UNIT 15 PLANNING AND SCHEDULING OF PLANT OVERHAULING AND SHUTDOWNS

Objectives

After going through this unit, the students shall be able to

- Understand the overhauling decision of an equipment, plant or components
- Plan and prepare schedule for plant shutdown
- Determine the interval between equipment overhaul, optimal overhaul cost limit and procedure of plant shutdown
- Get introduced with network planning method applied for planning and control of maintenance

Structure

15.1 INTRODUCTION

Overhauling of plant and equipment is a necessary task and has to be carried out periodically to restore the plant, or equipment, to a satisfactory working condition, or as nearly as possible to 'as good as new' condition, and also to reduce the incidence of unexpected failures. Although the primary intent of overhaul is restorative in nature, it is a preventive maintenance activity, since it is not carried out after a failure. Because it is essentially a restorative activity, in some industries in India, an overhaul goes by the name of 'capital repair' or 'capital maintenance'. Overhauls cannot be carried out while the plant, or equipment, is running, and accordingly, necessitates plant shutdowns. These are two aspects of planning and scheduling of plant and equipment overhauls and shutdown (note: these two aspects are two distinct parts of the job, one quite different from the other). The first one is the scheduling of plant and equipment overhauls, that is, deciding when to carry out the overhaul. Once the optimal overhaul interval, or the timing of overhaul is determined, the second aspect is one of planning the task of overhaul and scheduling of its numerous constituent activities. The second part of the job, that is, detailed planning of plant shutdown is as important as the decision of scheduling of overhauls, since overhauls are large and complex tasks and generally take a significant amount of time.

Both these aspects of planning and scheduling will be discussed in detail in this unit. The overhaul decision, that is, the problem of scheduling of overhauls will be discussed first, and thereafter, the job of detailed planning of overhauls and plant shutdown and scheduling of the numerous constituent activities will be discussed. However, before we can take up the discussion of planning and scheduling of plant and equipment overhauls and plant shutdowns, we must discuss the basics of maintenance. Thus, under introduction, we will take up for discussion the different types of maintenance first, and this will be followed by a discussion of preventive maintenance, and overhauling and overhaul decision.

15.1.1 Types of Maintenance

Maintenance was, till recently, synonymous with repair and consisted of breakdown maintenance. Then come preventive maintenance which took the forms of (i) routine activities like oiling/greasing, cleaning of the machine, the internals and the working surfaces, (ii) periodic replacements of wearing parts, which are not capital items. (iii) programmed replacements of bearings and other items with pre-determined lives, and (iv) periodic overhauls. Such routine maintenance, or periodic preventive maintenance, is based on the assumption that mechanical failures and the process of deterioration of components depend only on the running time of the machine. The limitations of periodic preventive maintenance are as follows:

i) This system of maintenance does not give full protection against breakdowns. This is particularly applicable to random failures possible due to random fluctuations in the plant operating conditions and if random failures are predominant, then periodic preventive maintenance, by itself, has no positive effect on reliability and plant availability.

ii) Some of the maintenance actions are unnecessary and sometimes the plant is maintained too frequently resulting in a corresponding loss of production.

iii) The components are, in many cases, not allowed to run till the end of their mechanical life and are replaced, at times, too early.

iv) Increased number of running-in failures caused by periodic overhauls, since incorrect assembly may occur during servicing and this is one of the principal arguments in favour of condition-based maintenance. Bhadury and Basu, in their report of the study conducted on a 210 MW thermal power unit [2], have noted the existence of a period of running in after a capital maintenance shutdown.

Since the failure rate of components is dependent on a combination of number of factors such as load fluctuations, lubrication, quality of materials used, quality of workmanship, environmental conditions etc., even for same or similar components, depending on the application and working conditions, the resultant life varies. However, failures are caused by processes of accumulation of damages to the components and such processes give rise to gradual changes in the physical properties of the component. Thus observations of specific parameter(s) rationally should make available such information through the analysis of which it is possible to predict the failure of the component. Such indicative parameters are called prognostic parameters and the basis of predictive maintenance, also called predictive preventive maintenance or condition-based maintenance, is the observation, measurement and analysis of these prognostic parameters. In some cases the observation of the prognostic parameter(s) can be done while the equipment is running, while in some other cases, the observation of the condition can only be carried out after the machine is stopped. The monitoring methods generally used are visual, performance monitoring, vibration monitoring, sound-level monitoring and wear-debris monitoring.

In the last fifteen years, vibration monitoring has become an important technique and is very widely used on rotating machines. However, condition-based maintenance should only be used for critical equipment and is not recommended for all the machines or equipment, which make up a plant. Since in large and complex process plants, random or incipient failures cannot be totally avoided and condition-based maintenance is either not feasible or cost-justifiable on all the equipment, the maintenance programme has to be a mix of emergency repairs or breakdown maintenance, planned maintenance periodic or routine preventive maintenance and condition-based maintenance, and this mix must be based on the analysis of past failure data, inferences drawn from condition monitoring data, as well as plant factors, which will dictate the necessity of stand-by units, production factors indicating the 'production windows' available and maintenance factors like availability of skilled tradesman, level of stock of spares and lead-time for procurement of spares.

Next, let us examine the formal definitions of maintenance, corrective maintenance, preventive maintenance and planned maintenance to see whether we can classify maintenance, identifying therein the various types of maintenance activities discussed earlier. Maintenance has been defined to include 'all work undertaken to keep or restore every facility to a specified acceptable condition', whereas corrective maintenance has been defined as 'that maintenance work which is performed to restore an item to a satisfactory condition after a failure' and preventive maintenance as 'that maintenance activity which is performed to keep or retain an item to a satisfactory operational condition'. Thus we may classify all maintenance activities under two main heads, namely corrective maintenance and preventive maintenance. This classification is along the lines of the accepted definitions, which are 'restore to' and 'keep in' an acceptable condition to optimize productivity and utilization of scarce resources. But as per the above definition, corrective maintenance seems synonymous to emergency repair, or at best generally to breakdown maintenance. Moreover, as far as breakdown maintenance is concerned, the B.S. Glossary of Maintenance Terminology (B.S.3811, 1964) further defines the following terms:

Emergency Maintenance**:** Maintenance work necessitated by unforeseen breakdown or damage, and

Planned Breakdown Maintenance**:** Maintenance work which is carried out after a failure, but for which advance provision has been made in the form of spares, materials, labour and material.

Thus we find that breakdown maintenance can be in the form of emergency repair or planned breakdown maintenance, but in both these cases, the link is that the component or the equipment is allowed to run, without any maintenance, till it fails. However, corrective maintenance is not just breakdown maintenance and McBrady and Kier defines corrective maintenance as 'the study of all equipment failures and breakdowns to determine that action is needed to prevent recurrences' [8]. But this after all is an activity, which should appropriately come under planned maintenance, since planned maintenance had been defined as 'that maintenance activity which is organized and carried out with forethought, control and records' [4]. Moreover, 'planning in maintenance and setting up of tasks in order of priority' has been differentiated from preventive maintenance [3]. This means that planed maintenance is a part of corrective maintenance and must consist of all activities emanating from the analysis of breakdowns and all corrective maintenance jobs resulting from the preventive maintenance inspections, both on-line and off-line, as well as the activities of repair, replacement or modifications as indicated by the analysis of data obtained through condition monitoring. This classification is based on the percept that the activities of inspection and monitoring of equipment on the analysis of data thus obtained is, in today's context, preventive maintenance work, and activities such as priority fixation, planning of tasks and actual corrective actions taken should appropriately come under corrective maintenance.

Such a classification will be useful in structuring and organizing of the maintenance department as well, particularly of large process plants and integrated iron and steel-works, since the education, training, skills, and personal traits required for the job of maintenance analyst differ very greatly from those required for planners, on one hand and maintenance fitters/mechanics, on the other. The classification of maintenance showing the various types of maintenance therein is given in *Figure 15.1*.

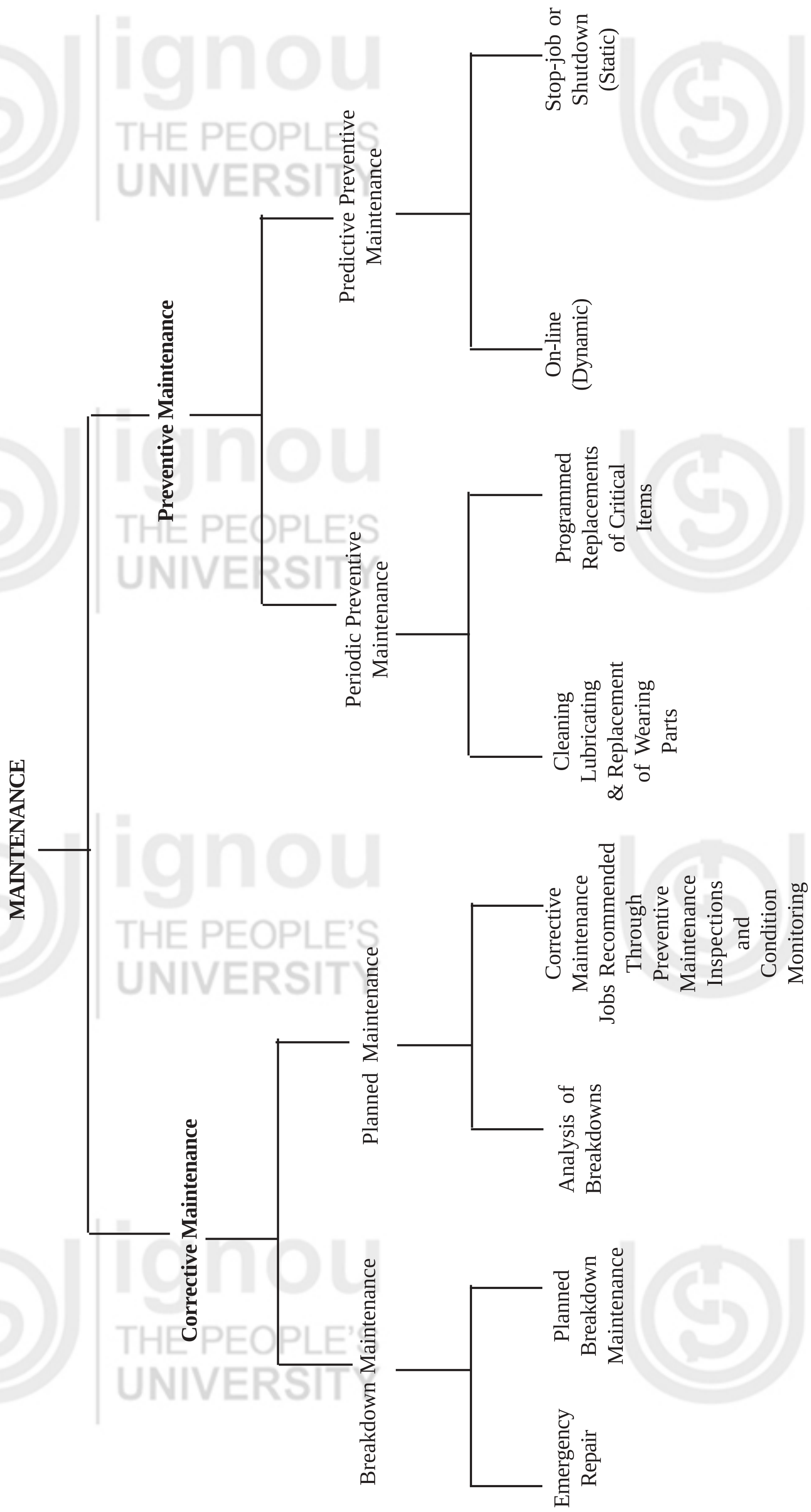

Figure 15.1 : Types of Maintenance

Activity A

Critically evaluate the equipment overhaul and plant shutdown procedure in your organization. What are the key steps followed in plant overhauling?

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15.1.2 Preventive Maintenance

Maintenance, as we have already noted, consists of all work undertaken to keep or restore, every facility that a manufacturing organization possesses, to a specified acceptable condition. Further, we have noted that preventive maintenance consists of such maintenance actions, which are performed to keep or retain an item of plant, equipment, or machinery in a satisfactory operational condition, whereas corrective maintenance consists of all maintenance actions, which are undertaken to restore an item of equipment to a satisfactory condition after a failure. Thus, broadly speaking, preventive maintenance is the total of all functions which are aimed at maintaining and improving, if possible, the reliability performance characteristics of assets in the form of plant, equipment and machinery. Preventive maintenance activities are undertaken because the cost of lost production from unexpected breakdowns is significant, and the cost of owning an asset is usually lower when the asset receives proper care during its useful life.

Preventive maintenance essentially includes periodic lubrication, replacement of wearing parts and capital items, like bearings, periodic adjustment and calibrations, if necessary, equipment inspection, and overhauls of equipment and machinery. Some authors sub-divide all maintenance activities, whether they be preventive maintenance or corrective maintenance jobs, as either running maintenance or shutdown maintenance; running maintenance consisting essentially of preventive maintenance activities which are carried out while the plant, or equipment, is running, whereas shutdown maintenance can either be preventive or corrective maintenance and consists of such activities which can only be performed while the plant, or equipment, is not running. Running maintenance activities are usually routine or periodic preventive maintenance activities like lubrication, running checks and tests on sub-systems and components, and minor adjustments which can be carried out while the plant is running. Running maintenance activities do not result in loss of equipment availability, and as such, all that is required is control to ensure that the necessary jobs are carried out timely. This control function can be carried out by first creating a periodic preventive maintenance activity file, based on engineering practices and manufacturer's recommendations, which lists all such activities for various equipment with the recommended periodicity/frequency, as for example, daily, weekly, or every 50 hours etc., and thereafter using this file to schedule these jobs on a weekly basis. Thus, in case of periodic preventive maintenance or routine maintenance, particularly of the running maintenance kind, there is no decision to be taken (however, in the case of routine, or periodic preventive maintenance, of the shutdown variety a decision is called for). Decision-making is necessary in cases of periodic replacements, periodic inspections requiring the shutdown of the equipment, and periodic overhauls.

Activity B

Define preventive maintenance. Is it different from Productive maintenance? Give examples.

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Activity C

Critically study your company's maintenance activities. Which one is in practice now: preventive or productive maintenance?

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15.1.3 Overhauling and Overhaul Decision

An overhaul of an equipment, or a system, involves subjecting the equipment and its components to strict inspection, readjustment and calibration or the equipment as required, replacement of worn components and servicing of the equipment, that is, cleaning of its components, greasing and replenishment of consumables, such as fuel, lubricating oil, compressed air etc. the overhaul action is taken to restore the equipment to a satisfactory working condition, or as nearly as possible to the ' as good as new' condition, to minimize the incidence of unexpected failures, but it is carried out before the equipment, or the systems, reaches a defined failed state. A decision to overhaul an equipment may be taken when the equipment operating and maintenance cost is found to be increasing, or, alternatively, when the equipment hazard rate shows a significant increase but this decision is taken when the equipment is working and not in a failed state. In some instances, the overhaul action may be preponed for the sake of convenience or the ease of operation, as for example, if the boiler is shut down due to a super heater tube leakage and the elapsed time from the preceding overhaul of the boiler is close enough to the statutory requirement, the power station may decide to carry out an overhaul of the boiler right after the repair of tube leakages. Thus although an overhaul is a restorative action, it is a preventive maintenance action* and not a repair, or a corrective maintenance action, since it is not carried out after an equipment failure.

In the case of continuous process plants, major systems, such as boilers or steam generation plants, are required to be overhauled at prescribed intervals as per statutory regulations. Thus in case of such pre-identified systems, there is no decision-making required in the sense that the interval is prescribed and the

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*Balaguruswamy [1] defines a preventive maintenance action as follows:

'Unexpected failures can be minimized by taking corrective measures at regular intervals of time. These are known as preventive maintenance actions'

Thus although an overhaul does involve some corrective work in the form of minor repairs and readjustments, it is essentially a preventive maintenance action.

management action consists of planning of resources necessary for the overhaul of the system required to be carried out at specified intervals. However, an equipment of the system, such as an air heater or a boiler feed pump, may deteriorate resulting in increased operation and maintenance cost. To reduce the total cost, which must include operation cost, cost of periodic overhauls, and loss of efficiency, and to minimize the incidence of unexpected equipment failures, the equipment may be overhauled at fixed intervals in between the system overhauls. Thus one of the decision problems involved is the determination of the interval between equipment overhauls and we shall discuss this problem first. There is also another decision problem and this is concerned with the determination of the optimal overhaul cost limit for an equipment. A decision to overhaul is taken to restore the equipment to the 'as good as new' condition but the overhaul of the equipment may or may not restore the equipment to the 'as good as new' condition whereas the replacement of the equipment will definitely restore it completely. Thus, at that time, a decision has to be taken as to whether to overhaul or replace the equipment. The degree to which an equipment is restored is a function of its age and this decision, namely whether to overhaul or replace, is taken on the basis of the estimated overhaul cost which, as stated is a function of its age. The estimated overhaul cost is compared with the overhaul cost limit and if it is less than the overhaul cost limit it is overhauled, otherwise it is replaced with a new equipment. The overhaul cost limit is the maximum amount of money which should be spent on overhauling an equipment of a given age and the problem then becomes one of determination of the overhaul cost limit which will minimize the total expected cost given that the equipments required to still operate for another n periods, say years. This problem will also be discussed.

The following decision-making problem has been discussed by some authors [6]:

The manufacturer of the equipment recommends that the equipment be overhauled every t_o time periods, say hours. After the acquisition of the said equipment, the user has meticulously recorded the necessary failure data and has derived good (dependable) estimates of the hazard rates of the critical failure modes. Armed with this knowledge and the manufacturer's recommendation of the overhaul interval, the user wants to determine the time between equipment overhauls. Thus, the problem is to determine the optimal overhaul interval, given that the equipment undergoes a complete overhaul either every t_o time periods or on failure, whichever occurs first.

If no failure occurs till t_o time periods, then quite obviously the equipment will undergo overhaul after t_o time periods. This is elementary, but the equipment user wants to protect himself against the undesirable event of an earlier failure. Let t_{ov} be the random variable representing the time between overhauls and let R(t) and f(t) be the equipment reliability and failure density functions, respectively. Then the mean time between overhauls (or the expected value of t_{ov}) can be found from the following equation:

$$\int_0^{t_0} \qquad (15.1)$$

If it is a case of constant hazard rate and the failure distribution is exponential, then

$$\int_0^{t_0} \qquad (15.2)$$

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*if the equipment hazard rate is decreasing, then overhaul becomes counter-productive since periodic overhaul may introduce new running-in failure modes.

Illustrative example: An equipment is scheduled for complete overhaul every 10,000 operating hours, or on failure. From relevant failure data, a constant hazard rate of 10^{-5} failures per operating hour has been obtained for the concerned failure modes. In this case, the mean time between overhaul will be:

$E(t_{ov}) = 10^{5}(1-e^{-0.1}) = 9516$ operating hours.

However, in practice one rarely comes across such a decision situation. Such reliable estimates of critical failure modes are generally not available, with the result that the decision to overhaul is brought on either by increasing operating and maintenance cost or sharply increasing hazard rate* (or both). As discussed, them there are two specific overhaul decisions, namely, determination of the optimal overhaul interval and optimal overhaul cost limit for a deteriorating equipment*.

Activity D

Visit a manufacturing unit and study the overhauling procedure followed there. What is the company's decision regarding the overhauling Vs replacement?

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15.2 SCHEDULING OF PLANT AND EQUIPMENT OVERHAULS

In this section, we will discuss the two overhaul decision problems noted above.

15.2.1 Determination of Optimal Overhaul Interval for Deteriorating Equipment

This problem deals with (and the models discussed can be applied to) an equipment of a continuously operating system (a process plant, say) in which the system is overhauled at fixed intervals as per statutory requirement and such system overhauls are called surveys (as discussed under section 15.3). Now the equipment of the system deteriorates with use, or operation, affecting the system operating and maintenance cost and the system efficiency. This equipment can be restored through periodic overhauls within this period between survey and the problem is the determination of the optimal overhaul interval for such equipment, which deteriorate with use. Davidson has presented a study which was conducted in a thermal power station in which the surveys on the boiler had to be conducted every fourteen months but within this period, deposits built up on the inside surfaces of the boiler affecting its efficiency [5]. To reduce the loss of efficiency, important parts of the boiler, such as air heater, economizer and super heater, could be thoroughly cleaned periodically and the study was conducted to determine the optimal overhaul interval of the air heater. Herein, we will discuss two possible decision bases, namely, one with the assumption that the interval between equipment overhauls is constant in as much as the system output between equipment overhauls is the same (and we shall also discuss a variation in which that time between equipment overhauls is kept constant) and the other in which this assumption is relaxed and a dynamic programming model is formulated.

The cost of an equipment overhaul consists of costs of labour and material required and can be estimated reasonably well. The equipment overhaul cost can be taken as constant, and let the overhaul cost be Cs*. Since the equipment deteriorates with use, the cost of operation and maintenance increases with use and can be taken to be a function of m, the system output, in terms of kilograms of steam generated etc., and in our case m is the system output upto the previous equipment overhaul. Therefore, the cost of operation or use for a system output of q units between equipment

overhauls is Cu= We now consider an overhaul policy in which Q kgs of

steam (or any other kind of system output) is produced between surveys, or system overhauls, with n equipment overhauls equally spaced in terms of system output, that is, the interval between overhauls is the same in each case. We thus assume that the interval between equipment overhauls is constant, that is, $q_1 = q_2 = q_3 = \ldots q_{n+1} = q$ as shown in Fig.15.2(a). Since there are n equipment overhauls in the period between surveys, there are (n+1) equipment overhaul intervals, and we have C(q), total cost = total cost of equipment overhauls +total cost, between surveys, of equipment operation

$$= n.C_s + (n+1)C_u$$

$$= n.C_s + (n+1) \qquad (15.3)$$

Now Q = (n+1).q and therefore, n = 1

So, C(q) = Cs (15.4)

Where Q = system output in the period between surveys,

q = equipment overhaul interval, that is, overhaul after q units of system output (as for example, q kgs of steam produced),

Cs = Cost of one equipment overhaul, and

Cu = = cost of equipment operation between equipment overhauls.

Since the equipment of the system deteriorates with use, there is a loss of system efficiency, which, in turn, affects Q, the system output between surveys. Thus Q may vary but past records provide enough information for its estimation, which can be the mean or expected value. Alternatively, two or more representative values of Q as for example, the maximum, minimum, and median/mean values, can be used in equation (15.4), which will then give two or more optimal values of q.

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* we have used the subscripts s to denote service (which, in common parlance, is used for overhaul) since the subscripts 0 is generally used to denote an optimal cost, quantity or item.

Equation (15.4) is the model of the problem relating the equipment overhaul interval q to the total cost between surveys. The optimal value of q is the value of q which minimizes C (q) as given by equation (15.4) and for this we have to differentiate C(q) with respect to q and equate it to zero. As is evident, the optimal value of q will depend on the form of Cu, the equipment operating cost. Herein, we may consider two possible forms namely:

i) Linear trend in equipment operating cost, f(m) = a + bm, and

ii) Modified exponential trend in equipment operating cost, $f(m) = A\text{-}Be^{-km}$.

Although the linear trend comes to mind first, herein as well it is felt that modified exponential trend will be more appropriate since the equipment operating cost will probably increase with increasing system output, m, up to a point, which is its maximum value, and then tend to level off. Davidson had also found that the case data on the air heater also fitted this form (5). In case the linear trend in equipment cost is found to be appropriate, that is, the available data on m and equipment operating cost is found to fit the form f (m), equipment operating cost = a + bm, then the optimal overhaul interval.

(15.5)

However, in case the modified exponential trend in equipment cost between equipment overhauls is found to be more appropriate, that is, the available data on m and the equipment operating cost is found to fit the form, $f(m) = A\text{-}Be^{-km}$, then q_o, the optimal overhaul interval can be found from

$$+ \left(\frac{B}{k}\right) e^{-kq_0} \left|\left(\frac{B}{k}\right) e^{-kq_0}\right| \left(\frac{B}{k}\right) e^{-kq_0} \; C_S \quad Bq_0 \quad {}^{-kq_0} \qquad (15.6)$$

Before we discuss the model in which the equipment overhaul interval is not necessarily kept constant, let us consider a possible variation of the model discussed above. Now there may be situations in which the system efficiency is not affected and the system continues to produce at its rated capacity but the system operating and maintenance cost increases due to the increase in the operating and maintenance cost of its constituent equipment which points to the fact that the equipment operating and maintenance cost, and, therefore, the system operating and maintenance cost, can be effectively reduced by carrying out equipment overhauls at fixed intervals of time in between two successive system overhauls, or surveys. Herein, please note that in the earlier model, we had considered a system, namely, a boiler, in which there existed a loss of system efficiency as well as an increase of the system operating and maintenance cost between system surveys. We will not consider a system in which there is not loss in system efficiency but the system operating and maintenance cost increases with increased use and such systems do exist in practice. In this case, therefore, the equipment operating cost is a function of time, or $C_u = f(t)$, and we are required to find the optimal equipment overhaul interval wherein equipment overhauls are carried out at fixed intervals of time, t_s. We are, therefore, required to determine the optimal value of t_s. For the derivation of the model of this case, referring to Figure 2(a), we find that instead of Q we not have T and since the times between equipment overhauls is constant, $q_1 = q_2 = \ldots = q_{n+1} = q$ is replaced by $t_{s(1)} = t_{s(2)} = \ldots = t_{s(n+1)}$ = ts. Therefore, in this case,

a) Constant Interval between Equipment Overhauls, that is, q, Steam Generated between Equipment Overhauls = $q_1 = q_2 =$ ....q_{n+1}

(b) Variable Interval between Equipment Overhauls - Dynamic Programming Formulations

Figure 15.2 : Determination of Optimal Overhaul Interval for Deteriorating Equipment

$C(T_s)$, total cost = total cost of equipment overhauls + total cost between surveys of equipment operation

$$= n\,.C_s + (n+1)C_u$$

$$= n\,.\,C_s + (n+1) \qquad (15.7)$$

also, $T = (n+1).t_s$ and therefore, $n = \quad 1$

$$\text{So, } C(t_s) = Cs \qquad \int_0^{t_s} \qquad (15.8)$$

Where T = time between surveys,

t_s = equipment overhaul interval, in time units,

C_s = cost of equipment overhaul (as before), and

C_u = cost of equipment operation between equipment overhauls = $\int_0^{t_s} f(t)\,dt$ (15.9)

Herein if we use the linear trend in operating cost, namely, f(t) = a + bt, the optimal equipment overhaul interval,

ified exponential trend in operating cost, namely, with f(t) = A - alue of the equipment overhaul interval, t_s can be found from

$$\left(\frac{B}{k} - C_s\right) = \left(Bt_s + \frac{B}{k}\right)e^{-kt_s}$$

$$t_s \quad 0 \qquad -kt_s \qquad (15.10)$$

Next we consider a decision base in which the equipment overhaul interval is allowed to vary, that is, the overhaul intervals are not necessarily kept equal. This is possibly a more realistic alternative in cases where use or operation results in a loss of system efficiency as well as an increase in the system operating and maintenance cost since the system itself deteriorates with use and influences the system operating and maintenance cost. This model is also based on the assumption that Q kgs of steam are generated between surveys with the basic difference that the n equipment overhauls need not be equally spaced as shown in Figure 15.2(b). The objective is to determine an overhaul policy, which will minimize the sum of the total costs of equipment overhauls and equipment operation between surveys. Now, let f_Q be the sum of the total equipment overhaul cost and total equipment operating cost incurred to generate Q kgs of steam starting with a fully restored system, namely, a boiler, and using an optimal overhaul policy. Further, let us consider the case where the final, or the nth, equipment overhaul occurs at a point where m kgs. of steam have already been generated by the system as shown in Figure15.2 (b). The problem then becomes one of determining m and $(q_1, q_2, \ldots, q_n)$ such that the sum of the total cost of generating m kgs. of steam, the operating cost incurred for generating the remaining (Q-M) kgs. of steam and the equipment overhaul cost is a minimum. Thus we can now write a functional equation, which is of the form:

F_a – (15.11)

Where f_m = sum of the costs of equipment overhauls and operation for generating m kgs. Of stream, or m unit of system output.

= (n-1). Cs + n

Also the end condition is f_o(that is, with Cs(m)=0 at m =0, and otherwise =C_s

Also the end condition is f_o (that is, with m = 0) = 0. Using the functional equation (15.11) and inserting derived values of F(m) dm, given, for example, that f(m) = A–Be^{-km} as before, and C_s (m) enables a numerical solution to the problem to be found. For this, given a value of Q, the various possible values of q need to be considered at every recursion. The use of the model has been illustrated by Davidson in his paper, wherein, for example, given that Q = 600 × 10^6 kgs. Of steam, he has used q values of 20,40,60 and 80 kgs. of steam to derive the optimum number of overhauls [5]. As is obvious, in this case, initially the equipment overhaul intervals will be farther apart and will decrease with use, that is, with increase in the value of m.

The models discussed in this section are based on the fundamental assumption that a preventive maintenance action in the form of overhaul restores the equipment fully, that is at least to as good as it was at the beginning of the period. However, an equipment overhaul may only restore the equipment partially and the degree to which it is restored is a function of its age, that is, the elapsed time from the previous overhaul/replacement. Thus one has to decide whether to overhaul the equipment or to replace it and this decision is based on the overhaul cost limit, and we shall discuss the determination the optimal overhaul cost limit in the next section.

Activity E

Visit a manufacturing unit. Take the maintenance statistics from the last 5 years. What is the trend observed in regards to its maintenance cost? Does the trend change after the plant / equipment/ component overhauling?

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15.2.2 Determination of Optimal Overhaul Cost Limit for Deteriorating Equipment

Wherever the owner of a vehicle takes his vehicle for a major overhaul, he always compares the estimated cost of overhauling the vehicle with some sort of an overhaul cost limit, which is essentially his bound, or his notion of the maximum amount of money that should be spent on overhauling the vehicle. Now the cost of overhauling the vehicle is a function of its age and at the same time, his decision on whether to overhaul or replace the vehicle depends on (i) the period of time, or the number of years in the future, for which the vehicle is required to be operational, and (ii) the cost of acquisition of a new vehicle. Thus the overhaul cost limit is determined so that the total cost of operation and overhaul over a fixed period of time in the future is minimized. Therefore, given the estimated overhaul cost for equipment of different ages and also the fixed future period of time over which the equipment is required for use, the problem is to determine the optimal overhaul cost limit. For the derivation of the model, let

n be the number of periods for which the equipment is required for use,

I the age of the equipment at the beginning of the period,

J the age of the equipment at the end of the period and referring to Figure 15.3, note that J = I+ 1 if the equipment is overhauled and otherwise J=1 since the decision then is to replace it,

f_I (c) the probability density function of the estimated overhaul cost for equipment of age I, and L_I the overhaul cost limit for equipment of age I, and

P the cost of acquisition of a new equipment, that is, the cost of replacement.

From Figure 15.3, we see that there are two possible decisions, namely, that given an estimated overhaul cost C, there is a probability $P_{I, I+1}$ that $C \leq L_I$ in which case the decision is to overhaul the equipment, and a probability $P_{I,1}$ that $C > L_I$ and if $C > L_I$, the equipment is replaced at the end of period I. Also it may be noted that as per the statement of the problem we are assuming that the time required to effect an overhaul, T_s, or a replacement, T_r, can be neglected. This is a reasonable assumption since the model is being formulated for a problem of whether to overhaul or replace [illegible] n estimated cost of overhauling the equipment. Now that we [illegible] d L_I, we can define m_I (L_I), which is the mean overhaul cost [illegible] with an overhaul limit of L_I given the $C \leq L_I$.

$$\int_0^{L_I} f_I(c)\,dc + P\left(1 - \int_0^{L_I} f_I(c)\,dc\right)$$

$$\int_0^{L_I} f_1(c)\,dc$$

Therefore, $m_I(L_I)$ = (15.12)

Next, we define f_n (I) as the minimum expected total cost of overhauling and replacing the equipment over n periods in the future starting with an equipment of age I. Thus the objective is to determine the overhaul cost limit L_I such that the minimum expected total cost f_n(I) is achieved. Let C_n(I,J) be the expected cost of the first decision with n periods still left and starting the equipment of age I. Therefore,

C_n (I,J) = expected cost of overhaul x probability that the overhaul cost is less than or equal to the overhaul limit + cost of replacement x probability that the overhaul cost is greater than the overhaul limit.

= m_I (L_I) (15.13)

For convenience of notation, let $\int_{o}^{C^t}$ $F_1(L)$

Therefore, C_n (I,J) = $m_I(L_I)$. $F_I(L)$+P {1-$F_I(L)$} ….(15.14)

Now we define $f_{n-1}(J)$ as the minimum expected total cost over the remaining (n-1) periods, and we get,

$F_{n-1}(J)$ = minimum future cost if equipment is of age (I+1) × probability that the overhaul limit was not exceeded at time n + minimum expected future cost if equipment is of age 1 x probability that the overhaul limit was exceeded at time n

= f_{n-I} (I+1). F_I (L) + f_{n-I} (1){1-$F_I(L)$} ———(15.15)

Therefore, the expected total cost over n periods in the future starting with an equipment of age I

=C_n (I,J) + f_{n-1} (J) —— (15.16)

Moreover, since the objective is to minimize this total cost by the selection of appropriate overhaul limits, $f_n(I)$ can be written in the form of a recurrence relation as follows:

$f_n(I)$ = min {C_n (I,J)+$f_{n-1}(J)$}

= min {m_I (L_I). $F_I(L)$ + P{1-$F_I(L)$}+ f_{n-1}(I+1). $F_I(L)$ + f $_{n-1}$(I){1-$F_I(L)$}

for $n \geq 1$ ……..(15.17)

with $f_0(I) = 0$ for all values of I (since n = 0)

Figure 15.3 : Determination of Optimal Cost Limit

From the recurrence relation of equation (15.17), given the probability density function of the estimated overhaul cost for an equipment of age I, I= 1,2,3, …., (n-1) and the cost of acquisition of a new equipment, one can determine the optimal overhaul cost limits for the equipment. The dynamic programming model discussed above is taken from Jardine [7] and provides a very useful basis for decision-making. In practical situations, however, there are a few other considerations, which also affect decision-making. One very important consideration is the availability of funds. Sometimes the cost of replacement and consequently difficulties encountered in making adequate budget provisions is an important hurdle. In such instances, it may be worthwhile to consider the reconditioning and retrofitting of the available equipment since one can reasonably expect that the cost of reconditioning and retrofitting will be significantly lower than the cost of a new equipment and if a good job of reconditioning and retrofitting is done, the equipment, in more instances, will be as good as a new equipment. Accordingly, then the decision is whether to overhaul (in house) or to recondition and retrofit the equipment, and P, in that case, is the cost of reconditioning and retrofitting the available equipment.

Before we conclude our discussion of overhaul decisions, an important point needs our attention. Jardine has discussed a combined overhaul/repair policy for equipment subject to breakdowns and has formulated a very refined dynamic programming model to minimize the total expected cost over n periods of time in the future [7]. The model is similar to the one discussed above except for the fact that it uses discrete transition probabilities. The model is based upon the tenet that if an equipment at the beginning of a period is operational, that is, in 'good' state, the decision then is either to repair or replace it. The essential point here is that the first problem of overhaul vs. replace has already been discussed in the earlier model (that is, the one on optimal overhaul cost limits) and the second problem of repair vs. replace is rather theoretical in its treatment since replacement decisions, both for capital equipment and unit machines, are taken on different considerations (generally based on engineering economic analysis). Also one must appreciate the fact that an overhaul action involves quite a bit of repair in addition to readjustment, calibration, servicing, and replacement of worn components so much so that in many Indian industries, overhaul is termed as capital repair. Moreover, the replacement decision for capital assets, in the form of plant and equipment, is a major decision and in case an equipment can be restored, even partially, by an overhaul action, then overhaul is actively considered. Thus for an equipment with high frequency of failure and/or low availability, or significantly increasing hazard rate, or with increasing operating and maintenance cost, when a major failure occurs, one of the decisions which may be considered is to subject the equipment to an overhaul after attending to the repair job. At this point, the decision-making comes down again to one of overhaul vs. replace.

15.3 PLANNING AND SCHEDULING OF PLANT SHUTDOWNS

Usually periodic overhauls of plant and equipment constitute major plant shutdowns, and these jobs pose planning problems, which are quite different from those for the normal workload of the maintenance department. Plant shutdowns are essentially projects, since they are (i) non-routine, large and take significant amount of time, and (ii) complex consisting of a multiplicity of inter-related activities which must be executed in a defined order for completing the entire task. All these activities have to be carried out in a coordinated manner. Therefore, plant shutdowns must be recognized and managed as separate undertakings calling for different methods of planning, scheduling and monitoring of progress.

Figure 15.4: Barchart - Overhaul of Furnace

Accordingly, project planning, methods are generally used for planning of maintenance shutdowns. A wall-mounted bar chart, as shown in *Figure 15.4*, may be quite adequate for planning a plant shutdown with upto 50 activities. However, major plant shutdowns may involve upwards of few hundred activities, and many tens of these activities may be simultaneous. Network planning method is used for planning these shutdowns. Moreover, for smaller shutdowns, such network analysis may be manual with extraction onto a bar chart to facilitate control. However, for large projects, network planning and associated scheduling and control must be computerized.

15.3.1 Basics of Project Planning

A project is a collection of inter-related activities, which must be executed/performed in a defined order, with well-defined start and finish times, for completing the entire task to accomplish a specified objective that fulfills the needs of the organization. A project is characterized by the existence of precedence relationships. Some activities cannot be performed until some preceding activities have been completed. (The activity that has to be performed just before a particular activity is its predecessor activity and the one that immediately follows it is its successor activity). This requirement establishes a technical precedence relationship. Other activities may be performed independently. Thus together with precedence relationships, in a project certain activities can be done simultaneously, if the resources permit. Task independence (exemplified by parallel/simultaneous activities) and precedence relationships need to be indicated on the project network and incorporated into the job plan.

Kelly and Walker developed the critical path method (CPM) for project planning and scheduling in 1959. In CPM, the following assumptions are made:

1. All time estimates are deterministically known for every activity of the project.

2. The precedence relationship is known for all the activities.

3. The project can be represented as a directed graph in which the time (or cost) estimates are deterministic, and the longest path of the network is the indicator of the project duration (also called its critical path).

A path is a chain of sequential activities beginning at the project's start and ending at its completion. In a project network, several, or many, paths may exist, and all the activities, and hence all the paths, must be completed before the project is finished. The path, which has the longest expected elapsed time, will determine the completion date of the project. This path is called the critical path of the project. The assumption of deterministic activity times can be relaxed with the use of the program evaluation and review technique (PERT), which was developed by the U.S. Navy in 1964. PERT deals with probabilistic activity duration, and uses three time estimates for each activity, namely, its optimistic, most likely, and pessimistic times. The mean time of the activity is then derived from these three time estimates, using the Beta distribution approximation.

The analysis of a CPM, or PERT, network is done by the use of critical path analysis (CPA).

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*Kelly uses this term in his well-known book on maintenance planning and control. The student is strongly advised to refer to this book (details are given under bibliography). However, the student's attention is drawn to the fact that A-O-N representation is used in this book (chapter 9: Planning and Scheduling of Plant Shutdowns). This Kelly is not the same person as the enunciator of CPM.

The general methodology of CPA is as follows:

Step 1: Break up (Conceive) the project in terms of specific activities and/or events. Determine the time of each activity.

Note: in CPM, it is a deterministic estimate, and in PERT, it is probabilistic with three estimates, as noted above.

Step 2: Establish the interdependence and sequence of specific activities (also called precedence relationship, as noted above).

Step 3: Prepare the network of activities and/of events. *

Step 4: Assign time – estimates and/or cost-estimates to all the activities of the network.

Note: In PERT, these are the mean activity times derived from the optimistic, most likely and pessimistic estimates.

Step 5: Identify the longest path (time-wise) on the network. This is the critical path of the network, and project completion time equals the critical path time (sum of times of activities on the critical path)

Step 6: Determine slack (or float) for each activity, not contained on the critical path.

Note: The activities on the critical path do not have any slack time.

Step 7: Use regular monitoring, evaluation and control of the progress of the project by preplanning, rescheduling and relocation of resources, such as manpower, funds etc., as needed.

From Step 5, we find that the critical path determines the project completion time and activities on the critical path do not have any slack. This stresses the following points:

1. If any activity on the critical path gets delayed by t_{ij} time units, the total project will be delayed by t_{ij} time units. Strict monitoring is essential for these activities.

2. Since activities which are not on the critical path have some slack time associated with them, from time to time, some resources from these activities can be diverted to the activities on the critical path.

3. If the total project time needs to be compressed (shortened), then quite obviously one has to focus on the activities on the critical path. The times of some of these activities can be compressed (reduced) by deployment of additional resources. This is called crashing; and the project duration can be effectively crashed by the use of additional resources selectively on the activities on the critical path.

An example of a small project network is shown in Fig.15.5. The identification of the critical path, in step 5, necessitates the calculation of the earliest expected and latest expected times of all events, or nodes, of the network, given the duration of all activities of the network (all t_{ij} 's). Forward pass is used for the calculation of the earliest times and backward pass, or backward calculation, is used for the latest times of the nodes. From these two, the earliest start time (EST), latest start time (LST), earliest finish time (EFT) and the latest finish time (LFT) of all the activities have to be determined. These, I turn, enable the determination of slacks (or floats) and the identification of the critical path. We will not discuss the method of calculation of these times in this unit.

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*Two kinds of networks are in use, namely, activities-on-arcs (A-O-A) and activities-on-nodes (A-O-N). of these two, a-O-A is more commonly used.

Figure 15.5 : Activity Network — Small Project of Seven Activties

15.3.2 Network Planning for a Maintenance Shutdown

Hereinunder, we will discuss two aspects of the use of network analysis for planning and monitoring of maintenance shutdowns. In the first paragraph, we will highlight certain points with regard to the use of the CPA methodology, and in the second, we will discuss two practical situations wherein network analysis can be most effectively used for planning and monitoring of plant shutdowns.

The first three steps of the CPA methodology are usually done together and constitute the first stage of the use of network analysis. The output of this stage is the activity network, or the logic diagram*, of the maintenance shutdown (project network). State one starts with the preparation of the list of activities, which will constitute the shutdown. This requires careful enquiry and detailed discussion with the concerned personnel.

The points to remember here are the following:

i) each activity must have a well-defined (and recognizable) start and finish, and

ii) although an activity usually consumes both time and resources, there exist some activities which consume only time (a example is 'waiting for paint to dry').

Then the relationships between the activities are identified and noted clearly on the activity list. This list forms the basis on which the network, or logic diagram, is drawn. While drawing the network, please keep in min that an activity cannot start till all its Predecessor activities have been completed, and the network start with the first node (first activity is 1-2) and ends with the last node (final activity is (n-1) –n). With the network drawn, in the second stage, the activity durations, or times, are obtained, noted on the list of activities and incorporated in the activity network. The estimates of the activity times can be obtained either through discussions with maintenance engineers, supervisors and mechanics, or through comparative estimation (estimating using benchmarks, which have earlier been developed through the use of pre-determined time standards (PMTS) or time study) (please refer to appendix 4 of Kelly's book). In cases where one deterministic time is difficult to estimate and quite a few things can go wrong (and this is often the case with maintenance jobs), three estimates- optimistic, most likely and pessimistic- can be obtained, as noted earlier, and the means activity time can be derived there from. In stage 3,the EST, LST, EFT, and LFT for all the activities are calculated with the help of the activity times/ durations, and the critical path is identified. Thereafter, with the help of the plan from this network analysis, regular evaluation and monitoring of progress are initiated, and resource leveling and crashing, as needed, can also be taken up.

There are two important situations encountered in practice. In plant shutdowns of short durations, time is the largest constraint and generally the availability of necessary resources does not present much problem. So the first situation is one of unlimited resources and limited time. On the other hand, in case of large shutdowns, usually we have the case of limited resources and/or limited time (in many cases, both). In the first case of unlimited resources, the control of project duration is comparatively simpler and is attained through the control of activities on the critical path and use of float on the non-critical activities. The objective here is to ensure that the activities on the critical path are started and finished at the earliest, and the distribution of resources, say manpower, in order of criticality can also help in the attainment of this objective. The total shutdown time in short duration shutdowns can be reduced by applying extra resources on the activities on the critical path. The progress of work can be better displayed through the use of a bar chart, and accordingly, bar charts are used for short duration plant shutdowns. The necessary bar chart is extracted from the updated activity network. The use of network analysis is most effective in longer duration plant shutdowns. Bar charts cannot be used in these projects because of the exceedingly large number of activities. More importantly, network analysis enables an objective analysis of resource requirements for the constituent activities. Resource leveling can be done with the aim of ensuring that the shutdown duration does not extend beyond the planned project duration (namely, the critical path completion time). Selective crashing is also enabled and through such selective use of additional resources, wherever possible, the incidence of time overruns can be significantly reduced.

Activity F

Explain how does CPM/PERT help in long duration maintenance shutdown. Make a shutdown schedule of an equipment in your organisation using CPM/Pert technique.

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15.3.3 Advantages of Computerized Network Planning

Network planning of large plant shutdown should be computerized, and in industries, nowadays, it is normal practice to use computers for planning and monitoring of large shutdowns. According to Kelly, use of computer is justified if either the shutdown is purely time limited and the number of activities in the network is greater than 250, or if the shutdown has resource constraints but is not time limited and the number of activities is greater than 150. Given that computers are much more accessible and affordable nowadays and the cost of computer time has also not increased significantly, it is worthwhile considering the use of computers even for smaller projects, say, with or without resource constraints and with more than 100 activities in the network (in the author's opinion, in real life situations, time is constrained in all cases) the advantages of computerized network planning include, among others, the following.

i) Very high speed and accuracy.

ii) Fast access and easy retrieval of data for control purposes.

iii) Updation of the network and availability of printouts (or updated data) within a very short time.

iv) Optimization of resource utilization, particularly in large networks.

v) Generation of various management reports, as necessary.

Activity G

Review maintenance software of your organization. Critically evaluate its features and limitation. Give suggestion to improve upon the existing maintenance software.

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15.3.4 Establishment of a Shutdown Programme

Planning of a plant shutdown consists of the following activities:

1. Preparation of the shutdown and start-up procedures (listing of operations in proper sequence together with cautions and special instructions, if any).

2. Preparation of a preliminary activity list and breaking it down under trades and disciplines, such as mechanical, electrical, piping/hydraulic/pneumatic etc.

3. Preparation of the detailed activity list and estimation of activity times and resource requirements.

4. Definition of precedence relationships and construction of the activity network.

5. Network with the maintenance contractor and manpower contractor, as needed (note: some of the activities may be subcontracted and for some unskilled and semi-skilled jobs, manpower may be obtained from a labour contractor).

6. Negotiation with the maintenance contractor and manpower contractor, as needed (note: some of the activities may be subcontracted and for some unskilled and semi-skilled jobs, manpower may be obtained from a labour contractor).

7. Carrying out preparatory work.

8. Assembling/collecting necessary tools and tackles, and protective clothing, as needed.

Note: the monitoring and review of progress (control of the shutdown project) is taken up once the actual shutdown commences.

For large shutdowns, planning takes a long time, and must be started 8 – 10 weeks (around 50 working days) before the shutdown is due to start. Accordingly, an essential prerequisite of a formal system of planning of individual shutdowns is an annual plan showing the timing of each of the major shutdowns. The most important features of the 50-day planning programme are as follows:

1. A formal meeting of the management to decides (and agree on) the extent of the shutdown (planned scope of work).

2. Availability of a good data retrieval system of estimating activity times and resource requirements/loadings for standard repetitive activities.

3. Active association of personnel responsible for implementing the shutdown. The planning engineers must encourage these persons to comment on the construction of the activity network/logic diagram for their particular areas of work.

4. Availability of computer service/computing facilities.

5. Availability of adequate arrangements for issuing work orders and for monitoring of progress.

6. Proper planning and control of preparatory work.

Monitoring of progress, issue of necessary job instructions, as and whenever needed, review of activities and updating of the activity network are the basic activities, which ensure the proper implementation of the detailed programme. The monitoring of progress should be done on an hourly basis, and progress reports should be delivered to the Central Planning Office/Maintenance Planning Bureau every two, or four hours.

The progress report must contain he following information:

i) estimated completion times for all 'life' activities,

ii) actual completion time of activities,

iii) review of pending activities,

iv) excesses or shortfalls on resources, and

v) additional work arisen, or expected to arise.

The report should be checked by the planning engineers, and the content of the report should be registered on the bar charts. Any additional work, which arises, must be planned, that is, broken down into elements, and durations and resource requirements must be estimated. If the deviation from plan is small and can be corrected, then there is no need for updating the network and bar chart(s). If, however, a major unforeseen activity comes up, then this should be adequately analyzed, as noted above, and incorporated into the plan, superimposing it on the computer print out and bar chart(s). The allocation of resources will be a difficult problem. Herein, reference should be made on the 'float' or 'slack' available, and manpower should be transferred from the activities, which have the most slack. Large deviations from plan can be avoided by strict monitoring and review of progress and timely corrective actions. Otherwise, if unattended, small deviation can grow into large disasters, which can cause time and cost over-runs.

15.4 SUMMARY

An overhaul of an equipment, or a plant, involves subjecting the plant, or equipment, and its components to strict inspection, and this is followed by readjustment and calibration of the equipment as required, replacement of worn components and servicing of the equipment. Overhauling is done to restore the equipment to a satisfactory working condition and to minimize the incidence of unexpected failures, but it is carried out before the plant, or equipment, fails. A decision to overhaul an equipment may be taken when the equipment operating and maintenance cost is found to be increasing, or alternatively, when the equipment hazard rate shows a significant increase, but this decision is taken when the equipment is working. Thus although the aim of plant and equipment is restoration, overhaul is a preventive maintenance activity since it is not carried out after an equipment failure.

Overhaul of plant, or equipment, invariably calls for shutdown, and the plant, or equipment, in question has to be shut down during the period of its overhaul. Thus the decision to overhaul is an important decision. Determination of the interval between equipment overhauls has been discussed, followed by the problem of determining the optimal overhaul cost limit for a plant, or an equipment.

Overhauling of a plant, or equipment, is a non-routine task consisting of a large number of inter-related activities, which must be done in a defined order for completing the entire task of overhaul. Thus plant and equipment overhaul takes the form of a project-usually a large and complex one. Moreover, plant shutdowns result in a loss of productive capacity and this implies that all shutdowns of plant and equipment must be adequately planned and monitored so that the task of overhauling is executed efficiently. Network planning methods can be effectively applied for planning and control of maintenance shutdowns.

15.5 SELF-ASSESSMENT QUESTIONS

1. Overhauling of plant and equipment constitutes an important part of the preventive maintenance effort of a manufacturing organization'. Discuss.

2. 'Plant shutdowns for equipment overhauls need to be adequately planned'. Why? What will happen if this is not done? What are the various steps of planning of maintenance shutdowns?

3. Consider an equipment-overhauling shutdown, which is expected to take 200 hours (total estimated project duration). The project consists of a total of 80 activities. Project planning has been done with the help of network analysis and the necessary bar charts have also been extracted. How should this project be controlled? Discuss the progress review and monitoring activity necessary for this project, enumerating the steps, which need to be taken. What kind of report is needed; and how often should the progress be reviewed?

4. What are the various techniques, which can be used for scheduling and monitoring of projects? Why is network analysis preferred? (Note: what are their advantages over other methods?) What is the basic difference between CPM and PERT?

5. What are the causes of time and cost over-runs of projects? Briefly describe the steps, which can be taken to keep the cost of the project under control.

6. The following Table gives the necessary data on the activities involved in a small project of nine activities. Draw the network diagram. Compute the earliest and latest start and finish times and determine the total float and free float for each of these nine activities. Then, locate the critical path and show it on the network.

Activity	**Activity Duration (in Days)**	**Preceding Activity**
A	2	None
B	5	None
C	5	A
D	3	B
E	9	B and C
F	2	B and C
G	7	E
H	6	F
I	2	G &H

Consider a small project of ten activities, each of which requires a certain amount of time and a given number of men. The network diagram (A-O-A representation) of the project is given in the figure, and the duration and resource requirements of each of the ten activities are given in the table.

Activity	A	B	C	D	E	F	G	H	I	J
Duration (in Days)	1	4	3	2	2	2	2	3	1	3
Manpower Requirements	7	1	4	3	5	8	2	6	9	10

Assume that all the men are interchangeable, that is, a person working on a given activity can be used for any of the other activities. Next, suppose that only 10 men are available on any given day. How should the activities of the project be scheduled so as not to exceed this constraint (of 10 men) but still to complete the project as soon as possible?

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