MANPOWER REQUIREMENTS PLANNING IN A CHEMICAL MAINTENANCE FACILITY: A TIME-DEPENDENT INTERACTIVE SIMULATION

William W. Williams

ABSTRACT

A GPSS simulation model was developed to investigate the behavior of a maintenance support group of a large fiber processing facility. Data were collected and appropriate frequency distributions constructed for call-in repair rates, repair resource requirements, and service times. Complications inherent in the problem environment that were incorporated in the simulation design included a non-stationary arrival pattern and an interaction in service resource requirements. Analysis of simulated responses suggests the model's internal structure represents reality to an adequate degree. Results of simulated experience of fourteen manpower configurations provide decision makers with enriched information on which to base staffing needs.

INTRODUCTION

A problem common to many manufacturing, as well as service organizations, is the determination of appropriate manpower requirements and the establishment of associated work schedules across a finite planning horizon. This decision is often complicated in many instances by uncertainties attendant to the aggregate demand for manpower services. A further entangling consideration may result from inherent variability in the time required to render service.

The existence of these two stochastic elements converge to create a most complex situation since human service capability cannot be physically inventoried to buffer and absorb fluctuations in requirements. If, in a given time period, demand for manpower services exceeds manpower supply available, demand cannot be completely accommodate and some portion most be queued, backlogged, or lost. On the other hand, if demand for manpower services is less than available manpower capability, the system is characterized by slack resources with concomitant opportunity costs. Consequently, the system's designer is faced with the task of balancing the total cost of delayed or foregone demand with the total costs of service provision in ascertaining manpower levels.

Because of the pervasiveness of this problem, and its importance to the efficient operation of many diverse types of organizations, the determination of manpower requirements has attracted the attention of the academic community. The development of "optimal" staffing strategies has been investigated within a broad spectrum of organizational environments. For example, the appropriate manning levels in telephone operator systems has long been a source of concern (Whitten 1961; Church 1973; Larson 1972). In the non-manufacturing area the problem has been studied in such diverse contexts as retail stores (Paul and Stevens 1971), supermarkets (Walsh 1974), fast-food restaurants (Bekiroglu 1977; Thomas 1974), drive-in banks (Foote 1976), expressway toll booths (Edie 1954), and refuse collection systems (Miller and Burgess 1975). In the field of health care delivery alone, employee allocation decisions have been examined in the staffing patterns of outpatient clinics (Rising etal. 1973) and hospital nurses (Flagle 1960), as well as manpower configuration in radiology departments (Johnson and Happ 1977), anesthesiology groups (Reisman 1977), emergency rooms (Hannan 1975), patient escort services (Magazine 1976), and combat medical support teams (Richards etal. 1977). In the manufacturing sector, effort most often has been focused toward the establishment of proper crew sizes for maintenance and/or machine repair support (Jaunsen 1977; Graver and Lehoczky 1977; King 1970; Bawa and Nair 1966; Fetter 1955).

Approaches to the formulation and solution of the manpower requirements problem have also varied considerably, ranging from deterministic decision rules (Walsh 1974; Flagle 1960) to more complex and comprehensive analytical or simular methods (Church 1973; Hardy and Krajewski 1975). A hallmark of many studies, with the notable exception of those focusing on telephone operator requirements, has been the assumption of a stationary distribution describing manpower demands or loads over time. This is especially conspicuous in the case of the extant machine maintenance and repair literature wherein the overwhelming majority of the analytical models have assumed that requests for service follow a static Poisson process. It does not seem unreasonable, however, to suggest that mean demand for service may be time-dependent (i.e., cyclic throughout a given time period), reflecting the influence of exogenous variables as system start-up, lunch breaks, shift changes, etc.

Furthermore, again with few exceptions, most approaches have operationalized the service entity as one characterized by homogeneous attributes.

However, in many environments, service capability is heterogeneous, comprised of varying skill mixes and possessing differential proficiency levels with respect to similar tasks. In addition, the satisfaction of a service request may depend upon either the simultaneous or the sequential interaction of two or more server skills (Graver and Lehoczky 1977).

Several investigators have explicitly incorporated the phenomenon of dynamic "arrival" distributions, but have assumed homogeneity and similarity in service response (Whitten 1960; Church 1973; Larson 1972). Conversely, other approaches have recognized the diversity of skills, but have assumed the demand for a given skill requirement to be known with certainty (Krajewski and Thompson 1975).

The research reported in this paper focuses on a problematic situation in which requests for manpower are time-dependent and the service entity is comprised of mixed skills. Additionally, demand for service may engender the application of one or more skill. Due to the complexities of the problem structure, a simulation modeling perspective was adopted.

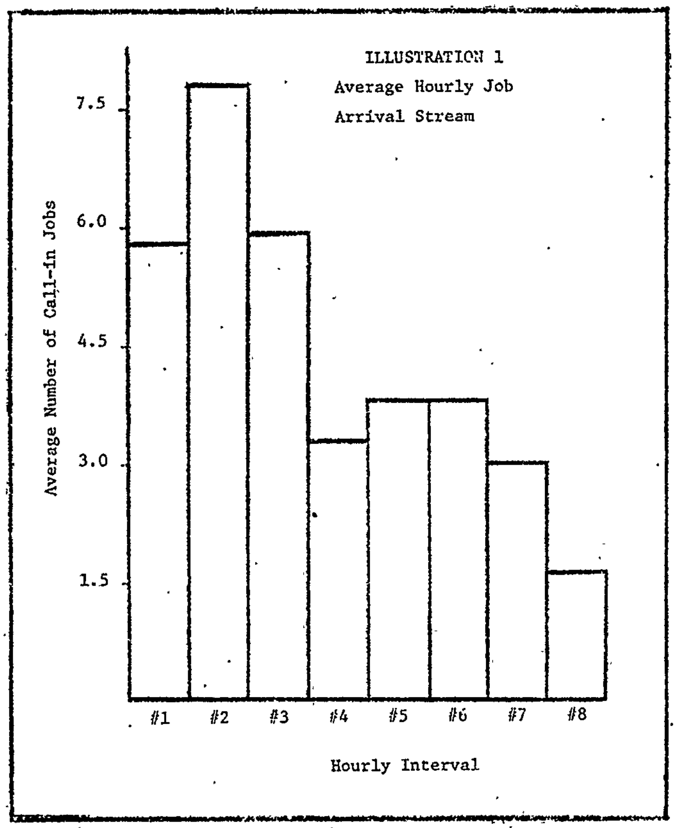
BACKGROUND AND SIMULATION DESIGN

This study embodied a primary concern for the determination of crew size and craft mix for a mechanical maintenance group dedicated to the support of a large fiber processing facility. The maintenance support group is responsible for the discharge of three distinct missions: call-in or emergency repair, preventive maintenance, and spare parts repair. The shop is staffed by three distinct occupational specialties: millwrights, pipefitters, and welders. At the time the study was initiated, four millwrights, four pipefitters, and two welders were assigned to the maintenance funtion. Due to occupational training, as well as labor work rules, substitutibility of skills between craft operations is limited. However, successful completion of some jobs entering the maintenance shop occasionally required the collaboration of skills of more than one specialty.

Because of recent loses of two employees, the general maintenance supervisor evidenced some concern that the level of existing manpower (10) was inadequate to properly maintain spare parts inventories and conduct preventive maintenance since all call-in repair work received top priority. Only after all emergency work was accommodated could residual time be directed to the two remaining tasks. In addition, the maintenance supervisor also questioned the current skill composition of the support group as to its efficiency in responding to call-in jobs.

INPUT SPECIFICATION: CALL-IN REQUEST RATE, CRAFT REQUIREMENT, AND SERVICE TIME DISTRIBUTIONS

An eight week period of call-in activity was reviewed and the data used to construct time dependent load distributions for manpower services. The incidence of emergency job requests were recorded by five minutes intervals for each day during an eight hour shift. Inspection of the eight week time series suggested neither an apparent trend nor autocorrelation was present in the data. However, when call-in requests were aggregated by hour of origin, it became obvious that the "arrival rate" of jobs across a day could not be assumed stationary (See Illustration 1). Empirical "arrival" frequency distributions were constructed for each hourly interval and compared to theoretical distributional expectations, estimated on the basis of the mean and variance of the observed data. The Kolmogorov goodness-of-fit test was employed since this test is considered more exact and powerful for small samples than the chi-square test (Conover 1971). For each of the eight intervals tested, the hypothesis that the actual hourly call-in rate was described by a Poisson process could not be rejected. Hence, for simulation purposes, emergency job "arrivals" were assumed to exhibit a non-homogeneous Poisson configuration, ie., call-in jobs would be randomly distributed across a given hourly interval, but each hour would reflect a singular mean "arrival" rate.



Data were next gathered from weekly labor report logs to determine craft manpower required by call-in requests. Approximately 76% of all emergency dispatches required the service of only one specialty while the remaining requests necessitated mixed skills. Partitioning of total single skill requirements disclosed that 47 percent were for millwrights, 39 percent were for pipefitters, and 14 percent were for welders. In addition, occasionally jobs were of such magnitude that the scheduling of two or more "servers" was required. The breakdown of multiple resource request is shown in Illustration 2. Finally, for mixed skill jobs a tabulation of dispatches revealed that approximately 55 percent were for a combination of millwrights and pipefitters, 20 percent were for a combination of millwrights and welders, 17 percent were for a combination of pipefitters and welders, and 8 percent for a combination of all three skills.

ILLUSTRATION 2

Multiple Service Requirements

	1	2	3
Millwrights	.72	.27	.01
Pipefitters	.75	.23	.02
Welders	.97	.03	-

Investigation of the craft service times proceeded analogous to that performed on the call-in request rates. Examination of the labor logs indicated time charges against each craft specialty. Frequency distributions were constructed for each of the three occupations. Since for all three specialties the coefficient of variation was found to be approximately 1.0, it was decided to test the empirical service time distributions against the exponential distribution. Employing both the Kolmogorov and chi-square tests, the hypothesis that service times follow an exponential pattern could not be rejected at the $\alpha = .01$ level.

MODEL LOGIC AND VALIDATION

Once the call-in arrival rate, resource requirement, and craft service time distributions had been specified, a GPSS/360 (General Purpose Simulation System) model was developed to simulate the behavior of the maintenance facility over time. GPSS was chosen primarily because of its flow orientation (i.e., call-in requests "arriving" at multiple capacity, mixed attribute service facilities) as well as the programming ease attendent to its housekeeping and output conventions. A brief discription of the simulator logic follow.

The model was constructed around an implicit time unit of one second, with each run comprising one eight hour shift in simulated time. The selection of a realtively small time increment in relation to mean job inter-arrival and service times was predicated on the well-documented truncation properties of the GPSS processor. Basically, as the simulation proceeds dynamically, call-in request transactions are GENERATEd according to a Poisson process. Each hour, the operand of the GENERATE block is updated via an indexing procedure to reflect the current mean inter-arrival rate. The "request" transactions are then routed through a stochastic TRANSFER block which randomly determines whether the job is single or multi-craft. If the job is single resource consumptive, a TRANSFER block operating in the function mode routes the transaction to the appropriate service entity location in accordance with historical frequencies. Likewise, multiple resource usage is ASSIGNEd at this point by sampling from appropriate distributions. If requisite capacity is available, the service entity is "captured" and exponential service time elapses as the job is "held" in an ADVANCE block; if service capacity is exhausted, the job is queued. Likewise, if the job is multi-craft, a funtion TRANSFER randomly determines the skill composition required and routes the job to appropriate entity locations[1]. Mixed skill jobs are given service priority in the event of "time ties" as well as in backlog queues. Call-in jobs are GENERATEd for a period of eight hours at which time the GENERATE block becomes inactive. The simulation continues, however, until all in-process and/or queued jobs are completed.

A total of ten replications were produced for each of fourteen manpower configurations. Five separate runs were made utilizing different random number needs and multipliers. Subsequently, five additional runs were made with the identical sequence of needs and multipliers, but adopting the technique of antithetic variates to provide maximum negative correlation between replications (Shannon 1975). In addition, correlated sampling procedures were incorporated between runs of experimental configurations via selective use of RN generators to insure a similar historical sequence of stochastic events for all manpower levels and minimize the introduction of random error. Each run consumed approximately 9.5 seconds of CPU time on an IBM/360 system.

Inspection of output streams of a number of pilot runs suggested that the call-in rate and service time generators displayed reasonable conformance to the actual events (Illustrations 3 and 4). Since the study was undertaken with the primary objectives of augmenting the decision maker's awarness and understanding of the maintenance facility, as well as exploring the system sensitivity to changes in manpower configurations, small errors in input specification do not seem intolerable.

SIMULATION RESULTS

Fourteen alternative manpower configurations were simulated under controlled conditions and output statistics gathered on four important criteria variables. Total maintenance staff simulated ranged from a low of ten individuals (the current workforce level) to a high of fifteen (the upper limit on staffing possibilities). The criteria set was comprised of: the maintenance "service level" (i.e., the proportion of call-in jobs that were serviced immediately without wait), the proportion of call-in jobs currently being processed

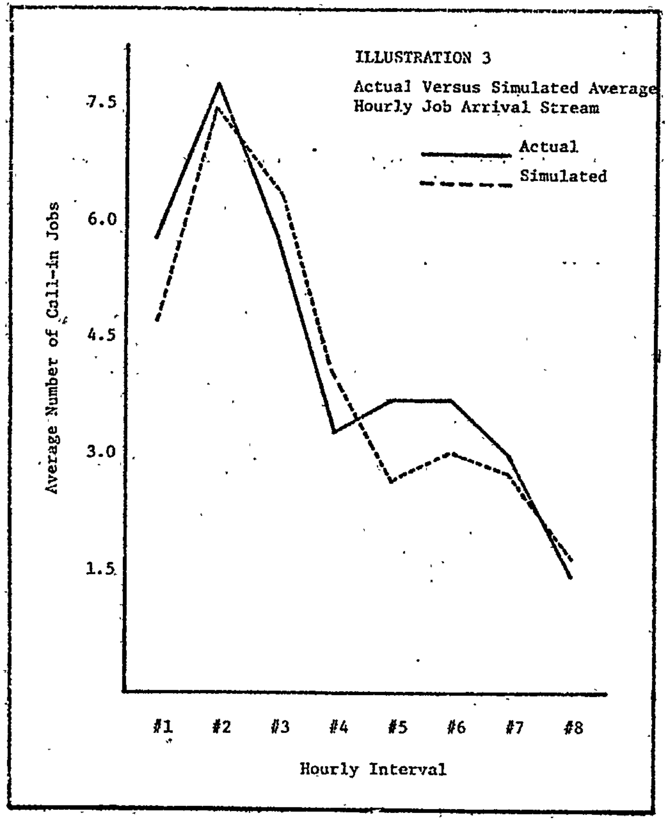


ILLUSTRATION 4

Actual Versus Simulated Mean Service Times (Minutes)

	Millwrights	Pipefitters	Welders
Actual	170.4	175.8	157.8
Simulated	160.2	171.6	172.8

and/or completed at the end of an eight hour shift, the average job waiting time, and the utilization of the service entity. Statistics were recorded for each of the three individual craft specialties, as well as for the queue behavior of jobs that required some combination of the three resources. A summary of the simulated results appears in Illustration 5. As anticipated, the performance characteristics of the current staffing configuration (four millwrights, four pipefitters, and two welders) is generally poor in terms of overall service level and average job wait. In addition, craft utilization rates are relatively high indicating little residual time available for preventive maintenance and/or spare parts repair. The observations of the maintenance supervisor of actual operations of the facility generally confirmed these findings.

Supplementing the workforce with either a millwright or a pipefitter improves performance markedly: approximately a 35 percent increase in service level and a 40 percent reduction in average job wait. The addition of one more welder has a similar impact on service level and an even greater effection job delay times. However, the addition of one, or even two, employees appears to have little appreciable impact on the queue behavior of call-in jobs requiring mixed skills. Evidently, increments of one or two have a negligible effect in relieving "bottleneck" conditions evidenced in the remaining craft specialty.

As expected, the addition of three or more employees reveals continued improvements in individual craft queue behavior. More importantly, with a workforce of thirteen or more, significant improvements in performance of mixed-skill call-in jobs materializes This implication is supported by correlations between combinations of workforce additions and maintenance system behavior (Illustration 6). These correlations suggest that greatest improvements in performance of mixed-resource jobs would be achieved by adding some combination of millwrights and pipefitters as opposed to any other combination.

ILLUSTRATION 6

Correlations Between Workforce Additions And Selected System Performance Criteria

	Mixed Resource Service Level	Mix Resource Job Wait
Total Workforce	.81*	-.95*
Millwrights/Pipefitters	.90*	-.89*
Millwrights/Welders	.36	-.67*
Pipefitters/Welders	.42	-.74*

At the time of this writing work is continuing with a focus on total workforce levels of thirteen and fourteen. A larger set of replications will be developed to enhance statistical confidence in the stability of output streams. Furthermore, the possibility of altering the actual dispatching system from "first-come, first-served" to a "shortest-estimated-processing-time" rule is being explored. If this is found to be feasible, simulation of criteria sensitivity to this new dispatching procedure will be undertaken. Finally, an effort is underway to assess the cost of call-in delays and backlogs so that an estimated "total cost" of various manpower configurations can be computed.

ILLUSTRATION 5

Summary of Simulation Results

Configuration[a]	Maintenance Service Level[b]				Jobs in-Process or completed				Potential Job Wait (hours)				Facility Utilization		
	Mill	Pipe	Weld	Mix	Mill	Pipe	Weld	Mix	Mill	Pipe	Weld	Mix	Mill	Pipe	Weld
4-4-2	.34	.35	.49	.23	.66	.68	.76	.55	3.04	2.35	1.84	4.43	.84	.82	.70
4-4-3	.33	.27	.74	.27	.76	.53	.91	.65	2.25	3.75	.42	3.71	.82	.87	.54
5-4-2	.50	.33	.52	.25	.79	.77	.79	.51	1.73	2.05	1.71	3.81	.79	.84	.67
4-5-2	.35	.48	.54	.22	.64	.80	.74	.61	2.81	1.30	1.45	3.54	.83	.79	.66
5-5-2	.41	.51	.54	.28	.78	.76	.79	.65	1.71	1.43	1.83	2.67	.81	.80	.66
5-4-3	.44	.29	.73	.25	.79	.69	.93	.58	1.61	2.54	.39	3.55	.78	.85	.56
4-5-3	.33	.50	.73	.24	.67	.79	.93	.66	2.63	1.35	.38	2.77	.83	.81	.55
5-5-3	.50	.45	.73	.26	.81	.70	.93	.72	1.53	1.97	.57	2.15	.77	.80	.58
6-5-2	.56	.50	.58	.32	.90	.80	.71	.65	.85	1.29	1.93	2.40	.75	.79	.70
5-6-2	.43	.65	.60	.36	.78	.83	.83	.68	1.98	.76	1.52	2.48	.80	.73	.62
6-6-2	.52	.66	.54	.41	.85	.88	.81	.69	1.10	.57	1.69	2.09	.74	.75	.62
6-5-3	.53	.45	.73	.29	.87	.73	.95	.78	.84	1.42	.37	1.98	.73	.82	.59
5-6-3	.45	.58	.78	.35	.78	.80	.91	.73	1.88	.80	.49	2.06	.78	.76	.53
6-6-3	.53	.59	.72	.37	.87	.87	.93	.74	1.03	.63	.69	1.71	.74	.78	.56

[a]Expressed as #millwrights-#pipefitters-#welders

[b]Proportion of jobs that experienced no wait

FOOTNOTES

1. For simulation purposes, it is assumed that in case of both mixed-skill and multiple - resource jobs requisite service capacity must be simultaneously available before the request is filled; if it is not, the request is queued until such capacity becomes available. More often than not, this procedure was employed when actually dispatching jobs in the facility.

REFERENCES

[In an effort to conserve space, a detailed bibliography of citations has been omitted. A complete list of references is available upon request from the author].