3.	....	Signature of GF/Foreman/C-man
4.	....	....
		Signature of the inspecting Officer
		....

III-500 HRS. SCHEDULE FOR I.H. 100 PAYHAULERS

DATE... PAYHAULER NO. ....

TOTAL PROGRESSIVE HOURS ....

Description	Tick	Remarks,if any
I (a) Wash		
(b) Clean the glass surfaces (windshield and instruments)		
II (a) Fill water in radiator, check leaks and correct		
(b) Check engine oil leaks and correct		
(c) Drain and refil engine oil (Delvac 1330)		
(d) Clean crank case breather		
(e) Check the fluid level in the brake power cluster front and rear after cleaning the area around the filler cap. (Hydraulic Brake Fluid)		
(f) Change the oil in transmission (Mobile DTE oil light type C1)		
(g) Clean Transmission breather and reoil		
(h) Check Hydraulic tank oil level, add if necessary and clean hydraulic breather Mobile DTE oil		
(i) Remove the complete Air cleaner & clean		
(j) Bleed Air tank		
(k) Drain compressor oil and change		
(l) Clean the compressor housing and impeller of turbo charger		
(m) Check oil level in Differential		
(n) Check oil level in Drive axle		
(o) Check oil level in planetary reservoir		
(p) Check differential breather tube		
(q) Clean steering booster breather		
(r) Change lub. Oil filter after every 200 hrs		
(s) Change transmission oil filter after every 250 hrs.		
III (a) Drain fuel tank sump cock		
(b) Drain fuel filter sump		
(c) Fill fuel in the tank		
IV GREASE THE FOLLOWING POINTS (MPG)		
(a) Drag link front		
(b) Radius rod front		
(c) Drive line front		
(d) Steering Cylinder anchorer		
(e) Steering Cylinder end		
(f) Kings pins		
(g) Tie rods		
(h) Drag link rear		
(i) Radious rod (rear)		
(j) Drive line (rear)		
(k) Hoist Cylinder bearings		
(l) Lubricate the engine transmission		
V OIL CAN POINTS (Delvac 1330)		
(a) Hinge pin & spring case		
(b) Transmission shift linkage		
(c) Hood and battery box fasteners		
(d) Wind shield wiper motor		
(e) Throttle linkage		
(f) Hoist control linkage		
(g) Emergency brake linkage		

(h) Door hnges
(i) Door striker plates and latches

VI (a) Check the electrolyte in battery, add distilled water if necessary
(b) Check, clean and tighten battery terminals of bracket
(c) Check lights and switches, correct, if necessary
(d) Check generator and self starter. Lubricate with oil can (Delvac 1330)
(e) Check and clean generator & self starter carbon brushes, commutator
(f) Check and adjust generator belt tension, replace if necessary
(g) Check and adjust fan belt replace if necessary
(h) Check air pressure, water temp. & oil pressure gauges

VII CLEAN ENGINE AIR CLEANER
(a) Clean dust cap
(b) Inspect tubes and clean with brush
(c) Use new seal ring
(d) Service filter element replace if damaged or in doubt
(e) Check hoses, gasket for cracks/leaks rectify

VIII (a) Remove mud and dirt accumulation in brake drum
(b) Tighten the wheel rim clamp
(c) Inspect the tyres for damage presure front 50 lbs. rear 70 lbs.
(d) Check the torques of front axle and drive axle spring bolts(front axle "U" bolts Nuts 450 to 500 ft.Lbs.Drive axle 800 to 900 ft.Lbs)

IX (a) Adjust the valves and injector

Special remarks, if any

Quantity of fuel used Lubricants used	Other materials used	Name of mechanic
1.	....	Signature
2.	....	....
3.	....	Signature of GF/Foreman/C-man
4.	....	....
		Signature of the inspecting Officer
		....

Appendix 3

DAILY REPORT OF THE OPERATION OF EQUIPMENT GIVEN ON HIRE

Equipment Code No. .... Date ....

Name of Lessee............................ Shift ....

Where Used ....

No. of hrs. worked ....

P.O.L. issued Diesel -Lits
-Lits
-Lits

Defects noted during operation ....

Idle hours ....

Breakdown hours ....

Reasons for Breakdown ....

DAILY REPORT OF REPAIRS CARRIED OUT TO THE EQUIPMENT GIVEN ON HIRE

Equipment Code No. .... Date ....

Name of Lessee............................ Shift ....

Spare part used for repairs	Cost	Man-hours spent on repairs	Cost	Other mat erial or work done repairs	Cost
1	2	3	4	5	6

DAILY MAINTENANCE REPORT

Equipment Code No. .... Date ....

Name of Lessee............................ Shift ....

Detail of maintenance done during the day

Daily 50 hrs. 100 hrs. 500 hrs. 1000 hrs.

Details of adjustment done during the day.

Engine Transmission Clutch Final Drive Under Carriage Body Other parts

Report on Performance of different components of equipment

Engine Transmission Clutch Final Drive Under Carriage Body Other parts

Appendix 4

HISTORY BOOK

1. History Card

Equipment Code No.	....	Purchase reference	....
Description	....	Supplier's name	....
Capacity	....	Condition when purchased	New/Old
Shiping Wt.	....	If old, hours worked hen purchased	....
Overall dimensions		Purchase Price	
Length	....		
Width	....	C.I.F	....
Height	....	Custom duty	....
Wheel base	....	Taxes	....
Turning radius	....	Freight & Handling	....
Ground clearance	....	Total	....

	Years	Hours
Equipment	....	....
Tyre life	....	....

Weight distribution

	Empty	Loaded
Front	....	....
Drive	....	....
Trailer	....	....

Details of Component

Engine / Motor		Injectors		Compressors	
Make	....	Type	....	Type	....
Model	....	Make	....	Make	....
SI. No.	....	SI. No.	....	SI. No.	....
No. of Cylinders	....	Pressure	....	Pressure	....
		Starting system		Dynamo/Alternators.	
Cycles	....				
R.P.M.	....	Type	....	Make	....
H.P./K.W.	....	Make	....	S.I. No.	....
Max. Torque/Volts	....	Model	....	K.W.	....
Compression Ratio	....	SI. No.	....		
Super Charger/Turbo Charger		Generator (Main)		Other Motors	
Make	....	Make	....	Make	....
Model	....	Model	....	Type	....
SI. No.	....	K.W.	....	SI. No.	....
Battery		Volts	....	H.P./K.W.	....
Nos	....	Suspension		Torque/Volts	....
Size	....	Type	....	Control Type	
Make	....	Fuel pump			
Volts	....	Type	....		
Amp.Hour	....	Make	....	Transmission	
Hydraulic pump		SI. No.	....	Type	....
Make	....	Steering		Make	....
SI.No.	....	Type	....	Model	....
Brakes		Specification of grease		SI.No.	....
Type	....	1.	....	No.of Speeds	
		2.	....	Forward	....
				Reverse	....
Tracks					
No.of Shoes	....	3.		Max.Travel Speed	
Length	....	Liquid Capacities & Speci fication		Forward	
				1.	....
Width	....	Cooling System	....	2.	....
		Fuel tank	....	3.	....
Ground contact	....	Engine crank		4.	....
		Case	....	5.	....

No.of Rollers	....			Starting Engine				
track				Crank case	....		Reverse	
				Transmission	....		1.	....
Carrier	....			Final drive	....		2.	....
				Hydraulic	....		3.	....
Tyres								
Type	....			Filters Type &Nos			Wire rope specification size & length	
	F	D	R				1.	....
Size	....	....	....	Air	....	....	2.	....
Mos	....	....	....	Fuel	....	....	3.	....
Make	....	....	....	Lub.	....	....	4.	....
Pressure	....	....	....	Transmission	....	....		
				Hydraulic	....	....		
				Others	....	....		

* Capacities may be indicated as Bucket Capacity, lifting capacity, carrying capacity, drawbar pull etc.

2. Details of Accessories, Tools and Literature received with the equipment

Sl.No	Description	Quantity	Available at	Remarks

3. Record of Transfer

Name of Project / Division	Date of Arrival	Hrs.Done before arrival	Condition	Date of Transfer	Hrs.Done upto the date of Transfer	Condition
1	2	3	4	5	6	7

4. Details of Alteration / Modification

Date	Hour meter reading/ clock hours done	Details of Modifications/ Alterations carried out	Details of Spare parts/ Material used	Job Cost	Remarks
1	2	3	4	5	6

5. Details of spare parts consumed component wise
*(a) Engine (b) Transmission (c) Clutch (d) F.D. & U.C. (e) Attachments and other components

Date	Hour meter or clock meter reading	Details of spare parts used	Quantity	Cost
1	2	3	4	5

6. Details of Assemblies Replaced

Date	Hr.Meter/Clock hour reading	Assembly Replaced	Sl.No.& Part No.	Old assembly Discarded or sent for repairs	Date/hr.meter reading when old assembly is returned for replacement	Remarks
1	2	3	4	5	6	7

7. Details of repairs/Replacements carried out to different components and cost of repairs

*(a) Engine (b) Transmission (c) Clutch (d) F.D. & U.C. (e) Attachments and/or other components

Date	Mfr's Sl.No.of Unit installed	Working hrs.of unit removed or repaired	Nature of repairs	Expenditure on Repairs Spare parts	Labour	Other mate rials	Workshop Overhead	Total	Removed unit if not reinstalled retd. To
1	2	3	4	5	6	7	8	9	10

*Separate sheet should be maintained for each component

8. a. Tyres & Tubes

Date of installation/ replacement	Tyre position	Tyre No.	Make	Type & PR	Condition retreaded/ repaired/ New/Old	Hours worked by repaired tyre	Cost of repair/ replacement	Reasons
1	2	3	4	5	6	7	8	9

8. b. Batteries

Date of replacement	Battery No.	Make	Specifica tions	Condition New/Recon ditioned/ recharged	Reasons for replace ment	Hours done	Cost of repair/ replacement	Remarks
1	2	3	4	5	6	7	8	9

8. c. Wire Ropes-Position-Scheduled size,Length & Formation

Date of replacement instalation	Make	Hours done since last replacement	Cost	Time taken for replacement	Remarks
1	2	3	4	5	6

8. d. Cutting Edges / Dipper Teeth etc.

Date of replacement instalation	Make	Condition New rebuilt	Reasons for replacement	Hours done before replacement	Cost pf rebuild Replacement	Remarks/ Observations about rate of wear etc.
1	2	3	4	5	6	7

9. Monthly Record of hours Worked and Consumption analysis

Year ....

Month	Avail able hours	Hours worked	Hours under repair	Standby hours	Consumption of				Nor mal/ abnor mal	Reasons for ab norma lity	Action taken	Re marks
					Fuel		Lubricants					
					Total	Per Hr.	Total	Per Hr.				
1	2	3	4	5	6	7	8	9	10	11	12	13

10. Yearly record of depreciation and repairs costs

Installed Cost.................................

Rate of Depreciation...........................

Life...

Years	Hour worked	Amount of Depreciation	Residual value	Repairs Cost		Remarks
				Spares	Labour	
1	2	3	4	5	6	7

11. a. Condition of parts and components after overhaul / repairs

Engine	1st.	2nd	3rd	4th.
No. of Overhaul				
Date of Commencement				
Date of completion				
Clock hour/hour meter reading				

Condition of parts after overhaul

Crank shaft

- (i) Main
- (ii) Big end

Pistons

Rings

Camshaft

Head Cylinder

Block Cylinder

Fuel pump

Injectors

Turbocharger / Supercharger

Compressor

Radiator

Lub.Oil Pump

11. b. Track Components

	1st.	2nd	3rd	4th.
No. of overhaul				
Date of commencement				
Date of completion				
Clock hour/hr. meter reading				

Condition of parts

Sprocket
- LH
- RH

Idler
- LH
- RH

Track links
- LH
- RH

Track Rollers

Carrier Rollers

Grouser Shoes