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An investigation or the capacity vs. product mix relationship in a multi-stage, multi-product, dynamic, between stages inventory production system.

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AN INVESTIGATION OF THE CAPACITY VS. PRODUCT MIX RELATIONSHIP IN A MULTI-STAGE, MULTI-PRODUCT, DYNAMIC, BETWEEN STAGES INVENTORY PRODUCTION SYSTEM

by

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ABSTRACT

The investigation undertaken deals with the operating and performance characteristics of a multi-stage, multi-machine, multi-product, dynamic, between stages inventory production system. Actual performance statistics are analyzed as a function of the plant workload in order to determine if a definable capacity measure exists and if there is a quantifiable relationship between workload and capacity. The particular facility under examination is a large scale tire manufacturing operation. The investigation indicates that the capacity of the system in terms of pounds of product produced per man hour invested is a linear function of the workload in terms of number of tires per size to be manufactured. The conclusion made from the investigation is that a definable capacity measure exists which can be described in terms of output per man hour as a function of tires per size produced, and that there is an economic trade off between the workload scheduled and the related unit capacity cost of the facility.

Chapter 1

INTRODUCTION TO THE GENERAL PROBLEM

In the planning, scheduling, and controlling of manufacturing systems, the concept of capacity automatically surfaces as a basic input into the decision making process. The Third Edition of the American Production and Inventory Control Society Dictionary defines capacity as "the highest, sustainable output rate which can be achieved with the current product specifications, product mix, worker effort, plant and equipment." [19:5] This definition implies a systems viewpoint; that capacity is a function of many variables and that it is a dynamic measure depending on the states of the independent variables at any given point in time.

Capacity determination analyses are plentiful and their scopes are broad. Methodologies surveyed in the literature vary from micro applications to macro applications. The first look at capacity generally occurs at the micro level, in other words, at the work station or departmental level.

The factors affecting capacity can be classified into two groups: Planned Factors and Monitored Factors.

Planned Factors include:

Land	Days worked per week
Facilities	Overtime
Labor	Subcontracting
Machines	Alternate routing
Tooling	Preventative [sic] maintenance
Shifts worked per day	Number of set-ups

Monitored Factors include:

Absenteeism	Material shortage
Additional set-ups	Scrap and re-work
Labor performance	Unusual tool problems, etc.
Machine breakdown	

In general, management decrees planned factors when performing long and medium range planning. Monitored factors are less subject to direct control and are usually involved in medium range capacity planning and short range capacity control [1:116].

Using these factors, a method for determining machine or work center capacity has been developed. If historical data (monitored factors) indicate that machine utilization is 85%, and that operator efficiency is 90%, then along with the assumptions (planned factors) of three shifts, eight hours per shift, five days per week, two machines available, and no overtime, the machine center capacity could be calculated as

$$\text{Machine center capacity} = (.85)(.90)(3)(8)(5)(2)$$
$$= 183.6 \text{ standard hours per week.}$$

This figure could then be multiplied by the standard hours per piece to arrive at a "pieces per week" unit capacity figure if that is a more desirable measure.

This method is used widely in areas which have established some type of standard or estimated hours per unit for purposes of planning, scheduling, or control. It is a simple measure based on a historical set of data, which it is presumed, will not deviate greatly from average in the near future. Once this machine loading analysis has been performed and it has been determined that either too much or too little capacity is available, several methods involving different time frames have been suggested in order to alter capacity:

Long range:

Change land and/or facilities	Change capital equipment
Change work force	Etc.

Medium range:

Change make/buy decision	Change work force where feasible
Plan alternate routings	Add additional tooling
Subcontract over long periods	Etc.
Re-allocate work force	

Short range:

Schedule overtime	Re-allocate work force
Subcontract over short periods	Etc. [1:117]
Select alternate routings	

In essence, the capacity determination method mentioned above combines historical data with stated factors and thereby derives an average expected capacity figure based on "yesterday's" performance. This is by far the most frequently used method for capacity determination and Greene summarizes this procedure by stating:

> Some companies calculate plant capacity on a periodic basis from time study data and other sources of information, while others derive their plant capacity from history. The management knows that the plant has put out certain quantities in the past and assumes that this will continue in the future. This is the common way and is why one sees so little written on the subject [10:340].

Greene continues in this frame by stating that capacity is a dynamic measure and that effective managers will not only review capacity figures periodically, but they will also be aware of the costs involved to alter the capacity of the facility.

An awareness of the costs involved when contemplating alterations to a facility in order to change capacity may be elusive. A good example of this would be the cost-benefit ratio attributable to increased in-process inventories. Whereas the purchase of a new piece of equipment yields a quantitative measure of increased capabilities based on the operating data of the machine, the impact of increased inventories is often difficult to quantify.

Even when production managers are aware of the costs involved, the process of meeting the production goals of top management may result in conflicting direction. Managing production facilities when trying to accomplish goals which overtax plant capacity may result in goal accomplishment; however, the effects are often extremely expensive and unprofitable. Hence, not only must a production facility be concerned with the "highest sustainable output rate which can be achieved," but also with the costs involved in attaining the desired output. There is an economic trade-off involved in the selected versus potential capacity level.

Plossl and Wight present an overall model for use when discussing the concepts of capacity and load in the form of a bathtub model (Figure 1). Whereas the "load" on a facility is analogous to the level of water in the bathtub, "capacity" is analogous to the rate at which the water is flowing out of the bathtub. The distinction to be made between "load" and "capacity" is important; although the concepts are closely related, their meanings are significantly different [17:31]. Load is generally defined as "the

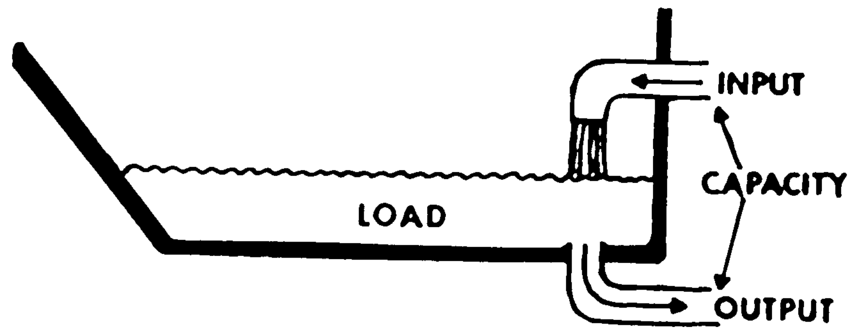

Figure 1

Load vs. Capacity

amount of scheduled work ahead of a manufacturing facility usually expressed in terms of hours of work." The usage of "hours of work" as a measure is usually better than the usage of "number of units" to be produced. If units of product is used as the capacity measure, it may be possible to increase capacity (or decrease capacity) enormously through alterations to the product mix.

Increasing capacity without increasing the total investment in capital equipment is also possible. Logically, by increasing the levels of in-process inventories, longer runs and more independent operation of departments can take place. Consequently, in-process inventory as a capacitated facility within the manufacturing system is generally acknowledged by production management's eternal comment: "We never have enough inventory!" Having now ascertained that there is never enough, how much should there be?

Greene offers another "fluids" model which attempts to tie together single stage capacities into a system capacity (Figure 2). It is implied by the figure that different departments have different capacities and that an effort to increase the capacity of a non-restricted department in hopes of improving overall capacity would be futile.

Greene's model also details a storage department and implies that storage has a capacity as mentioned before. The problem with describing inventory capacity is that it is expressed in different terms than production (ie., available hours versus maximum number of units which can be stored) [10:340].

Generally, the determination of the capacity of a facility is based on historical data in conjunction with estimates of the future conditions which will exist throughout the time frame upon which the capacity determination is based. For this reason, many capacity determination methodologies tend to be "rough cuts" of the system. Accurate and reliable historical data is often

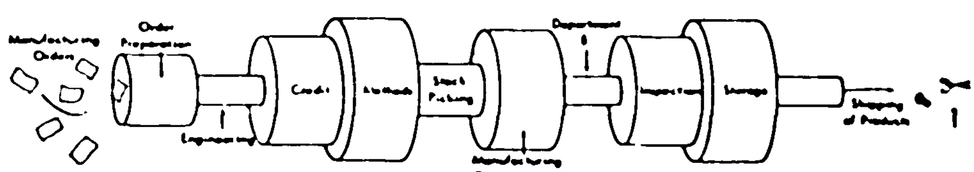

Figure 2

Fluids Analogy of Production

difficult to obtain; if obtained, the independent variables involved in determining capacity may be so numerous that the system description or model becomes intractable. Assuming away some of the characteristics of the system allows for easier model development, but if facilitating assumptions are made then the actual system is not being accurately described. Any results derived from estimates of a system remain estimates.

Chapter 2

BACKGROUND TO THE SPECIFIC PROBLEM

The specific system under investigation can be described as a multi-stage, multi-product, dynamic, with in-process inventory production system. This production system can be found in industries such as paper manufacturing, textile manufacturing, and tire production. The primary similarity of process in all three industries generally involves a production sequence as follows:

1.) Raw materials are processed into semi-finished goods or components in lots

2.) The semi-finished goods and/or components are stored and become in-process inventory

3.) Components and semi-finished goods are withdrawn from in-process inventory and are processed or assembled into a specific end product in lots

4.) The end products are placed in in-process inventory and are stored

5.) The end products are withdrawn from end product inventory for finishing or final processing

6.) The end product is then warehoused and stored prior to shipping.

This type of system is process oriented and involves the production of many different types of finished products from many common components. The system usually runs "lots" of products on an intermittent basis. In large operations, there will be multiple machines producing within any given process or product area. The dynamic nature of the system is due to the fact that the ever-changing lot sizes and production items generate a new set of constraints at the conclusion of each production run.

When the problem of capacity determination is addressed for this type of production system, the following types of inputs and independent variables are considered:

1.) Number of machines per area or department

2.) Production rate per machine

3.) Number of units which can be stored in in-process inventory

4.) Number of departments (stages) in the system

5.) Lot size per production item by department

6.) Special product characteristics

7.) The expected change in product requirements over time.

Obviously, in a large production system, the model description could become very unwieldy, if describable at all. The general capacity model was described previously; the problem of in-process inventory storage capacity was not discussed quantitatively nor was the dynamic nature of the system addressed. When discussing a specific production system capacity determination methodology, it is easier to analyze the particular characteristics of the system.

Various methodologies can be found in the literature for the determination of facility capacity when limited to the multi-stage, multi-product, dynamic, in-process inventory system. Wilhelm [21] describes a probabilistic model which could be used for planning purposes in a job shop system. The author's intent is to model random variables which might comprise workload and develop a composite measure which evaluates the capability of the system to produce the planned workload. The capacity rating (CR) index is defined for each work center as

$$CR = P_r \Big| \text{ (workload} \leq \text{availability)}$$

in any given planning period. Wilhelm and Doty [23] recognized, however, that the capacity rating methodology would result in the development of certain structural characteristics, especially with regard to queuing. The authors evaluated the relationships between the static capacity rating measure and the dynamic operation of a job shop via a simulation model. The system simulated involves a two product, one machine per work center, three work center system. It was concluded for the three cases simulated that a static measure such as the CR index is more sensitive to the dynamic operations of the job shop than are deterministic measures. Nonetheless, the meaning of any CR index must be evaluated in the specific job shop in which it will be applied. In addition, the CR measure appeared to be an economic alternative to simulation when analyzing the consequences of certain management decisions on the job shop system.

The majority of the models described for this system are to be found in the operations research literature. Johnson and Montgomery [12] discuss the dynamic nature of this system and offer various scheduling alternatives subject to production capacity constraints. These models involve interstage inventory balancing equations, and as a result, cannot consider constraints on inventory capacities. Interstage inventories act as buffers to absorb imbalances between the production rates of successive stages; accordingly, the larger the interstage storage system, the more independence between stages. Inventory balancing equations serve to relate the ending inventory for the first stage to the beginning inventory for the second stage. Their function is to assure continuity of product flow through the stages and cannot be used to explain the effect of inventory capacity restrictions on the system. Zangwill [24], Buzacott [3,4], Freeman [7], and Okamura and Yamashina [14], among others, have examined this characteristic using operations research and queuing methodologies. Gorenstein [9] models a tire production system almost exactly as described in this paper, but again does not consider the between stage inventory capacity limitation in his linear programming model.

Ignall and Silver [11] have considered the two stage, multiple machines per stage production system with limited storage and unreliable machines and describe a heuristic procedure for estimating the output of the facility. Although the Ignall and Silver analysis does not consider the complicating effect of multiple products in addition the the other system characteristics, the results are interesting. The authors begin with Buzacott's results for the no storage and infinite storage, two stage, one machine system and then adapt the results to obtain an approximation of the output that increases continuously between these two known extremes as interstage inventory capacity increases. The one machine per stage model is then replaced by multiple machines per stage and the heuristics are developed and tested by simulation (Figure 3). It should be noted that in additon to varying the buffer capacity, this model could be used to analyze variation in failure rates and repair times while holding the buffer capacity constant. Theoretically, the effect of increased changeovers on capacity due to product mix changes might be estimated if failures and repair times are equated to frequency of changeover and set-up times.

Rice [18] has also examined the behavior of a multi-product, multi-stage, multiple machines per stage, buffer stock production system using GPSS (General Purpose System Simulation). The objective of the study was to determine the through-put times of orders issued to the shop. Although Rice's analysis allowed forecasting of job completion times from schedules, the method employed could be extended for use in evaluating production capacities.

Lastly, Evans [6] presents a heuristic model of a deterministic, multi-product, multstage, limited interstage inventory production system utilizing a network flow technique. The heuristic solution to the problem involves "relaxing" the constraints of the arc capacities and then solving the network for feasible solutions utilizing an out-of-kilter algorithm. Evans indicates that the results are generally within 7% of the optimum cost for the production plan.

In summary, although the capacity rating index, simulation, heuristics, linear programming, and network flow analysis are all

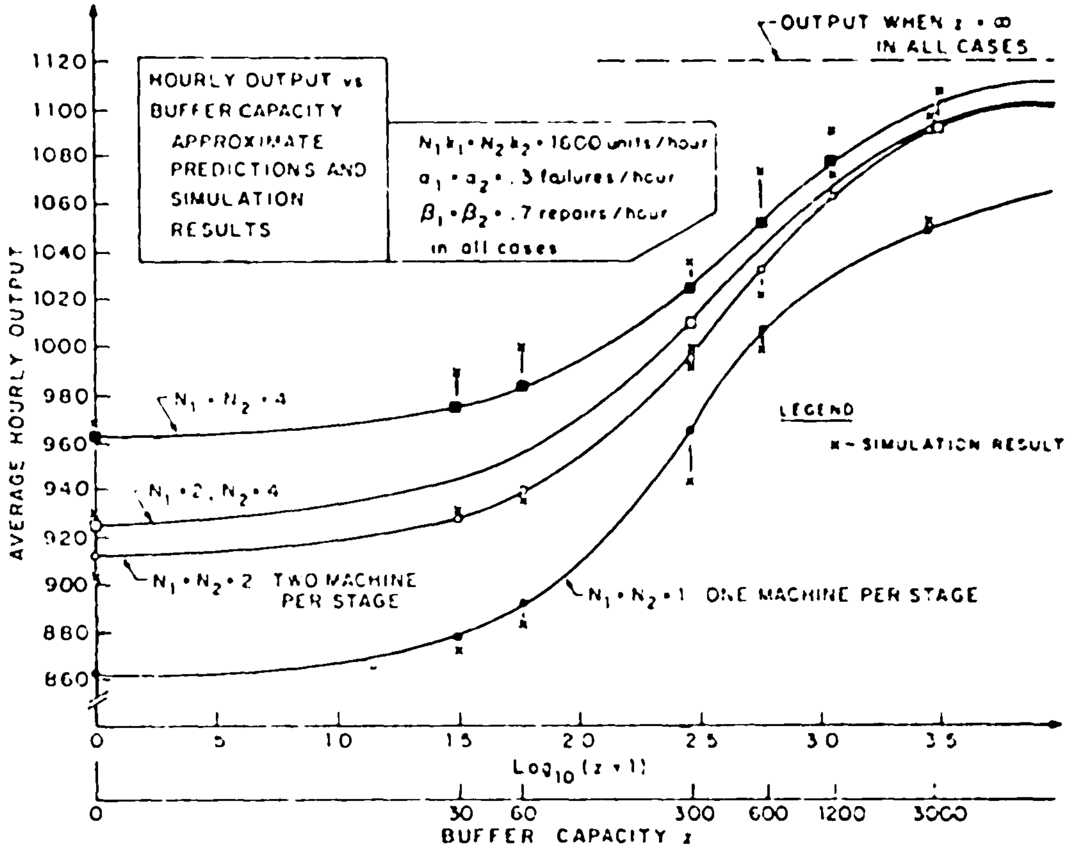

Figure 3

Hourly Output vs.
Buffer Capacity: Approximate
Predictions and Simulation Results

techniques which have been described in the literature as methods by which the capacity of this particular system can be analyzed, all of the techniques suffer from one major failing: they do not describe an existing "live" system. Assorted assumptions have to be made in order to create the model; once these assumptions are made the "real" system is no longer being described. In its place is an artificial system which is more manageable and more easily evaluated. Production personnel would not object to handling a cumbersome method (computers are readily available now) if the results pertained to the system they were working with. The statement "that's great in theory but it won't work on the floor" is directed toward the theoreticians who present solutions to the problem that have assumptions which make the analysis neater but which also make the solution inapplicable. The models do not accurately describe the reality they were designed to duplicate.

Apparently, the best method available which can be used to describe this system is simulation. A minimum of assumptions have to be made and independent variables are readily varied in order to perform sensitivity analysis. As simulation can adapt to the dynamic nature of the system, a better feel for the ongoing occurrences is possible.

Chapter 3

STATEMENT OF THE PROBLEM

Many times the personnel involved in the day-to-day operation of a production facility find themselves in a position of defenselessness. According to the operations analysts (Industrial Engineers and the like), the system is capable of producing a specified number of items daily and at a targeted cost, but in actuality, the goal is not being accomplished. The scheduling people are frustrated because everything on the floor is "hot" and yet more and more items are finding their way into the system before any of the original "hot" items have a chance to get out. The question then arises: What is the facility's capacity? Is the facility actually being overloaded, and if so, can it be determined what level of production or load the facility should be operated at in order to obtain the desired return on the capital invested?

The facility under investigation produces passenger radial tires, passenger bias tires, truck and bus tires, industrial (lawn and garden, trailer, forklift) tires, innertubes, and retread rubber. The facility is housed in a multi-story building which was purchased and put into tire manufacturing operation in 1945. The official plant unit capacity is rated at 27,500 tires per day, which is the sum of the rated capacities for the different types of tires produced.

Total employees in the tire division (staff and production) number about 2300; most production employees are members of the United Rubber Worker's Union (International Union of United Rubber, Cork, Linoleum, and Plastic Workers of America, AFl-CIO, CLC).

Stop watch time study is used in the plant to determine standard times for use in the incentive piecework system. Not all of a production worker's pay is based solely on piecework earnings, however; since 1958 no wage increases were incorporated into the rate structure. As a result, there is an hourly rate of pay which is "guaranteed" to all employees to which is added incentive monies earned from piecework production.

The primary concern of the facility is in the production of tires; monthly performance statistics are compiled and used as productivity indicators. The most popular measure employed is "pounds per clock man hour," which is defined as the monthly warehoused production weight divided by the total number of manhours that were logged in obtaining that weight.

The assembly and finishing of tires is a combination of two types of production systems. Components and subassemblies used in tire assembly are produced in process oriented departments and are time phased into the assembly department. From tire assembly on, tire lots are finished through stages much like a flow process job shop system. In-process inventories are used to facilitate more efficient scheduling within the departments.

The component and subassembly manufacturing system is not as complex as the tire assembly process. Usually only one or two components (such as rubber compound plus fabric) are processed into a subassembly (such as plies). Although there are only three broad classifications of tire components, each tire may require several different components from each classification. Figure 4 overviews the broad component classifications and the assembly and finishing process of producing a tire. It should be noted that the production system can be described as having the following characteristics:

1.) Multi-stage processing
2.) Multiple machines in each stage
3.) Multiple products produced simultaneously
4.) Multi-period time frame
5.) Limited interstage storage areas for work in process
6.) Unreliable machines (due to changeovers, operational downtime, lunch and breaks, etc.)

Tire production is seasonal, running a heavy winter product mix during the spring and summer months and predominantly regular tires during the fall and winter months. Tire production is generally done in lots; only original equipment or extremely popular items will stay in continuous production. The limiting factor in the determination of item production rates is the quantity of molds available for that particular item. As a mold is an "engraved" replica of the finished tire (including brand name, size, etc.), there are a large number of molds in inventory as compared to constructions of tires produced at any one time. In many cases one

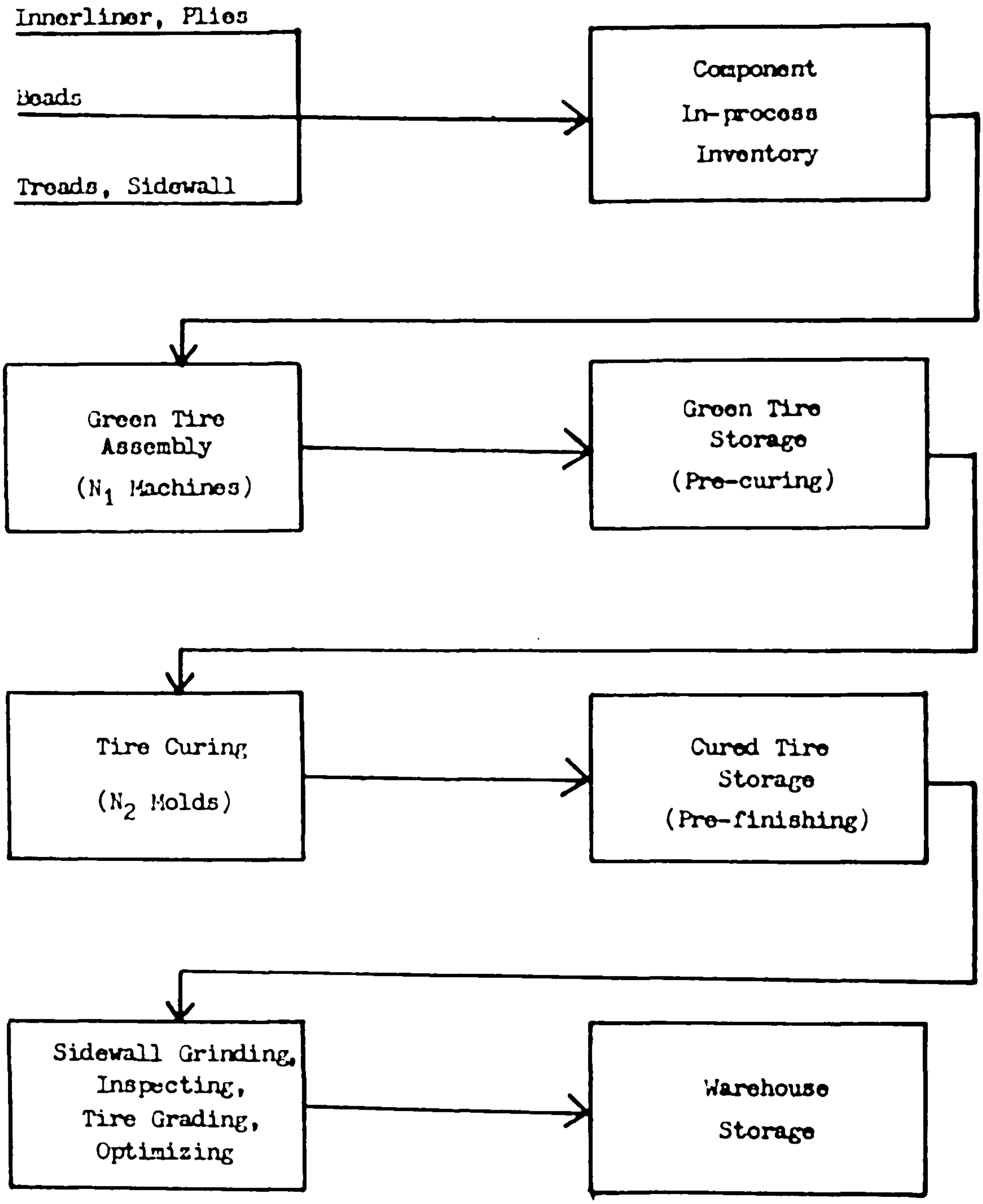

Figure 4

Tire Assembly and Finishing Process

particular construction of green tire will produce multiple brand names of tires; this type of tire and mold arrangement is called a "common green tire" because the tire can be used in many molds.

Due to the production restrictions imposed on the system by the mold inventory, curing becomes the focal point for all plant scheduling. The molds compete for press allocation of the floor, and as the capacity of a tire building machine significantly exceeds the curing rate of one mold, tire building machines change from one specification to another in order to keep multiple molds supplied with green tires.

No forecasting or medium to long range production planning is done at the producing facility. The corporate office of production planning transmits a weekly "ticket" which is a production plan detailing quantity and type of tires to be manufactured in the coming week.

Production plans can be varied dramatically. The work force is unionized, therefore, layoffs and recalls are rather matter-of-factly accomplished. Consequently, there is no need for aggregate workforce planning or scheduling.

The union at the plant is fairly strong. A piecework incentive system is used throughout the plant on every operation that is measurable. Unfortunately, as the plant has aged, so too has the piecework system. After 30+ years of operation the piecework program is significantly different in its appearance, operation, and effect than the system which was originally employed. Earning "caps" are widely employed in the areas where the time standards have all but disintegrated. As a result, production rates are fairly predictable.

The past ten years has seen an increasing market demand for the radial tire. Product proliferation was occurring as a result; the plant that had had to deal with only two types of construction technologies (Bias and Bias Belted) now had to deal with upwards of four types of construction technologies (Bias, Bias Belted, Flat Drum Radial, and Multi-stage Radial). In essence, the demand on the production facility was increasing dramatically even though the volume of production required was not.

The measures used when discussing a plant's capacity can be expressed in terms of many variables. The first is the sheer number of tires to be warehoused over a specified time period. This measure does not allow for wide variances in the tire characteristics; certainly the capacity of a plant producing earth mover tires would be significantly different in terms of units involved than a plant producing 13" passenger tires. As a result, a plant's capacity is usually expressed as units per day available by type of tire. This measure has difficulty allowing for product mix within a grouping, however. Product mix becomes a significant input when it is realized that a plant producing only one type of tire has the potential for greater output than does the same plant trying to produce 100 types of tires on the same equipment. As components and subassemblies proliferate, the number of changeovers and set-ups increase proportionately. Therefore, in order to maintain the same production level with increased product complexity, either operating efficiency must improve or additional equipment must be started up. It is generally unlikely that operating efficiency would improve with an increasingly complex production plan; more than likely the effect of handling increased types of components and subassemblies will place a strain on storage areas and in-process inventory control which may affect overall equipment utilization. Therefore, not only must quantity and complexity of the production plan be considered; cost of production at a given capacity is also an important factor in determining the overall capacity performance of a facility. The factor chosen as an "equalizing" device is "pounds of product per production of "clock" man hour." As a performance measure this is a good one; pounds per clock man hour analyzes how effectively the organization utilized the resources available in accomplishing the specified production plan. Pounds per clock man hour can also be an indicator of the relative capacity of the plant. Given a fixed number of workers, "over-loading" the plant with an increased number of products will necessarily result in decreased output and increased costs. Thus, pounds per clock man hour should go down. Theoretically, the pounds per man hour could be driven to a limit of 0; in the real world, however, it is usually the case that only a certain maximum production cost is tolerable. Once this tolerance level is reached, the managerial system will react to the unsatisfactory indicator and will attempt to turn the trend around. Hence, we can expect a "minimal" value which would represent the worst period for the operation. The other end of the scale should represent the best period; although the figure may not be the maximum capacity for the plant, it will indicate what was actually accomplished given the particular production plan. Some references as mentioned earlier will define this actual output as the plant's capacity. Perhaps this is an accurate use of the word; however, it seems that many usages of capacity really mean "potential." A plant has a potential to handle a much larger volume than it does an actual capacity based on the current product mix, personnel, labor-management relations, scheduling inefficiencies, etc.

Based on the aforementioned characteristics of the system, a question arises as to what type of production plan the system can accommodate and still maintain a satisfactory cost performance. It is hypothesized that a facility of this type will encounter capacity bottlenecks as the load increases. These bottlenecks could occur due to shortages in equipment, manpower, or in in-process inventory storage areas. It would be of value to investigate the described system to see of the unit capacity of the plant can be related to the workload demand on the facility.

Chapter 4

EXPERIMENTAL PROCEDURE

Monthly operating statistics were compiled for the subject plant. The data begin with the month of December, 1973 and continue through March 1976. The months of April, 1976 through August, 1976 are not included in the sample due to the industry wide strike which took place that summer. The data then continue from September, 1976 through November, 1977 (Table 1).

Examination of the data indicate the dynamic nature of the production plan issued to the facility. Early 1974 saw a high demand for gross units which approached a ticketed production level near to that of the plant's rated capacity of 27,500 tires per day. From a peak ticket of 27,425 tires per day in January, 1974, the ticketed requirements gradually decreased to a low of 18,577 tires per day in September, 1975. This decrease in demand was attributable to the recessionary economic conditions prevalent in the country and represented roughly a 68% utilization of the available plant unit capacity. In anticipation of the forthcoming labor difficulty and in order to stockpile goods, there was an increased tire per day production requirement from October, 1975 through the month preceeding the four and one-half month strike. In the nine months immediately following the strike, demand was extremely high due to tire shortages caused by the strike. The tire

Table 1

Facility Production Data by Month

Month	Prod. Plan Tires/Day	Product Mix Sizes/Day	Complexity Tires/Size	Performance Lbs./C.M.H.
Dec 1973	27212	90	302	50.3
Jan 1974	27425	68	403	53.5
Feb	27399	70	391	53.7
Mar	27406	74	370	51.8
Apr	27403	89	308	48.3
May	25892	104	249	49.6
Jun	25797	102	253	47.6
Jul	25885	104	249	45.8
Aug	25885	113	229	46.5
Sep	25476	113	225	44.9
Oct	27165	90	302	46.5
Nov	26568	97	274	44.1
Dec	24600	97	254	47.9
Jan 1975	22000	101	218	47.2
Feb	22000	89	247	46.2
Mar	22000	89	247	47.0
Apr	20185	95	212	45.8
May	19885	99	201	44.5
Jun	19085	99	193	42.7
Jul	19085	95	201	41.8
Aug	19055	93	205	44.1
Sep	18577	78	238	44.6
Oct	18977	70	271	45.7
Nov	20785	59	352	46.7
Dec	20785	64	325	49.2
Jan 1976	22635	70	323	50.2
Feb	23135	79	293	48.8
Mar	23335	74	315	49.8
STRIKE				
Sep	25067	79	317	44.8
Oct	26800	86	312	50.5
Nov	26900	87	309	49.1
Dec	27300	83	329	48.4
Jan 1977	26990	82	329	48.7
Feb	27160	85	320	48.8
Mar	26990	83	325	48.5
Apr	26990	95	284	48.4
May	26650	110	242	46.9
Jun	25550	102	250	46.3
Jul	24610	105	234	45.4
Aug	24570	98	251	47.4
Sep	24322	95	256	47.1
Oct	23570	79	298	47.7
Nov	23112	74	312	50.5

per day production requirements were increased to a near rated capacity figure of 27,300 tires per day in December, 1976. With the start up of new plants, industry wide production capabilities exceeded the demand rate, hence, the months of January, 1977 through November, 1977 saw another gradual decrease in the production level required.

The data collected for the number of sizes handled per day represents an average for the month based on statistics tabulated for the sorting and loading area in the plant. Green tires produced in tire assembly are placed on a common conveyor which carries them to a sorting line. Like green tires are removed from the conveyor belt and placed in segregated piles for storage before being re-loaded for delivery to curing. A slotted and labeled conveyor which is suspended over the conveyor delivering the green tires from tire assembly is loaded with the specific size and carries the green tire to its corresponding mold in curing. Three types of sorting and loading can occur as a result. Firstly, a green tire can be received from tire assembly and sorted into green tire storage; secondly, a green tire can be received from tire assembly to be sorted and then loaded onto the overhead conveyor for delivery to curing after a short storage period right at the belt; or thirdly, a size can be delivered from remote green tire storage to the sorting belt for loading onto the overhead conveyor and subsequent delivery to curing. At any given time then, there will be sizes handled at the sorting belt which are being built but not cured, being built and cured at the same time, or being cured only. The sizes per day handled data represent the sum of the sizes falling into each one of these three categories. The number of sizes handled per day ranged from a low of 59 in November, 1975 to a high of 113 in August and September, 1974. The number of sizes handled is dependent on the production plan issued to the plant by the corporate planning group.

In addition to the production plan tire per day statistic and the sizes per day handled, a performance measure of pounds per clock man hour was tabulated. This figure represents the gross poundage of product which was warehoused as a function of the number of production man hours expended to obtain the subject poundage.

A measure of the relative complexity of the production plan was obtained by dividing the production plan tires per day requirements by the number of sizes per day handled. This quotient represents the average number of tires per size to be handled daily by the facility in each month. This figure ranged from a low of 193 tires per size in June, 1975 to a high of 403 in January, 1974.

Two sets of data were analyzed using regression. The first regression employed a linear model to investigate the effect that the number of sizes per day handled had upon the monthly performance rating of pounds per clock man hour. A second order model regression for this same set of data was also performed. The second sets of data regressed were the monthly performance achieved in pounds per clock man hour as a function of the number of tires per size handled daily. Again, first and second order models were examined. After selection of the best performing model was accomplished, the prediction equation was used to forecast the performance level of the three months succeeding the end of the data collection period. The forecasted months were December, 1977 through February, 1978.

It should also be noted that during the time span in which the data were collected, no significant capacity expansions or additions were made to the facility. The total number of machines in the various stages of production and the in-process inventory storage area capacity remained relatively static. The only factor which was varied significantly was the number of clock card employees. As the ticketed number of tires per day required increased or decreased, so too did the manpower level.

It is also important to note that no assumptions were made in order to simplify or reduce the complexity of the sytem under investigation. The data collected represent the actual performance of the system. A more realistic investigation into the actual "real life" operation of the plant can be performed by tabulating actual results. It is acknowledged, however, that many other variables are present which affect the overall plant performance. For this reason, it is desired to examine the characteristics of this particular production system from a macro viewpoint in order to observe the overall affect actual inputs have on the actual outputs of the system.

Chapter 5

RESULTS

The statistical results of the regressions are tabulated in Table 2. The first sets of data analyzed regressed the number of sizes handled daily against the performance figure, pounds per clock man hour. Both the first and second order models yielded similar results with the exception of the t statistic values for the explanatory variables. The t value for the first order model is significant at the $\alpha = .05$ level whereas neither t value in the second order model is significant at this level. More important than the t values, however, is the correlation between the variables. A correlation of -.49 indicates a moderate relationship between the independent and dependent variables. The R-bar squared statistic indicates that only 24% of the change in pounds per clock man hour is explained by the changes in the sizes per day handled. In addition, the Durbin-Watson statistic of .71 and .70 indicates that these models have serious positive autocorrelation. Overall, the use of a first or second order model appears to be of little value when attempting to describe the relationship between the number of sizes handled per day and the pounds per clock man hour performance measure. Figure 5 represents the plot of the data and the resultant first order prediction equation line.

The second sets of data analyzed yield much better results.

Table 2

Regression Analysis Results[1]

Statistic	Pounds per clock man hour vs.			
	Sizes		Tires per size	
	Model	Model	Model	Model
	$Y = A+Bx$	$Y = A+Bx+Cx^2$	$Y = A+Bx$	$Y = A+Bx+Cx^2$
Correlation	-.49	-.49	.80	.80
Durbin-Watson	.71	.70	1.62	1.62
R-bar squared	.24	.24	.64	.64
Standard error of estimate (SEE)	2.28	2.30	1.57	1.59
t value, x^1	-3.60 *	-.49	8.48 *	.64
t value, x^2		.19		.24
Variance unaccounted for by the regression	5.18	5.30	2.48	2.54

* Significant at the $\alpha = .05$ level

[1] Results obtained by using the LEAPS (Lehigh Amalgamated Package for Statistics) program.

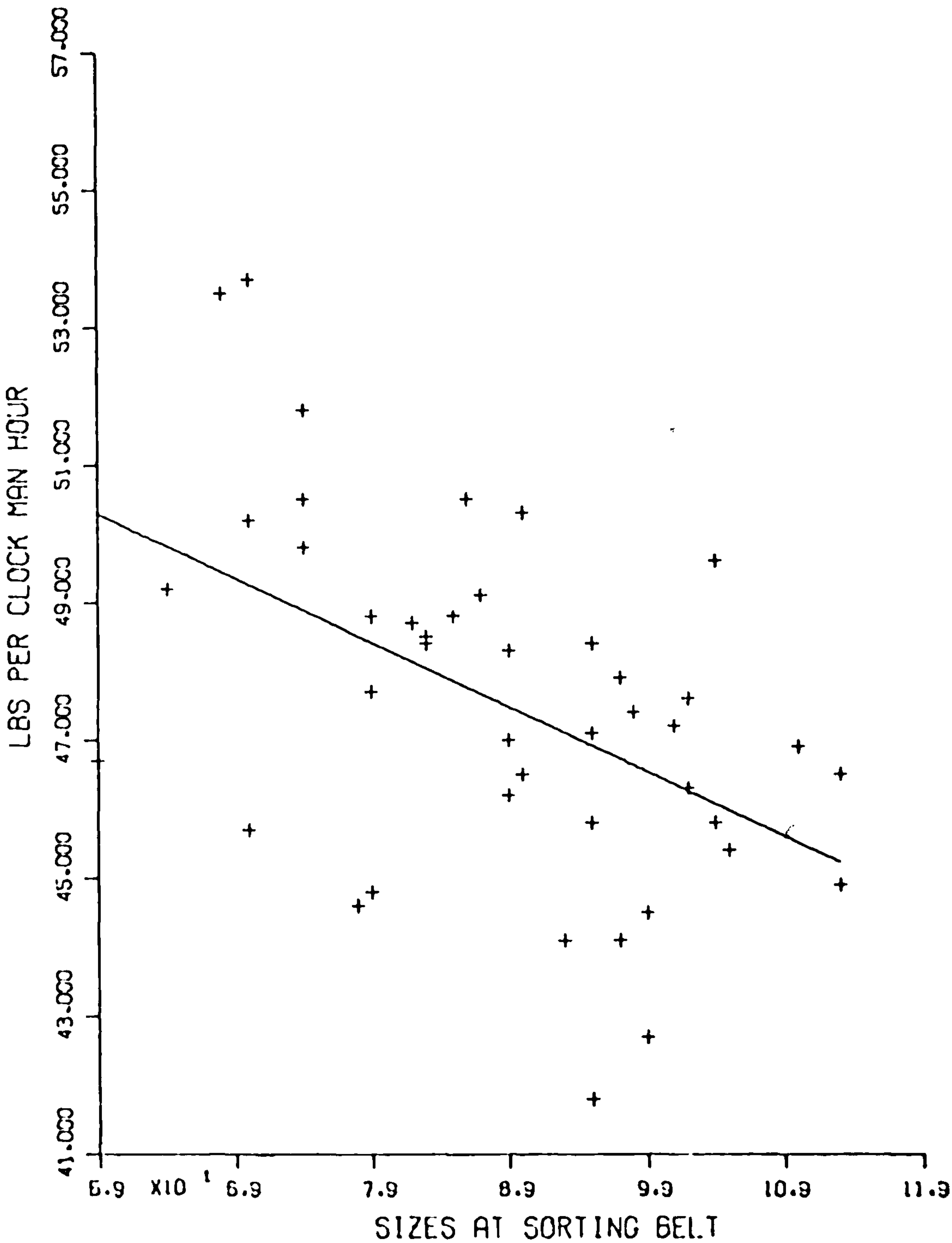

Figure 5

Sizes Handled Daily
vs. Pounds Per Clock Man Hour

Again, there was little difference between the regression statistics for the first and second order models excepting the t values. The statistical results for the regressions based on the second sets of data indicate a much better relationship between the dependent and independent variables, however. Correlation between the two variables is .80, with R-bar squared indicating that 64% of the error is explained by the regression. The Durbin-Watson statistic of 1.62 indicates that there is not serious autocorrelation in the regression equation. The standard error of estimate and the variance unaccounted for by the regression also improved significantly from the values indicated for the first set of data analyzed. Figure 6 details the graph of the tires per size handled daily versus the pounds per clock man hour and the resultant first order regression equation line.

The "best" prediction equation was obtained from the first order regression for tires per size versus pounds per clock man hour and is as follows:

$$Y = 36.4712 + .0395X$$

where Y represents the plant performance in pounds per clock man hour, and X represents the number of tires per size handled daily.

Inputs to the system for the months of December, 1977, January, 1978, and February, 1978 are as follows:

Month	Prod. Plan Tires/Day	Product Mix Sizes/Day	Complexity Tires/Size
Dec 1977	22182	64	347
Jan 1978	22332	66	339
Feb 1978	22405	72	311

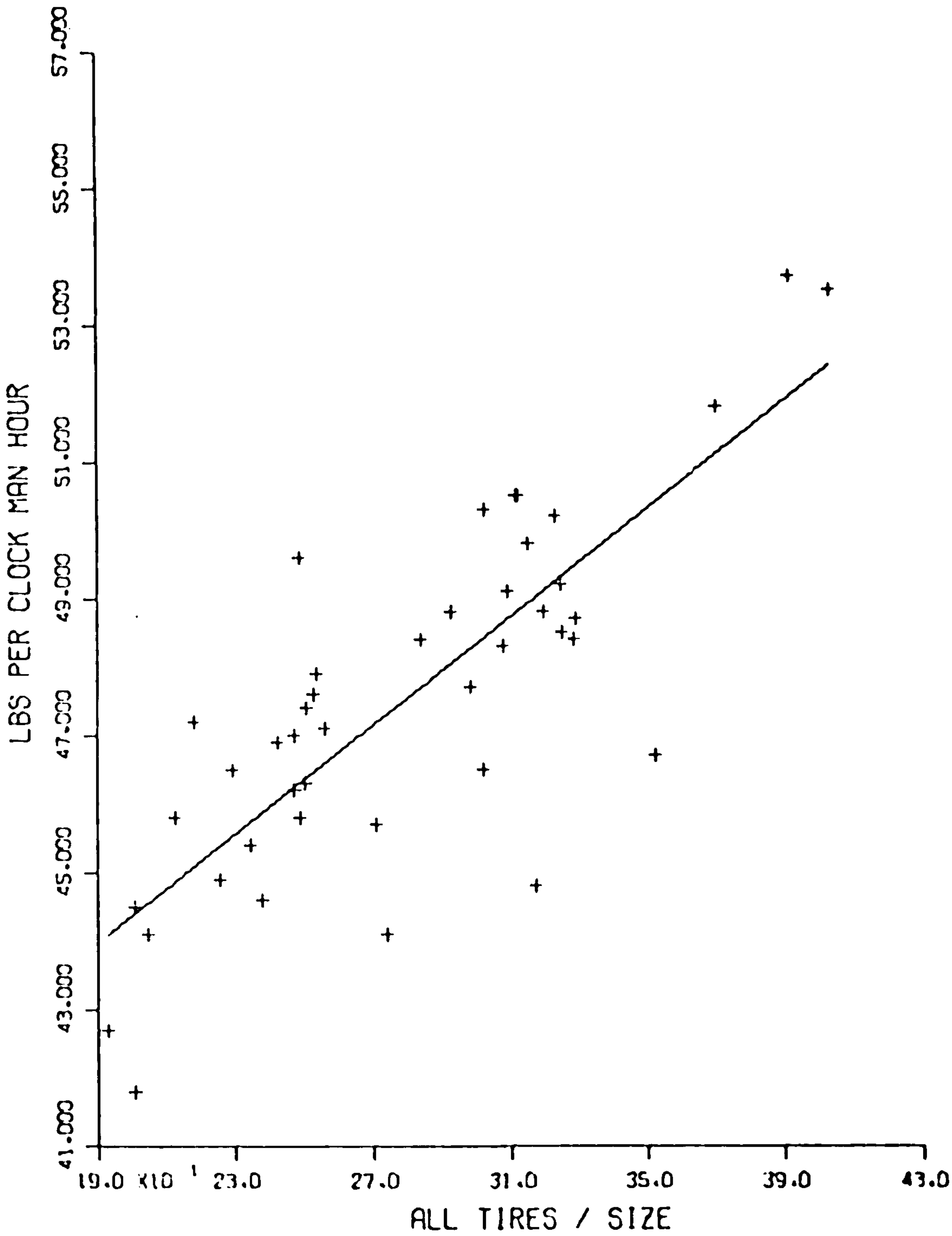

Figure 6

Tires Per Size Handled
Daily vs. Pounds Per Clock Man Hour

The actual plant performance when compared to the predicted plant performance and the resultant deviations are as follows:

Prediction Lbs./C.M.H.	Actual Lbs./C.M.H.	Residual	As Per Cent
50.2	50.3	.1	.2
49.9	47.8	-2.1	-4.4
48.8	50.2	1.4	2.8

The standard error of estimate for the predictive equation is 1.57; two of the three predictions above had residuals less than 1.57 and all three residuals were less than 3.14 (2 x SEE).

Chapter 6

CONCLUSIONS

From the experimental results it can be concluded that there is a strong relationship between the number of tires per size handled daily and the overall cost and productivity performance of this plant. The important point to be made is that a facility has a price associated with its unit capacity. In the case of this plant, it seems that historical data implies a certain ticket-to-size ratio is important in determining the overall profitability associated with a given production plan. If upper management, through price structure analysis, determines that the facility must achieve a minimum pounds per clock man hour figure of 48.0 in order to break even, then the ticket-to-size ratio should exceed 292 tires per size handled daily. In other words, at a daily ticket level of 22,000 tires per day, the number of items handled daily should not exceed 75. This figure can be estimated by using the first order regression equation for tires per size versus pounds per clock man hour.

A "quick and dirty" investigation of plant capacity is of substantial value when the system is as complex as the multi-stage, multi-product, dynamic, between stage inventory system cited. Overloading a system such as this only serves to increase the price of the capacity obtained. Plossl and Wight have stated that the capacity of a facility as it stands is fixed, and this appears to be true. If the number of available man hours does not change significantly for a specific production level, but the complexity of the production plan does, then the end number of units which are produced by the sytem will decrease due to the additional number of required hours generated in order to accomplish the task. Essentially, the point to be made is that management personnel cannot increase the workload of a facility and expect the facility to adapt to the increase successfully without modification to the system in order to facilitate the accomplishment of the increased load. A system such as the one described has intrinsic characteristics which determine the eventual output, and depending upon the level of capacity selected as normal, no drastic improvements in capacity can be realized without substantial alteration to the system.

Chapter 7

SUGGESTIONS FOR FURTHER STUDY

The intent of this investigation is to determine if a definition of capacity for a specific production system exists, and if so, what the effect of altering the workload on the subject system is in terms of the subsequent performance obtained. Given that such a measure of capacity does exist and that the effect of workload changes can be determined, it would also be of value to analyze the effect of system alteration on the real life capacity. Theoretically, capacity can be changed a number of ways, but the actual net effect of changes to an operating system would be of value. Specifically, in the multi-stage, multi-product, dynamic, with in-process inventory production system, it would be interesting to evaluate the real life operating results of the following alterations to the system:

1.) The effect of varying one or all of the in-process between stage inventory levels

2.) The effect of utilizing manpower more efficiently through the use of "open" machines within a department or stage

3.) The effect of group technology on a system such as this

4.) The effect of decreased or increased lead times between stages

5.) The effect of planned maintenance (preventive maintenance)

6.) The effect of increased or decreased scrap on the overall capacity of the system.

One of the most valuable research tools which could be used for this type of system would be simulation. A simulation model which was carefully developed and which could be validated as a model which accurately represented a real life system could be used to accomplish all of the above analyses in addition to being a valuable tool for management planning. This type of model development would be a significant undertaking, however, due to the complexity of the system involved. In the tire industry especially, a model such as this which was valid would be of tremendous value in the analysis of plant performance under varying conditions and in the justification analysis of capital expansions.

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