consists of pothole patching, permanent asphalt patching, or grading and graveling.

At the same time that normal maintenance or immediate repair is occurring, all streets in the city are evaluated on a systematic basis to determine if major repairs are needed. This evaluation is based on pavement deflection data and the computerized historical maintenance record file. Dynaflect tests are run on all arterial and collector streets in the city on a periodic basis. Benklemen beam tests are run on all local streets with a history of requirements for immediate repairs. Coring is also done on an as-needed basis.

If the analysis indicates that major repairs are needed, a decision based on a pavement design is made concerning whether to do pavement rehabilitation or pavement reconstruction of the street section.

Results of the computerized maintenance records are used to identify sections that require high maintenance as well as to detail the type of maintenance and quantities of materials and man-hours required for repairs. High maintenance sections are defined as those locations where the maintenance crew is required to return for repairs more than three times per year, or locations where large quantities of materials are required to effect the repair.

A list of high maintenance sections is prepared and compared with results of the deflections tests. In 1982 two categories of information were gained from the comparison. The first category dealt with street sections that were experiencing both surface and base failure. These sections appeared on both the high-maintenance list and the high-deflection list. The second category dealt with street sections that were beginning to experience surface failure but still had a stable base. These street sections appeared on the list of high-maintenance frequency but did not necessarily appear on the high-deflection list.

The indication from comparison of the two categories is that many times the surface of a street section fails before the base begins to fail. By quickly locating and identifying sections of surface failure, repairs can be made before the base failure begins. The computerized maintenance record system enables rapid identification of surface failure and has allowed major pavement surface repairs to be made before base failure has occurred.

RESULTS

In addition to the reduction in full-time staff previously discussed, several other measurable benefits have resulted from the program. In 1979 there were more than 600 sites that required major pothole repair. In 1982 the number of sites was reduced to 252, primarily because of the rapid method of problem identification and repair.

Since 1980 the maintenance budget has been increasing at a rate of 5 percent per year, even though costs of labor have been increasing at more than 10 percent per year and costs of materials have been increasing at a rate of more than 15 per- cent per year. Repair costs would have been much higher if the program had not been implemented.

The key to being able to add contractors into the process, has been a contracting technique termed "small public works contracts." In January each year the city advertises a number of contracts that request bids for certain types and quantities of work without specifying the location of the work. Following this process, contractors are selected, on 12-month contracts, to do base and paving maintenance, concrete maintenance, landscaping maintenance, or traffic signal maintenance. Contractors are also selected on an hourly rate basis to provide drivers and various pieces of construction equipment. A contractor is also selected (through a competitive bid) to do all the overlay work for one construction season. Having the contractors selected and available to work on short notice enables the maintenance foreman to have the assistance he needs when it is needed.

The maintenance process has enabled the city to move from a crisis basis, where personnel, equipment, and material were always used to do catch-up, short-term repair work, to a basis of preventative maintenance, where maintenance is systematic and more of the budget is spent on permanent repairs instead of on patching. It is anticipated that cost savings for maintenance will become significant by the end of 1984 because more of the maintenance budget is being spent on overlays and pavement reconstruction and also because the frequency of crisis repairs is decreasing.

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Optimum Shop Staffing Levels: An Application of Queuing Theory

G.L. RAY

ABSTRACT

Optimum equipment shop staffing levels are determined for the Louisiana Department of Transportation and Development by application of a simple queuing model. Poisson arrival and exponential service distribution assumptions are used and verified to a limited degree. Louisiana's equipment management system is used to obtain source data

with which to develop waiting costs. An optimum solution is computed for each shop based on the unique conditions that affect that particular shop. The optimum statewide staff is 197 welders and mechanics. Currently, there are 219 employees on this staff. Centralization of shop activity within a transportation district is expected to create additional efficiencies and allow reduction of another 18 positions. It is expected that 40 positions will be eliminated through normal attrition as a result of this study.

SHOP PERFORMANCE

Shop performance is dependent on two principal factors: (a) productivity and (b) economic optimization. Productivity may be equated with efficiency and controlled at an expected level to ensure the most utility from existing resources. Economic optimization involves determination of the resource level that produces minimum costs throughout the system. The latter topic is the primary thesis of this paper.

The determination of economically optimum shop staffing levels is basically a determination of the optimum number of mechanics and welders required to meet the demand at a particular shop. This determination is part of an overall fleet management decision process and is, to a large degree, dependent on fleet selection, replacement, and utilization decisions.

Several variables associated with an equipment fleet influence the frequency and severity of repairs. Although it is generally assumed that equipment operating costs tend to increase with age, in Louisiana this trend has been documented and the rate of increase established for prediction purposes. This prediction, in turn, enables the Louisiana Department of Transportation and Development to determine the optimum age to replace different equipment units. In the equipment selection process certain design factors are specified within an allowable range. Because most government bodies are limited by the low bid process, different makes and models with different design variations are incorporated within the fleet. Significant performance differences have been revealed between different makes and models within a machine class. This difference is presumed to reflect variation from design or quality-control efforts of the respective manufacturers. Utilization is another factor that significantly influences frequency and severity of repairs. Machines that are not properly used for the purpose intended will often exhibit higher repair costs and greater downtime than machines that are properly used. When all of these factors are combined, the complexity of the problem is greatly increased. The effects of age, variation between manufacturers, type of equipment, and fleet utilization characteristics combine to produce a demand on the repair shop for service that can be measured in terms of frequency of arrival and labor hours required for repair.

In addition to the fleet variables that affect staffing levels, personnel variables also interact to increase the complexity of managing a repair shop. Some of the personnel variables that affect staffing levels are knowledge, skills, and abilities of welders and mechanics; turnover problems; motivation; scheduling; and shop management. All of these factors tend to influence worker productivity. Productivity must be quantified in some manner in order to develop a mechanism for determining optimum staff levels.

SHOP PRODUCTIVITY

In Louisiana shop productivity standards are still being developed and were not available for use in this study. Overall measures of productivity were used in lieu of more precisely determined standards. When shop standards are mentioned, a flat-rate manual normally comes to mind, with standard labor requirements for tune-ups, piston replacement, and so forth. The Department is currently in the process of developing a modified flat-rate approach for evaluation of shop productivity. Equipment repair work is being coded to the equipment subsystem (engine, driveline, transmission, and so forth). Managers can monitor the amount of time spent repairing subsystems for different makes and models and can relate failures to the fleet variables outlined previously.

Unfortunately, the development of precise standards is much more complicated than merely measuring the amount of time it takes to replace spark plugs. In most cases the mechanic or shop superintendent has the option of either repairing a part, exchanging a part, or overhauling and rebuilding a subsystem. In many cases a trip may be required from a central shop to a piece of equipment that is inoperative in the field. Because flat-rate manuals often do not consider all of these options, a large amount of time-study work must be performed to develop local standards and make them specific to a given shop for each type of repair. This would also require detailed reporting in order to compare actual productivity with expected productivity levels. Although attempts to establish productivity standards have not been abandoned, it was imperative that total staff requirements be determined by using available data. If and when specific productivity standards are developed, they will be used primarily by shop managers to maintain a target level of efficiency, identify improvements, and make the best use of available resources. The overall shop productivity measures may still be used to determine optimum staffing levels and will reflect any improvements in efficency that can be realized.

Overall productivity measurement consists of simply determining the distribution of service rates. Service rate is defined as the amount of time required to service an equipment unit. Because the cause-and-effect relationship between demand and the significant variables that affect demand for service is not established, overall productivity measurement (i.e., the present service-rate distribution) may not be the best productivity goal for a given shop. Nevertheless, it is the final measure of service. Establishment of the cause-and-effect relationship between fleet and personnel variables and the service-rate distribution will provide a tool for development of an expected service-rate distribution. Correlation and regression analysis or simulation techniques may be used to quantify this relationship, which can then be compared with a similar determination from a flat-rate manual to ensure reasonableness. It is not expected that the shops will achieve the productivity shown in a flat-rate manual because of the diversity of equipment and demand for service at a state repair shop, in addition to the many repair options mentioned previously.

Another factor that affects shop productivity concerns the use of outlying (secondary) shops in some districts in Louisiana. Although secondary shops were organized to increase efficiency of repair operations by bringing the shop closer to the equipment, the opposite result is apparent. The difficulty of supplying parts and the administrative overhead required for operating a small secondary shop has reduced the overall efficiency of shop operations. Administrative overhead is high for secondary shops, and only minor service can be performed effectively. The travel time saved by secondary shops does not appear to offset the higher operating costs associated with these operations. The issue is still under study, but it has been tentatively decided to centralize shop operations in each district. This tentative decision is reflected in the planning criteria contained in this paper.

Because the equipment repair shop is established primarily to service the equipment fleet, miscellaneous activities related to bridge repair, ferry operations, leave, building repair, and so forth tend to reduce the overall productivity of the shop. These miscellaneous and overhead requirements must be considered in any carefully developed plan for optimum staff determination. Although the procedure for doing this is straightforward, it must be applied after an initial solution is obtained from the queuing model.

QUEUING THEORY

The optimum number of mechanics and welders required to perform repair services in each district can be computed through the proper application of queuing theory. Queuing theory involves the mathematical study of queues, or waiting lines. Formation of waiting lines is a common phenomenon that occurs whenever the demand for service exceeds the capacity to provide that service. Queuing theory has been applied to similar problems in industry and government with a great deal of success. Determination of the optimum number of mechanics and service personnel is a difficult problem. Too many mechanics result in excessive costs, whereas too few result in repair jobs piling up or forming a queue. When repair orders are backlogged, excessive cost is also the result. For example, a tractor waiting for an engine repair may be holding up a mowing operation, which then results in a dollar loss because of idle employees and reduced service.

The goal is to reach a balance between the cost of service (number of mechanics) and the cost of waiting (downtime for a machine in the queue). The application of queuing theory does not accomplish this directly. It merely provides a mathematical technique for predicting the length of the waiting line and thus the average time in the queue for various service levels (number of servers). These predictions can then be used to construct a cost model to evaluate alternate levels of service.

QUEUING SYSTEM

A general description of a queuing system is shown in Figure 1. Units that require service are generated from time to time by an input source. The input source in this case is defined by the equipment population. When an equipment unit requires service (such as an engine repair), it becomes a calling unit and enters the queue. The queue does not have to be a physical line of machines one behind the other. The queue represents a state of waiting for service. For example, a mowing machine has a broken frame and is entered into the queue. The machine may remain at the parish site and await a welder or it may be taken to the welding shop. In either case the machine has entered the queue, or waiting line. Units are selected from the queue for service by some process known as the service discipline. Usually the service discipline is assumed to be first-come, first-served. The required service is then performed for the unit by the service mechanism, after which the unit leaves the queuing system. The service mechanism dealt with here is the equipment repair shop and associated service personnel and equipment.

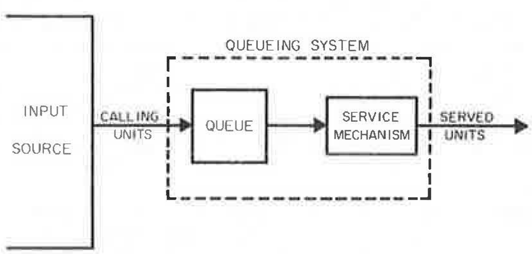

FIGURE 1 Basic queuing process.

The following analogy may be helpful in visualizing the queuing process. Consider a large jar (queuing system) that contains uncoated jelly beans (calling units). Suppose that a chief executive (input source) outside the jar occasionally tosses an uncoated jelly bean (calling unit) into the jar and one or more tiny bureaucrats (servers) inside the jar occasionally toss a coated jelly bean (served unit) out of the jar. Queuing theory will enable one to answer probabilistic questions concerning the number of jelly beans in the jar and the elapsed time they spend in the jar. Any situation that can be simulated in this way can also be formulated as queuing system, thereby enabling mathematical prediction of performance.

INPUT SOURCE

One characteristic of the input source must be considered before any effective analysis. This characteristic is the size of the source. The size of the input source is the total number of equipment units that may require repair from time to time. It may be assumed to be either finite or infinite. The finite case is more difficult to analyze because the number of units in a system affects the number of potential calling units outside the system at any time. The finite assumption must be made if the rate at which the input source generates calling units is significantly affected by the number of units in the queuing system. It is improbable that this rate would be affected at the district level because several hundred equipment units comprise the input source, whereas a maximum of 20 to 30 equipment units are in the queue on a given day. For this reason the input source is assumed to be infinite. Observation of the number of units in a shop each day confirmed this assumption. In addition, for the selected model to be valid, the arrival rate is assumed to be independent of the number of units waiting for service. The assumption is valid for this problem because it is unlikely that the customer will go another shop due to the length of the waiting line. This is also confirmed by random observation.

The statistical distribution by which calling units are generated over time must also be specified. The common assumption is that the arrival process follows a Poisson distribution. The Poisson distribution is a basic observable phenomenon that is often used in operations research. This distribution is appropriate in many situations where an event occurs over a period of time. An example would be the arrival of an equipment unit at a district repair facility, when it is as likely that this event will occur in one time interval during the normal work day as in any other, and the occurrence of an event has no effect on future events. The number of customer arrivals in a fixed time has been observed to have a Poisson distribution. Figure 2 shows a comparison of the assumed Poisson distri-

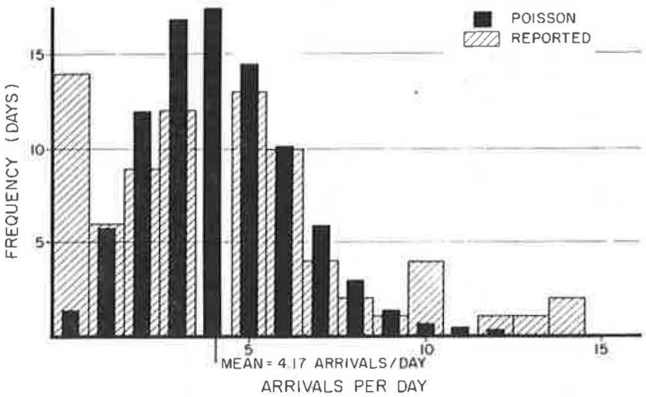

FIGURE 2 Arrival-rate distribution.

bution of arrival rates and reported distribution of arrival rates for equipment in need of welding services. Differences are attributed to holding mowing machines until just before the beginning of the mowing season and sending them in for welding all at once. This occurred in at least one district. The Poisson distribution appears to be sufficiently close to the measured arrival rate to provide a valid description of the arrival-rate function in this case.

SERVICE MECHANISM

The next parameter that must be considered before choosing a queuing model is the service rate. The exponential distribution appears to describe the variation in service rate for at least the welding portion of the repair process. This distribution covers the type of situation where the specific tasks required of the server differ among the calling units. The broad nature of this service may be the same, but the specific type and amount of service will differ. For example, automobile arrivals at a repair facility are often for battery replacement, tune-up, and minor service, but occasionally an engine overhaul or other extensive service is required. The comparison between the assumed exponential distribution and the reported distribution of service rates for welding jobs is shown in Figure 3. The agreement is remarkable. For this reason

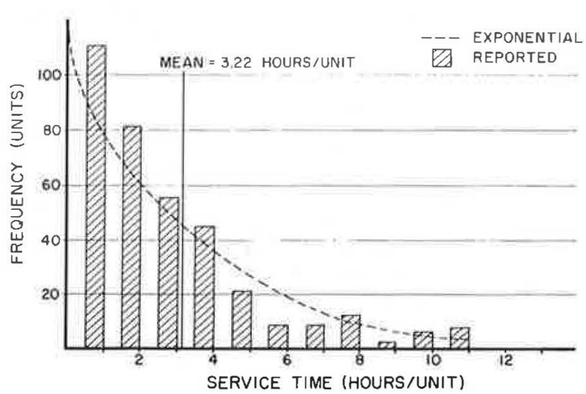

FIGURE 3 Service-rate distribution.

the exponential distribution is considered a valid description of the service-rate distribution.

In order to use the queuing model two additional assumptions must be made. The particular model in question is formulated on the assumption that service rate is not state dependent. This assumption is valid as long as shortcuts are not taken as the work load increases. It is also assumed the service-time distribution is the same, regardless of the mechanic performing the service. Although this is not strictly true, mean values are used, and the size of the group of servers required is predicted. Individual productivity variation is expected to remain consistent about the mean.

COST MODEL

To develop a cost model two primary costs must be recognized and quantified. The cost of equipment waiting for repair and the cost of service must be estimated with a reasonable degree of accuracy to ensure success of the model. The cost of service is easy to estimate. It is merely the variable cost of providing the server (mechanic or welder in this case). Salary and fringe benefit costs are readily available through payroll reporting systems. A standard average cost was computed and applied to all shops because personnel cost variation was not considered to be a desirable factor to include in the cost model. By using an average cost, each shop could be compared and staff determined on a uniform basis.

Determination of the cost of waiting is somewhat more difficult to estimate. Waiting costs are dependent on the type of equipment and the period of inactivity imposed while waiting for repair in the shop. In Louisiana this period of waiting is called downtime, and downtime information in the equipment management system is retained by the Department. Downtime in the field is extremely difficult to measure because equipment-related delays do not necessarily cause delays to planned maintenance activities. The disruptive effect of equipment downtime can often be countered by supervisor action, including planning of alternate activities, use of substitute equipment, and use of alternate procedures. Downtime in the shop, however, can be accurately measured and a cost penalty can be applied. .

If it can be assumed that enough second-line equipment units are available to mitigate the effects of downtime, the cost of shop downtime becomes defined by the cost of maintaining second-line equipment. This is the procedure used in Louisiana to penalize an equipment unit for loss of reliability. This cost is also used for the replacement analysis, and it provides an excellent mechanism for determining the cost of waiting. The measured variables that affect shop demand and service are given in Table 1 for each shop throughout the state. The number of vehicles includes the total number of individual equipment units serviced by the shop for fiscal year 1982. The arrival frequency measures the number of times these individual vehicles entered the shop facility. Arrival rate per vehicle is determined by dividing the arrival frequency by the number of vehicles serviced. Total labor hours is the total amount of time spent working on individual equipment units. Downtime hours are the total time the equipment unit is down because of shop activity. Time is measured from the point when the shop superintendent schedules the equipment for repair to the point when the repair is completed. This time is priced for the individual equipment unit by multiplying the rental rate for that class of equipment by the downtime hours to obtain a dollar amount.

The cost model and its solution are further de-

TABLE 1 Shop Demand and Service

Shop ID No.	No. of Units	Arrival Frequency	Avg Arrival Rate per Unit	Total Labor Hours	Downtime Hours	Downtime per Day (hr)	Avg Arrival Rate per Day	Avg Service Rate (hr)
02071	563	2,789	4.9	22,224.7	75,018.3	300.0	10.72	7.9
03071	585	1,940	2.2	14,741.5	42,358.7	169.4	7.46	7.5
03702	153	533	3.4	3,682.0	11,727.1	46.9	2.05	6.9
03510	120	463	3.8	1,811.0	8,029.8	32.1	1.78	3.9
03540	88	191	2.1	613.0	4,303.5	17.2	0.73	3.2
04071[a]	567	2,471	4.3	12,274.5	29,004.0	129.5	9.50	4.9
04072[a]	294	927	3.1	8,849.0	26,740.0	119.4	3.56	9.5
05071[b]	668	2,791	4.1	12,422.5	30,542.7	136.4	10.73	4.4
05073[b]	198	750	3.7	2,568.0	9,418.0	42.0	2.88	3.4
05530	39	218	5.5	1,022.0	1,101.0	4.4	0.83	4.6
05560	97	327	3.3	1,380.0	3,158.5	12.6	1.25	4.2
05580	77	266	3.4	1,076.0	1,173.0	4.7	1.02	4.0
07071[a]	669	3,959	5.9	18,379.0	35,412.7	158.1	15.22	4.6
07072[a]	286	1,904	6.6	6,528.0	20,440.8	91.3	7.32	3.4
07073[a]	199	801	4.0	6,033.0	9,644.8	43.1	3.08	7.5
08071	684	3,407	4.9	22,577.9	53,178.8	212.7	13.10	6.6
08072	221	1,294	5.8	5,822.5	16,304.8	65.2	4.97	4.4
08073	250	1,396	5.5	5,841.0	10,108.2	40.4	5.36	4.1
41071	975	3,234	3.3	31,798.0	62,484.0	249.9	12.43	9.8
58071[a]	312	1,149	3.6	11,230.0	24,836.0	110.1	4.41	9.7
58072[a]	218	781	3.5	3,724.0	6,517.4	29.1	3.00	4.7
58510	75	236	3.1	1,512.0	1,773.5	7.1	0.90	6.4
59002	67	461	6.8	1,753.5	3,475.7	13.9	1.77	3.8
61071[b]	734	3,320	4.5	35,153.1	93,617.1	374.5	12.76	10.5
62071	636	2,959	4.6	25,006.0	68,689.5	274.8	11.38	8.4
62075	57	250	4.3	832.0	849.8	3.4	0.96	3.3
62580	36	128	3.5	452.5	784.5	3.1	0.49	3.5
Total	8,868	38,945	4.3	259,306.7	651,302.3	136.4[c]	149.78	6.6

Note: Data are for 260 working days, July 1981 through June 1982.

[a]Shop personnel worked four 10-hr days, April 12-June 30, 1982. The shop was open 4 days a week, and 248 work days were used for computing downtime per day.

[b]Shop personnel worked staggered shifts of four 10-hr days, April 12-June 30, 1982. The shop was open 5 days per week.

[c]Weighted average for typical district repair shops only.

scribed in the next section. Results of the trial-and-error solution of the model are given in Table 2. The objective was to minimize the expected total variable cost per unit time. Note that the minimum expected total variable cost per unit time is $467.71; this occurs when there are 19 mechanics available for repair of equipment. This is the solution for the district 42, gang 071 shop located in Baton Rouge, the central repair shop. A solution was computed for each shop throughout the state. The FORTRAN computer program used for solution of the cost model is shown in Figure 4.

TABLE 2 Solution of Cost Model for the Central Repair Shop

No. of Mechanics	ρ	Length of Queue (avg no. of units)	Cost of Queue ($)	Cost of Service ($)	Expected Total Cost ($)
16.0	0.991	—	7,879.92	15.53	7,895.45
17.0	0.933	9.708	741.28	121.10	862.37
18.0	0.881	3.718	283.92	226.67	510.58
19.0	0.834	1.774	135.48	332.23	467.71
20.0	0.793	0.918	70.06	437.80	507.87
21.0	0.755	0.490	37.44	543.38	580.81
22.0	0.721	0.265	20.21	648.95	669.15
23.0	0.689	0.143	10.88	754.51	765.40
24.0	0.661	0.076	5.81	860.08	865.89
25.0	0.634	0.040	3.05	965.66	968.71
26.0	0.610	0.021	1.57	1,071.23	1,072.80
27.0	0.587	0.010	0.80	1,176.79	1,177.59
28.0	0.566	0.005	0.39	1,282.36	1,282.76
29.0	0.547	0.002	0.19	1,387.94	1,388.13
30.0	0.528	0.001	0.09	1,493.51	1,493.59
31.0	0.511	0.001	0.04	1,599.07	1,599.12
32.0	0.495	0.000	0.02	1,704,64	1,704.66
33.0	0.480	0.000	0.01	1,810.21	1,810.22
34.0	0.466	0.000	0.00	1,915.78	1,915.79
35.0	0.453	0.000	0.00	2,021.35	2,021.36

SHOP COST MODEL

The following variables are used in the shop cost model:

- Cw = cost of waiting per unit time for one machine arrival;
- Cs = marginal cost of a welder per unit time;
- E(C) = expected total variable cost per unit time;
- L = expected line length, including units in service and units in queue;
- Lq = expected queue length;
- λ = mean arrival rate (expected number of arrivals per unit time) of calling units;
- μ = mean service rate (expected number of units completing service per unit time);
- s = number of servers in the system; and
- Pn = probability that exactly n calling units are in the queuing system.

Given that the service rate = μ (units per day) or $1/\mu$ (days per unit), the arrival rate = λ (units per day), the cost of waiting = Cw (dollars per day), and the cost of a welder = Cs (dollars per day), the objective is to minimize E(C) = sCs + CwL.

Because the time that machines spend waiting while being serviced is unavoidable, L may be replaced by Lq. Furthermore, the service costs incurred while the servers are busy cannot be reduced; therefore sCs can be replaced by $(s - \lambda/\mu)$Cs. The objective function is reduced to the expected total variable cost of idleness (idle mechanics or machines waiting to be served) per unit time. The new objective function becomes

$$\text{Minimize } E(C) = (s - \lambda/\mu)\, Cs + CwLq \quad (1)$$

The only remaining variable to be determined is

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C
C
C SHOPQUE COMPUTES THE COST MODEL SOLUTION MATRIX FOR A FIRST-COME-FIRST
C        -SERVED QUEING SYSTEM WHERE THE INPUT SOURCE IS DOTD NUMBERED
C        EQUIPMENT AND THE SERVICE MECHANISM IS A DOTD SHOP FACILITY.
C        COMPUTATION BEGINS WHERE THE INTEGER VALUE OF AR/SR IS
C        TRUNCATED TO THE NEAPEST WHOLE INTEGER.THEREFORE, THE MODEL
C        IS VALID ONLY WHEN TWO OR MORE SERVERS ARE REQUIRED.
C
C        THE FOLLOWING ASSUMPTIONS ARE MADE:
C        1)ARRIVAL RATE IS NOT STATE-DEPENDENT,
C        2)SERVICE RATE IS NOT STATE-DEPENDENT,
C        3)SERVICE TIME DISTRIBUTION IS CONSTANT BETWEEN MECHANICS,
C        4)INPUT SOURCE IS INFINITE,
C        5)POISSON ARRIVAL DISTRIBUTION,
C        6)EXPONENTIAL SERVICE TIME DISTRIBUTION.
C
C        EQUATIONS USED ARE AS FOLLOWS:
C        1) E(C)=(S-AR/SR)CS+CWLQ
C        2) RHO =AR/(S*SR)
C        3) PO  =1/ (SUM N=0 TO S-1 (AR/SR) NTH POWER/N FACTORIAL)
C                  +(AR/SR) STH POWER/S FACTORIAL*(1/1-RHO)
C        4) LQ  =PO*(AR/SR) STH POWER*RHO/S FACTORIAL(1-RHO) SQUARED
C        WHERE: LQ= LENGTH OF QUE
C               PO= PROBABILITY OF ZERO IN QUE
C               AR= ARRIVAL RATE(UNITS/DAY)
C               SR= SERVICE RATE(UNITS/DAY)
C               S = NUMBER OF SERVERS
C               CS= COST OF SERVER(DOLLARS/MAN-DAY)
C               CW= COST OF WAITING(DOLLARS/VEHICLE-DAY)
C               E(C)= EXPECTED DAILY TOTAL COST(DOLLARS)
C
C READ INPUT DATA
    10 READ(5,301) DIST,GANG,AR,SR,CW,CS
C IF DISTRICT = 0 ,LAST DATA CARD HAS BEEN READ ; TERMINATE PROGRAM
    20 IF (DIST) 30,310,30
C SKIP TO NEW PAGE AND SET UP HEADING
    30 WRITE(6,302) DIST,GANG,AR,CW,SR,CS
C COMPUTE INITIAL NO. OF SERVERS    AND STORE IN REAL AND INTEGER
C VARIABLES
    40 S1=AR/SR
    50 NS=AINT(S1)
    51 S=AINT(S1)
C IF AR/SR IS LESS THAN 1.0 SET NS AND S EQUAL TO ONE;THIS MEANS
C THE MINIMUM NO. OF SERVERS IS AT LEAST TWO
    52 IF (S) 60,53,60
    53 NS=1.0
    54 S=1.0
C COMPUTE INITIAL SERVICE LEVEL  AND INCREMENT OVER DESIRED RANGE
    60 DO290J=1,20
    70 NS=NS+1
    71 S=S+1.0
    80 RHO=AR/(SR*S)
C COMPUTE (S-1) FOR EACH SERVICE LEVEL
    90 IS=NS-1
C INITIALIZE PO COMPUTATION ACCUMULATORS FOR EACH SERVICE LEVEL
    91 SUM=0.0
    92 SUM1=0.0
   100 DO160N=1,IS
   110 ENP=0.0
   120 ENFACT=1.0
C COMPUTE "N" FACTORIAL (ADJUST FOR INABILITY TO SET N=0 LATER)
   130 DO150N1=1,N
   140 ENP=ENP+1.0
   150 ENFACT=ENFACT*ENP
C COMPUTE FIRST TERM IN DIVISOR OF PO
   151 SUM=SUM+((AR/SR)**N)/ENFACT
   160 CONTINUE
C ADJUST FIRST TERM IN DIVISOR OF PO FOR N=0 BY ADDING 1 TO TERM (SUM)
   170 SUM=SUM+1.0
   180 SP=0.0
   190 SFACT=1.0
C COMPUTE "S" FACTORIAL
   200 DO220K=1,NS
   210 SP=SP+1.0
   211 SFACT=SFACT*(SP)
   220 CONTINUE
C COMPUTE SECOND TERM IN DIVISOR OF PO
   230 SUM1=SUM1+(((AR/SR)**NS)/SFACT)*(1.0/(1.0-RHO))
C COMPUTE PROBABILITY OF ZERO IN QUE FOR EACH VALUE OF "S"
   240 PO=1/(SUM+SUM1)
C COMPUTE LENGTH OF QUE
   250 ELQUE=((PO*(AR/SR)**NS)*RHO)/(SFACT*(1.0-RHO)**2)
C COMPUTE COST OF QUE
   260 CWLQ=CW*ELQUE
C COMPUTE COST OF SERVICE
   270 CSERV=(S-(AR/SR))*CS
C COMPUTE EXPECTED TOTAL COST
   280 EC=CSERV+CWLQ
C PRINT COST MODEL SOLUTION MATRIX
   281 WRITE(6,303) S,RHO,PO,ELQUE,CWLQ,CSERV,EC
   290 CONTINUE
   300 GO TO 10
   301 FORMAT(F3.0,F4.0,F7.3,F7.3,F7.2,F7.2)
   302 FORMAT('1',T8,'DISTRICT ',F3.0,
      1T23,'GANG ',F4.0,//1X,T8,'ARRIVAL RATE :'
      2,F7.3,T33,'COST OF WAITING : ',F7.2,
      3/1X,T8,'SERVICE RATE :'
      4,F7.3,T33,'COST OF SERVER : ',F7.2,//1X,T8,'NO. OF',T31,
      5'PROBABILITY'
      6,T47,'LENGTH',T58,'COST OF',T70,'COST OF',T81,'EXPECTED',/1X
      7,T8,'MECHANICS',  T83,'TOTAL',/1X,
      8T10,'(S)',T21,'RHO',T31,'OF ZERO QUE'
      9 ,T47,'OF QUE',T61,'QUE',T69,'SERVICE',T83,'COST',/)
   303 FORMAT(1X,T9,F4.1,T19,F6.3,T33,F8.6,T47,F6.3,T58,F7.2,T69,F7.2,T81
      1,F7.2)
   310 CONTINUE
       STOP
       END

$ENTRY
```

FIGURE 4 FORTRAN program for computing optimum shop staff.

Lq (length of queue). To determine this factor, the following assumptions must be made.

1. Assume the arrival rate is not state dependent (the rate of machines or structures arriving for service is not dependent on the number of units waiting to be welded). This assumption appears to be valid for this application because the customer will not go to another shop because of the long waiting line.
2. Assume the service rate is not state dependent. This assumption is valid as long as shortcuts are not taken as the work load increases.
3. Assume the service-time distribution is the same, regardless of which one of the welders performs the welding. Although there will be some variance in service rate between welders because of variation in ability, the distribution will be consistent around a mean value. This makes the assumption a valid one.

Based on these assumptions, it can be shown that

$$Lq = [Po\,(\lambda/\mu)^s \rho]/[s!\,(1-\rho)^2] \tag{2}$$

where

$$Po = 1/\left[\sum_{n=0}^{s-1}\left\{[(\lambda/\mu)^n]/n!\right\} + \left\{[(\lambda/\mu)^s]/s!\right\}[1/(1-\rho)]\right] \tag{3}$$

and

$$\rho = \lambda/s\mu \tag{4}$$

CONCLUSIONS AND PROPOSED REFINEMENTS

Solutions for the primary shop in each district are given in Table 3. Once the optimum number of service personnel was determined, additional man-hours were added for ferryboat and movable bridge repair based on the history of shop support in each district for this type of work. An overhead and leave factor was computed and applied to the total productive man-hours to get the total man-hour requirement. Finally, total man-hours were converted to the planned total number of service personnel. These numbers are compared with the number currently on board and indicate that the Department should reduce the overall staff level of mechanics from 219 to 197. Planned versus on board personnel are compared for each shop as a whole in Table 4. The elimination of secondary shops is expected to reduce administra-

TABLE 3 FY 1982 Optimum Shop Staff Requirements

Shop	Computed Equipment Repair Optimum	Computed Man-Hours	Marine Man-Hours	Productive Man-Hours	Overhead and Leave Factor	Total Man-Hours	Planned Total Mechanics	Mechanics and Welders on Board	Change
02-071	14	29,120	1,380	30,500	1.27	38,735	19	17	+2
03-071	12	24,960	734	25,694	1.25	32,118	16	22	-6
04-071[a]	12	24,960	–	24,960	1.26	24,336	15	23	-8
05-071[b]	10	20,800	–	20,800	1.17	24,336	12	19	-7
07-071	21	43,680	466	44,146	1.21	53,147	26	24	+2
08-071	22	45,760	–	45,680	1.23	56,186	28	28	0
58-071[a]	10	20,800	–	20,800	1.20	24,960	12	17	-5
61-071[b]	21	43,680	241	43,921	1.24	54,462	27	24	+3
62-071	15	31,200	308	31,508	1.24	39,070	19	23	-4
42-071	19	39,520	–	39,520	1.16	45,843	23	22	+1
Total	156	324,480		327,529			197	219	-22

[a]Shop personnel worked four 10-hr days, April 12-June 30, 1982. The shop was open 4 days a week, and 248 work days were used for computing downtime per day.
[b]Shop personnel worked staggered shifts of four 10-hr days, April 12-June 30, 1982. The shop was open 5 days per week.

TABLE 4 Repair Shop Personnel: Planned Versus On-Board, November 4, 1982

District Gang	Planned Repair Personnel	On-Board Repair Personnel	Planned Administrative Staff[a]	On-Board Administrative Staff[a]	On-Board Service Station	Plan Total Shop	On-Board Total Shop
02-071	19	17	4	4	2	25	23
03-071	16	16	6	6	3	25	25
03-072	0	6	0	4	1	1	11
04-071	15	15	7	7	3	25	25
04-072	0	8	0	2	1	1	11
05-071	12	12	5	5	4	21	21
05-073	0	7	0	2	0	0	9
07-071	26	13	6	6	4	36	23
07-072	0	5	0	3	2	2	10
07-073	0	6	0	2	0	0	8
08-071	28	17	6	6	3	37	26
08-072	0	6	0	2	0	0	8
08-073	0	5	0	2	0	0	7
42-071	23	22	8	8	3	34	33
58-071	12	13	8	8	4	24	25
58-072	0	4	0	1	0	0	5
61-071	27	24	5	5	5	37	34
61-072	0	0	6	6	0	6	6
62-071	19	23	6	6	5	30	34
Total	197	219	67	85	40	304	344

Note: Data are from telephone survey of districts.

[a]Administrative staff includes clerk, low-boy operator, shop superintendent(s), radio operators, parts runner, and stock clerk(s).

tive requirements. The total impact of this study would be a proposed reduction of 40 positions.

Implementation of this staffing plan is anticipated along with other personnel reduction plans and efficiency producing moves. The Department has always been able to use normal attrition to adjust personnel levels in the past. The process is expected to take approximately 1 year to reduce the staff from 344 employees to 304 planned positions for the repair shops. Annual recomputation of the staffing plan by using queuing theory is foreseen as changes occur to replacement funding. If equipment replacement is funded at the optimum level, further reduction of staff requirements may be possible. Unfortunately, Louisiana is currently experiencing a decline in revenue. It is expected that replacement funding in fiscal year 1984 will be significantly below the optimum level.

Although the immediate future appears rather bleak, the Department is currently under a mandate to reduce staffing levels wherever possible. If equipment replacement funds are reduced as expected, the demand for mechanic service will rise. If the optimum staff level cannot be maintained, higher downtime cost will be experienced and a net loss will occur.

Refinements to the cost model may be considered if it becomes apparent that a more precise solution is needed. Simulation will provide for greater precision and the consideration of more options. Measured arrival- and service-rate distributions could be simulated for each shop without the limitations of the Poisson arrival, exponential service distribution assumptions. Although a simulation model will allow many factors to be precisely controlled, including the arrival-rate distribution and the service-rate distribution, simulation is not currently being considered. This degree of precision is not considered necessary, and simulation is much more expensive than the mathematical model used here. If the use of queuing analysis proves successful, the determination of optimum staffing levels will have been performed at least cost. If not, the Department can proceed with the development of a simulation model without having wasted a significant amount of time and effort in the process.

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Arkansas' Equipment Management System

DOUG NIELSEN

ABSTRACT

Arkansas State Highway and Transportation Department (AHTD) personnel have recently completed work on a contract with FHWA to test and evaluate an equipment management system (EMS) using the FHWA EMS manual as a guide. The AHTD EMS consists of four major systems: (a) parts and materials inventory system, (b) equipment maintenance and operations cost system, (c) equipment cost accounting system, and (d) equipment control system. The parts and materials inventory system design specifies on-line computer terminals in each district stockroom to process the normal accounting transactions and provide stock management information. Transactions and adjustments are keyed at the point of origin and subjected to detailed edits to assure data accuracy. The equipment maintenance and operations cost system, equipment cost accounting system, and equipment control system are more interrelated and provide information to better manage the equipment function as a whole. Input data have been consolidated on existing forms to limit paperwork. Reports are primarily batch and produced monthly. Summary and exception reporting are emphasized. Reports to each level of management are limited to only the information needed to make the equipment decisions for which that level is responsible. Reports presently in use deal primarily with management of overall equipment operation and repair functions. Once an adequate amount of data is accumulated under the new EMS, system components dealing with equipment needs, budgeting, replacement, and rental rates will be put into operation.

In recent years there has been a movement among state transportation agencies to develop systematized methods to better manage available resources. Some results of these efforts are the various maintenance management systems and construction management systems. This type of approach can also produce dramatic cost savings in equipment management. Equipment management is the process of managing equipment resources to achieve maximum availability and productivity at the lowest relative overall cost.

Top management of the Arkansas State Highway and Transportation Department (AHTD), cognizant of the potential cost savings in the equipment area, initiated action to develop a comprehensive equipment management system (EMS) in the summer of 1975. Initial emphasis was on formulation of a statewide preventive maintenance (PM) program. A well-functioning PM program is an essential element of sound equipment management.

The PM program that was developed outlines a simple system for planning and scheduling periodic service and reporting equipment deficiencies. The procedures provide a positive means of communication