Methods and Approaches for Maintenance Capacity Planning

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***Abstract*— Maintenance capacity planning deals with the determination of the required resources to perform the needed maintenance tasks at a high standard of quality. The resources include labor, equipment and tools, but the most important maintenance resource is labor. Therefore, the focus in this paper is on the determination of craft mix and the sources of the labor. The sources could be in-house, overtime work or contract. The objective of this paper is to present measures for assessing the adequacy of the available maintenance capacity and to propose models and methods for effective maintenance capacity planning. A prerequisite for capacity planning is an accurate forecast of the maintenance load. The methods and techniques for forecasting the maintenance load are outlined. The models for determining maintenance capacity are classified into two main categories. The first category is deterministic models that include the transportation model, linear programming, and integer programming. The second category is stochastic models that include stochastic programming, queuing models, and simulation. The input data and the solution algorithms required for using these models are highlighted.**

Keywords*— *Capacity planning; maintenance resources; deterministic models; stochastic models

I. INTRODUCTION

Maintenance capacity planning determines the resources needed to carry out the maintenance activities. Maintenance activities include preventive, predicative and emergency maintenance. Maintenance resources include materials, spare parts, and labor. Labor consists of all crafts and staff and it represent the most important and essential resource in maintenance. The key determinant of the maintenance capacity is the workload. The maintenance workload consists of two major components: planned work and unplanned work. Planned work consists of planned preventive and predictive maintenance, including planned overhauls and shutdowns. Unplanned work consists of emergency or breakdown (failure) maintenance. The first component is the deterministic part of the maintenance workload. The second component is the stochastic part that depends on the probabilistic failure pattern, and it is the main cause of uncertainty in maintenance forecasting and capacity planning.

The main objective in capacity planning is to provide maintenance capacity (resources) to meet random maintenance workload, in order to achieve several objectives that include maximizing system availability, safety, and utilization of limited resources. Maintenance capacity planning determines the appropriate level and workload assignment of different maintenance resources in each planning period. For each planning period, capacity-planning decisions include the number of employees, the backlog level, overtime workload, and subcontract workload.

The maintenance capacity-planning problem is a long-term planning problem. The typical planning horizon for this problem is three to five years. A major input to this planning problem is the accurate forecast of the maintenance load. This major input makes the problem stochastic in nature due to the change in operation levels and equipment age. Proper determination and allocation of the various maintenance resources to meet a stochastic varying workload is a complex and important practical problem.

The main purpose of this paper is to present measures to assess the adequacy of maintenance capacity, and to propose several techniques to address the maintenance capacity-planning problem. Section 2 defines the problem of capacity planning in maintenance, reviews the literature, and presents measures to assess the current capacity. Section 3 introduces forecasting techniques, which are a prerequisite for accurate capacity planning. Section 4 presents different methods and models for maintenance capacity planning and identifies the data required to use each method. Section 5 concludes the paper.

II. MAINTENANCE CAPACITY PLANNING

The objective of maintenance capacity planning is to determine the optimum level of resources needed to meet the demand for maintenance work in each period. The demand for maintenance work is stochastic in nature. Effective maintenance capacity planning is influenced by many factors that include the knowledge about the characteristic of maintenance workload, availability of resources, and the flexibility in deploying resources. Availability of the right resources in terms of quantity and quality is critical for responding to changes in demand for maintenance. Demand management in terms of forecasting the maintenance load, scheduling resources, and monitoring performance is part of overall capacity planning.

The process of maintenance capacity planning can be briefly described as follows:

The author would like to acknowledge the support provided by King Fahd University of Petroleum and Minerals.

1. Estimate (forecast) the total required maintenance capacity (maintenance workload) for each time period.
2. Select a model to determine the required resources over time. These models include deterministic mathematical programming models, and stochastic queuing and simulation models.
3. Assess the determined capacity plan using reliable performance measures.
4. Adjust the capacity if needed.

The usual objective of maintenance capacity planning is to minimize the total cost of labor, subcontracting, and delay (backlogging). Other objectives include the maximization of profit, availability, reliability, or customer service.

Capacity planning techniques are generally classified into two main types: deterministic and stochastic techniques [1]. Deterministic techniques assume that the maintenance workload and all other significant parameters are known constants. Three deterministic techniques that are presented in [1] and [2] are:

1. Heuristic techniques
2. The modified transportation tableau method; and
3. Mathematical programming techniques, including linear and integer programming.

Stochastic capacity planning techniques assume that the maintenance workload is a random variable. Statistical distribution-fitting techniques are used to identify the probability distributions that best describe these random variables. Since uncertainty always exists, statistical techniques are more representative of real life. However, statistical models are generally more difficult to construct and solve. The three most popular stochastic models and approaches are:

1. Stochastic programming;
2. queuing models; and
3. Stochastic simulation.

After determining the capacity plan using any given approach, it should be assessed regularly using reliable performance measures. The following measures are suggested to assess the adequacy of the maintenance capacity [1]:

1. Utilization of resources (labor utilization);
2. Response time;
3. Mean time to repair;
4. Maintenance backlog;
5. Inventory turnaround.

If the values of theses performance measures are outside the desired band, then an action to adjust the capacity plan is necessary.

III. FORCASTING MAINTENANCE LOAD

Prior to capacity planning or designing a new maintenance organization, an essential activity is to estimate the expected maintenance load. The load consists of the following components:

1. Failure and emergency maintenance workload. This can be forecasted using actual historical workloads and the appropriate techniques of forecasting that include moving average, regression, and exponential smoothing [1, 3].
2. Preventive maintenance and predicative maintenance workload. This mostly planned work will be obtained from planned maintenance program. This includes routine inspections and lubrications.
3. Deferred corrective maintenance. This can be forecasted based on historical records and future plans.
4. A forecast for overhaul of removed items and fabrication. This can be estimated from historical records coupled with future plans for improvements.
5. Shutdown, turnarounds, and design modifications. This can be obtained from actual historical records and the future maintenance schedule.

The forecasting of the maintenance load for a new plant is more difficult and must rely on similar plants‘ experiences, benchmarking, management experience, and manufactures' information.

After the maintenance load is forecasted, the forecast should be evaluated using standard error measures such as the Mean Absolute Percent Error (MAPE). Based on this evaluation, the forecast could be revised if necessary [1].

IV. METHODS AND APPROACHES FOR CAPACITY PLANNING

In this section, the approaches and models for capacity planning are presented. The focus is on deterministic models because they are more practical and easy to implement in real life. A brief outline of stochastic models is also provided.

A. Deterministic Approaches

The deterministic techniques include the transportation method, linear programming ad integer programming models [1, 2, 4]. In production planning, products from the current period can be kept in inventory to satisfy demands in future periods. However, this is not the case in maintenance planning. In maintenance, unfinished work is backlogged and performed in future periods at a higher cost. It is possible to divide the maintenance load into several categories by skill or priority and to perform capacity planning separately for each category. For example, Table 1 shows a tableau for a three-period maintenance plan for one kind of maintenance work, which is the mechanical workload. A similar table can be constructed for other types of maintenance work. The notation in the tableau is defined below.

C_r = cost per hour of in-house mechanical maintenance labor in regular time,
C_o = cost per hour of in-house mechanical maintenance labor in overtime,
C_s = cost per hour of subcontracted mechanical maintenance labor,
π = cost of backordering (doing work late) by one time unit

R_t = capacity of in-house regular time in period t
O_t = capacity of in-house overtime in period t
S_t = capacity of subcontracting in period t
M_t = forecasted mechanical maintenance load in period t.

If a work is backlogged from period (t) and performed at period ($t + i$) with regular in-house labor, it will have a higher cost of $C_r + i\pi$ per hour. Table 1 shows the data needed for a three-period planning horizon. The table shows the costs, capacities and maintenance load. The symbol ∞ in the cost cell means that a work cannot be done in this period. For example, if work came in period (t + 1), then it cannot be performed in period t.

A simple least-cost heuristic method can be used to compute the allocation of the maintenance load to different sources of labor supply. The least-cost method provide a good solution, however if the optimal solution is needed the stepping stone method can be employed.

In general, the transportation tableau method requires the following data:

- cost of maintenance for each source per man-hour for each period;
- cost of advancing (early maintenance) per man-hour per unit time,
- cost of backordering (late maintenance) per man-hour per unit time;
- maintenance demand (required workload) in each period.

TABLE 1. Transportation tableau with 3 periods and 3 resources

Execution Periods	Resource used	Demand Periods 1	2	3	Capacity
1	Regular Time	c_R	∞	∞	R_1
	Overtime	c_O	∞	∞	O_1
	Subcontract	c_S	∞	∞	S_1
2	Regular Time	$c_R + \pi$	c_R	∞	R_2
	Overtime	$c_O + \pi$	c_O	∞	O_2
	Subcontract	$c_S + \pi$	c_S	∞	S_2
3	Regular Time	$c_R + 2\pi$	$c_R + \pi$	c_R	R_3
	Overtime	$c_O + 2\pi$	$c_O + \pi$	c_O	O_3
	Subcontract	$c_S + 2\pi$	$c_S + \pi$	c_S	S_3
Maintenance Workload		M_1	M_2	M_3	

Linear programming (LP) is another deterministic model for capacity planning. LP is a mathematical model that minimizes or maximizes a linear function subject to linear constraints [5]. The linear programming model determines the optimal values of decision variables to achieve a given objective such as minimizing cost or maximizing profit. The capacity-planning problem can be formulated as a linear programming problem. This type of model can be solved by Microsoft Excel, Linear Interactive and discrete optimizer (LINDO), International Mathematical Software Library (IMSL), the Optimization Software Library (OSL) and the well-known CPLEX package. The LP solution provides the optimal values and sensitivity analysis. If linearity assumptions are not satisfied, nonlinear programming has can be used for the optimal planning of maintenance resources [6].

If the crafts and skill levels are required to be specified in terms of employees to be hired in a maintenance department, we either round up the linear programming solution to the nearest number of employees or reformulate the problem as a mixed integer programming model. This formulation requires the following notation:

F_{kt} = Forecasted maintenance load of grade k in period t.
B_{kt} = Backlog of grade k maintenance work in period t
UB_k = Upper limit for a healthy backlog for grade k work
LB_k = Lower limit for a healthy backlog for grade k work
U_{ijt} = Upper limit on the availability of skill i maintenance employee from source j in period t.
P_{ijk} = Productivity of a maintenance employee of skill i, from source j when performing grade k work.
r_{kt} = Cost of backlogging one man-hour of grade k work in period t.
n_{ijkt} = Number of employees of skill i, from source j, assigned to perform maintenance work of grade k in period t.
NH = number of hours worked by a regular in-house employee per period.
S_j = 1 for j = 1: full-time in-house employees; $0 < S_j < 1$ for j = 2: part-time or overtime employees.
U_{ijt} = Upper bound on the availability of employee of skill i from source j in period t.
C_{ijt} = Pay of an employee with skill i from source j in period t.

Assuming part-time and overtime cannot exceed 25% of full-time maintenance man-hours, the integer programming model for determining the optimum number of workers of different types and skills is stated as follows:

$$\text{Min} \sum_i \sum_j \sum_k \sum_t C_{ijt} n_{ijkt} + \sum_k \sum_t r_{kt} B_{kt} \quad (1)$$

Subject to:

$$\sum_i \sum_j (NH \times S_j) P_{ijk} n_{ijkt} + B_{kt} = F_{k,t} + B_{k,t-1} \quad (2)$$

$$n_{i2kt} - 0.25\, n_{i1kt} \le 0 \quad (3)$$

$$n_{ijkt} \le U_{ijt} \quad (4)$$

$$LB_R \le B_{kt} \le UB_k \quad (5)$$

$$n_{ijkt}, B_{kt} \ge 0 \text{ and integer} \quad (5)$$

The software packages mentioned earlier in this section have versions that can solve mixed integer programming models. The mixed integer programming model presented above is only a general-purpose example. Different components of this model could be added, deleted, or modified in order to tailor it to a specific maintenance capacity planning applications. The data needed to use or apply such types of models are:

- cost of advancing (backlogging) each maintenance hour by one period, i.e., cost of early (late) maintenance
- cost of regular time (overtime) maintenance per hour per work type for in-house maintenance
- cost of subcontract maintenance per hour per work type
- cost of hiring (firing) one worker
- maximum number of hours available for regular in-house maintenance, in each period
- maximum overtime hours available in each period
- maximum subcontractors hours available in each period
- demand (forecast) of each type of maintenance work in each period
- acceptable backlog levels for each work type per period

B. Stochastic Approaches

Stochastic approaches that may be used for maintenance capacity planning include:

1. Stochastic programming.
2. Queuing models.
3. Stochastic simulation.

The driver behind these models is the stochastic nature of the demand for maintenance work. To use them effectively, these models require probability distribution identification and large amounts of data. Experience has shown limited use and application of stochastic models in maintenance capacity planning. Therefore, these models are not presented in detail in this paper. For further reading on this subject, the reader may refer to [2], [7], [8], [9], and [10].

V. CONCLUSIONS

Maintenance capacity planning is an important practical problem facing organizations. This paper presented an overview of the problem of capacity planning in maintenance. A precise definition of the capacity-planning problem was provided. Measures to assess the adequacy of maintenance capacity were proposed. Several practical and easy to implement techniques were outlined. The methods presented include transportation tableau, linear programming, and integer programming. The data required for each method was identified. The algorithms to solve each model were described. Further work is underway to implement these models to address practical situations.

ACKNOWLEDGMENT

The authors would like to acknowledge the support provided by the Systems Engineering Department of Systems Engineering, King Fahd University of Petroleum and Minerals.

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