THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

# EVALUATION OF SPACIAL RELATIONS AND EMPIRICAL PLANT LAYOUT CRITERIA BY DIGITAL COMPUTER

Richard C. Wilson

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# PREFACE

The designing of manufacturing plants is an engineering art performed by many skilled practitioners working under the pressure of installation deadlines, operating failures, and cost restrictions. Their accrued experience has resulted in a large body of empirical knowledge, rules, and practices, but has produced little data on which to determine rigorously the appropriate procedure for resolving conflicts among this knowledge. Recently, some Industrial Engineers have begun to apply more sophisticated mathematical tools to the improvement of their specific plant designs. Efforts using new tools for enlarging existing knowledge and validating current practices however are few. This study therefore explores directions for needed research effort. In addition, it demonstrates new methods for enlarging the knowledge and improving the practice of plant layout designing. The study develops two computer programs, one to perform a spatial analysis of a proposed layout design so that suitable input data to the other, a general-purpose layout simulation, can be efficiently generated. The scale of both the simulation and analysis programs is sufficiently large for application to layout designs of a large number of forming and part-processing plants. The simulation is used to test experimentally the validity of two empirical rules recently proposed for selection of line or process layouts. Conclusions about the usefulness and limitations of the rules are inferred from the tests.

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# CHAPTER I

## 1.1. Introduction

A major objective of this dissertation is to improve the ability to predict the performance of physical arrangements of industrial processing facilities, or plant-layout material-handling systems. Expenditures for industrial capital facilities of this nature are commitments which can inhibit or enhance future operations for many years. Improvement in predicting facility performance therefore, is needed not only for initial design and selection of industrial facilities, but also for more efficient utilization during their subsequent life. Moreover, the potential rewards for improved prediction of the performance of plant-layout materials-handling systems are sizeable. In 1957 for example, more than $4 billion was expended for industrial buildings, offices, and warehouses, more than $1.3 billion for power cranes, shovels, overhead traveling cranes, monorail systems, conveyors, industrial trucks, tractors, and trailers, and more than $2 billion for machine tools and metal working machinery.(57) Even a one-percent reduction in the cost of these facilities justifies significant effort toward improving the accuracy and precision of the criteria used in their selection and arrangement.

A secondary objective of this dissertation is to investigate the use of electronic digital computers in performing routine measurements of spatial characteristics of alternative plant-layout material-handling proposals. The practice of representing proposed facility arrangements by drawings or three-dimensional models permits rapid qualitative evaluation of facility relationships. On the other hand, quantitative evaluation is tedious because of the large number of measurements required to trace the paths of many products through many different routings. If a computer can be used to trace the product paths, more accurate quantitative comparison will be achieved.

## 1.2. Current Practice

Plant layout proceeds in a logical sequence from the statement of the problem to the determination of the values of the independent variables, then to initial estimates of some design parameters, through a trial-and-error process until some bounds are established. Using several facility-product-assignment policies, logical flows are established from which is evolved a spatial utilization arrangement believed most satisfactory. Several alternative arrangements may be prepared originally, but a detailed design is usually prepared for only that one alternative which is deemed best. Preparation of equipment location drawings, and estimates of utilization, product costs, inventory costs, and capital requirements complete the layout task. Detailed descriptions of the design process are given by Monsell,(34) Moore,(35) and Muther.(37)

## 1.3. Flow Analysis and Planning

The designer begins by gathering basic information about the objective of the layout design. The nature of the problem will determine the scope of the design activity and the degree of restriction imposed by existing facilities or policies. Minor revisions to existing layouts allow few interruptions of operations and can justify little design effort. Planning a new plant, expanding an existing plant, or moving to a different plant requires more design man-hours, but offers more freedom of choice.

The designer draws on the product engineer for details of the material or product characteristics and condition. From the process engineer he will obtain detailed parts lists for each product and a routing sheet giving the sequence of operations. The product demands and demand trends must be based on forecasts and management planning policy. Purchasing must furnish material cost and availability estimates in order to determine "make-or-buy" policies. Individual machine space and service requirements must be obtained from suppliers, and production times from methods engineers. The designer may resort to many different schematic models such as process charts, man-machine charts, assembly diagrams, or operator charts in order to help reduce the data for easier analysis. Travel charts may be used to assist in establishing minimum move-volume flows between machines or departments. In a multi-product layout, the designer may separate the production facilities into line or process layouts, based on estimates of machine utilization. Machine requirements are calculated for predicted product demand rates using standard time per piece, adjusted for losses due to scrap and the expected work efficiencies. If a line layout is indicated, machine and labor balancing is attempted through methods, job assignment or speed adjustments.

## 1.4. Spatial Design

Having arrived at basic flow relationships, the designer prepares scale drawings to assist in developing an error-free layout and to help others understand and evaluate the plan. By adjustments and changes, the designer attempts to reach a design which will prove to be an efficient, workable layout. It must be free from errors due to machine, building, or material interferences; it must integrate material handling and process facilities; it must avoid excessive move distances or congestion; and it must provide high spatial utilization. He must provide adequate area, needed utilities, adequate room for maintenance, and means for handling material and scrap to and from each facility. Office, maintenance, inspection, shipping, receiving, storage and employee facilities must be coordinated with the production layout before total cost estimates can be prepared.

## 1.5. Relevant Research

A growing body of theory applies to portions of the plant-layout design problem. Little work, however, has been published about research on the spatial considerations required in plant layout, or on tests of commonly accepted empirical rules of layout. Work in areas of theoretical relevance and reports of applications of the theory to plant layout problems are summarized below.

Queueing theory (see Reference 20 for example) is easily interpreted to apply to plant flow, and Stover(46) reports a direct application of the theory to determination of the need for expansion of a chemical plant. Koenigsberg(27) reviews the implications of queueing theory in determining internal storage requirements of a transfer machine.

Because many plant design problems are too complex for solution by queueing theory, simulation has been used for predicting performance. Joyner(24) reports on the use of simulation to the scheduling of tractors at a repair depot; Boldyreff(5) describes an application to a railroad network. Simulation application to plant layout at General Electric Co.

is described in References 11, 21, and 28. Theoretical studies using simulation in areas related to plant layout have been carried out by a number of groups. Pure job-shop production scheduling and dispatching studies are reported by Dzielinski,(12) Jackson,(23) and IBM.(55) Huffman(19) carried out a unique simulation of an idealized warehouse system design. He described a warehouse sub-system as a three-dimensional cube and explicitly considered spatial factors in this investigation. The relationship among capacity, sub-system configuration, and handling effort for two different inventory policies was investigated: storing material in any empty location, or storing material only in designated locations.

Research in material handling operations has been carried out by a number of investigators. Work by O'Neill, et al.(41,43) has led to analytic formulation of dockside cargo handling as a "shuttle" process, to simulation of cargo-handling systems using field data, and to determination of optimum container sizes in shipping. Weldon(49) reports an economic study of containerization in West Coast-Hawaiian shipping. Kwo(28) and Mayer(31) develop analytic models and simulations of continuous conveyors of the hook storage-delivery type. Mandel(30) conclusively establishes the interrelationship between material handling methods and production control practice. He points out the efficiencies achieved by a material handling system which also performs as an integral part of the production control dispatch and scheduling functions.

Wimmert(52) reports a procedure for finding locations for machines which will minimize the sum of the move-volume-distance between them. The method is based on logically considering the rankings of move-volumes between machines and the distances between locations in a manner which eliminates the least desirable location assignments first. He points out, however, that his method is not necessarily optimal. If the move-volume between one pair of facilities is an order of magnitude larger than all others, or if the move-volume between several pairs is zero, ranking does not adequately describe the absolute importance of the move-volumes in selecting locations. We conclude that a computationally useful algorithm for finding the optimal assignment of machines to available locations is still needed.

The area of linear programming holds promise of useful application to material-handling plant-layout problems. The optimal assignment of fork-lift trucks to available routes is described by Klein(26) and Metzger.(32) A number of theoretical papers on maximizing network flow appear to be related to problems of (a) dispatching production to alternative facilities in order to maximize output;(4,8,13,14,33) (b) optimally allocating funds in order to increase the production capacity;(13,16) (c) optimally locating and sizing a group of sources so as to minimize cost of supplying destinations at fixed locations;(50,51) or (d) optimally shipping materials when costs include fixed charges.(42) No applications of the ideas of these papers to plant layout or industrial material handling are known. Theory and application of line balancing by computer are presented by Salveson,(44) Tonge,(47) and IBM.(54)

## 1.6. Basis for Selection of Line or Process Layout

Muther(37) points out broad factors which serve to split or combine plant facilities before explicit consideration of specific layout designs can be undertaken:

1. Size, weight, shape, or nature of the products

2. Basic material of the products
3. Process routing or sequence of operations
4. Equipment involved, or type of building structure to hold the equipment
5. Quality of workmanship required
6. Value or risk of loss of the products
7. Hazard or danger to personnel or property
8. Type of power, utilities, or auxiliary services
9. Organization structure of the company
10. External considerations such as property resale, appearance, taxes, etc.

In our subsequent development, we assume that prior consideration of these factors permits the selection of either a line or a process layout on the basis of consideration of production requirements alone.

According to Muther,(37) the first step in layout planning is:

> "the Product-Quantity analysis....sometimes called the volume-variety analysis. The purpose is to establish the production technique to be used for each product, whether it's production line assembly, job shop, or a combination of both."

To understand the analysis required, we need to examine the definition commonly used for line-production and job-shop-production techniques. Muther(38) says:

> "in its most refined state, line production is an arrangement of work areas where subsequent operations are located immediately adjacent to each other, where the material moves continuously and at a uniform rate through a series of balanced operations which permit simultaneous performance throughout, the work moving toward completion along a reasonably direct path."

D. C. Burnham(58) identifies four general types of manufacturing arrangements:

> 1. "Job Shop Operation-where parts are produced on standard types of machines in a plant laid out so that the machines of each type are in a separate group. Parts are moved from one group of machines to another throughout the plant. It is, without doubt, the most costly type of operation and the one which requires the greatest amount of paperwork to process parts through the plant.
>
> 2. The second type is the progressive line. By this we mean all the equipment required to make a specific part or product is arranged in a single department so that a minimum amount of transportation between operations occurs, and one supervisor has complete jurisdiction from start to finish.
>
> 3. The third type of operation is the conveyorized line. This step up the scale is an improvement to Step 2 whereby conveyors, slides, or other automatic transportation is used to carry parts from one machine to another and to control the flow of material within operation.
>
> 4. The fourth or ultimate step as we know it today is automation..taking the part from one operation to the next, loading and unloading the different machines mechanically. This requires the least amount of labor, but increases the skill of the labor which is left."

Muther agrees with Burnham's implication that it is desirable to move a plant layout higher up the scale of layout types, by stating categorically:(38) "Use production line layout as much as practical." Moore(35) also supports this point of view:

> "Without a doubt the product layout, or line production, is the most productive from the point of view of man hours invested per product. It has been mass production, utilizing the manufacture of interchangeable parts, that has brought about the high standard of living in this country. The product layout then should be utilized as much as is practical. Of course there will always be situations where it cannot be justified economically."

The question which first confronts the layout engineer is: "Shall the manufacturing facilities be grouped by similar processes, or in the exact sequence in which they will be used?" In a single-product plant with a product which never requires the same process facility twice in its production sequence, the use of line layout is both obvious and natural. If the sequence requires repeated use of the same type of processing facility, or back-tracking, the choice is more difficult. In a multi-product plant layout, the choice is even more complex, since some products could be manufactured on a line and others on a pure job-shop basis. Further, in an existing multi-product plant, the proper rules for deciding to switch a product from an existing job-shop production basis to its own independent production line are not well established.

Muther(38) states that layout by process will be used when:

"1. Machinery is very expensive and not easily moved
2. Making a variety of products
3. There are wide variations in times required for different operations
4. There is small or intermittent demand for the product."

and that layout by line will be used when:

"1. There is a large quantity of pieces or products to make
2. Design of the product is more or less standardized
3. Demand for the product is:
    a. fairly steady
    b. balanced operations can be obtained
    c. continuity of material flow can be obtained without difficulty."

In Reference 37, he presents a procedure, which he calls the "Product-Quantity Analysis," for selecting line or process layouts. A histogram of the activity (volume, weight, number of pieces, etc.) is drawn for different products arranged in order of decreasing activity. If the smoothed histogram, called the "P-Q Chart" is deeply concave upward, the products at the high activity end of the histogram should be produced on line layouts and the remaining should be produced on a process layout. A flat histogram indicates that a single process layout for all products is desirable. The method is intended to be a "practical" tool; simplicity and economy of use are therefore emphasized.

In contrast to Muther's recommendation, Deming(10) suggests that the decision to shift from a process to a line layout should be based on machine utilization, weighted by the capital invested. If the efficiency of capital utilization can be increased by changing to a line layout, Deming recommends the switch from a process layout provided that "demand for the product will continue to support the output level."

Each of these authors proposed a single but different criterion which purports to indicate the type of layout which should be developed. Our general hypothesis in this study is that important interactions exist between a number of other factors which can make either criterion alone misleading. In particular, since neither criterion explicity considers the effect of changes in production-demand characteristics, we hypothesize that this effect can be great enough to invalidate either of the criteria suggested, and cannot be ignored in layout design practice. We will investigate the interactions between a number of similar factors to test the empirical criteria for line or process layout selection proposed by Muther and Deming.

## 1.7. Objectives

The major objective of this dissertation is, first, to improve the prediction of operating results of plant layout designs, and, second, to investigate the application of digital computers to routine calculations of spatial characteristics of alternative plant layout designs. The specific means of attaining these objectives are two:

1. Two empirical rules currently used for selection of line or process type layout are compared by a series of simulation experiments. Completion times, in-process inventories, and equipment utilization for layouts designed by these two rules are compared in Chapter V.
2. The feasibility of using a computer to supplement drawings, templets, or 3-D models traditionally used in plant layout to evaluate spatial utilization is explored by development of a specific computer program described in Chapter III.

# CHAPTER II

# PLANT LAYOUT DEFINITIONS AND PARAMETERS

## 2.1. Definitions

The descriptions of pure line layouts and pure process layouts which follow will help to clearly distinguish between them. A pure line layout has the following characteristics:

1. Production facilities* must be arranged in the same order as the precedence of the operations required.
2. A unique production facility is associated with each required operation.
3. Static in-process storage between operations is restricted or not permitted.
4. Products cannot pass after they have been released to the production facilities. This is equivalent to a first-come first-served queue discipline.
5. Service on conveyor-type material handling equipment may be phased-lapped. That is, the conveyor may be loaded with additional products before the previous units have been removed.
6. Time for conveyorized transportation is a constant between any two production facilities, or has negligible variance.
7. Down time for set-up begins and ends simultaneously for all facilities in a line when a different product is introduced into the line.

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*The term "production facility" will be applied interchangeably hereafter to material handling equipment, work stations, or production processes.

A pure process layout has the following characteristics:

1. The sequence of product flows between facilities is not restricted.
2. Infinite in-process-storage can be provided (somewhere) between process operations.
3. Process facilities are arranged in groups which correspond to multiple channel queues (service facilities in parallel).
4. Products may pass each other in accordance with dispatching policy.
5. Operations are performed on batches or lots which move as single entities between operations.
6. Transportation distances (and hence times) between facilities have large variances because of the variable path and speed characteristics of material handling equipment common to process layouts (e.g., fork-lift trucks, cranes, and trailer trains).
7. Jobs, once set up on a particular facility, are completed before the next job is started on the same machine.

The following terminology will be used in the remainder of this study:

Processing time: the mean time to execute a specific operation on a part; operation service time.

Lead time: the sum of all mean processing and mean transport times required in the sequence of production of a part.

Delay or waiting time: the time a part spends in queues waiting for occupied service facilities to become available.

Completion time: the actual elapsed time between order release and completion of last operation on an order.

## 2.2. Layout Parameters

The design of a production facility requires consideration of a large number of parameters, some quantifiable and others not. For purposes of classification, these can be divided in two ways:

1. The extent to which they can be controlled by the designer.
2. The phase of the design process to which they belong; e.g., flow analysis and planning, or spatial design.

The first classification permits the identification of those design parameters over which the designer has control, and of the "independent" variables over which he has limited or no control. These are considered immediately below. The second classification, described in Sections 1.3 and 1.4, motivates the separate development of the Simulation and Spatial Evaluation Computer Programs. Selection of variables and parameters in each Program is determined by consideration of design decisions of primary importance in the flow analysis or spatial design phase.

### 2.2.1. Independent Variables

Material Characteristics and Condition. Size, shape, bulk, weight, and condition of the material are determined by product and process specifications. Process or handling requirements due to toxicity, fragility, radioactivity, corrosiveness, etc., are imposed by the nature of the end product desired.

Type and Sequence of Operations. The forming, treating, or assembly operations needed are determined by the end-product. The layout designer can alter these requirements only by substitution of alternative operations, or materials, and generally only within a narrow range of choices.

Number of Different Parts in a Product. Generally the layout designer must accept the complexity of the product and multiplicity of parts imposed by the product designer. Standardization of parts and materials, or simplification of the product, can achieve some reduction in absolute terms, but the order of magnitude of this variable is a product characteristic. The complexity of layout design increases with the magnitude of this variable.

Service Requirements, Physical, and Operating Characteristics of Process Machinery. Joint considerations of processing methods and layout are desirable to achieve economic balance; nevertheless, the study of processing methods is often not a part of the plant layout. Spatial, maintenance, hazard, noise, and auxiliary service requirements are restrictions imposed on the layout designer by the nature of the machinery needed for processing. The choice of materials handling equipment, however, is usually made by the designer.

The Distributions and Means of Operation Service Times. In forming or treating processes, the mean standard times established on the basis of estimated or observed production rates serve the designer as a measure of operation or process capacity, subject only to limited control through method changes and machine speed adjustments. Assembly line mean service time distributions are more extensively under the designer's control, since he can reassign components of a task to different operators in a somewhat arbitrary fashion.

Distribution and Mean of Set-Up Times. To use production facilities, a special set-up is often necessary for each different product type. The mean time to perform such a setup may be a function of the facility, or may be a function of the particular part on the facility. Further, the mean time in actual practice will vary because of the sequence of jobs scheduled for the particular facility. The layout designer rarely has control over these times.

Distribution of Product Demand Rates. This parameter is the criterion used by Muther in his "P-Q" (Product-Quantity) analysis cited earlier as the basis for splitting products into line and process layouts. It is estimated, for the planning period of the firm, from past records of sales or from forecasts of product demand. Usually the distribution (or product mix) will change with time, but the designer selects one or at most a small number of possible future distributions on which to base his design.

Individual Product Mean Demand Rate. This is a function of the sales requirements of the product, determined by the point in time on the life cycle distribution. Changes or trends in the rate change the distribution of product demand rates, and possibly the ordering of product production activity. (See Figure 1)

Seasonal Variations in Product Demand. Production planning can minimize the amount of variation between seasons, but the designer cannot control these variations directly. His choice of layout, however, may be

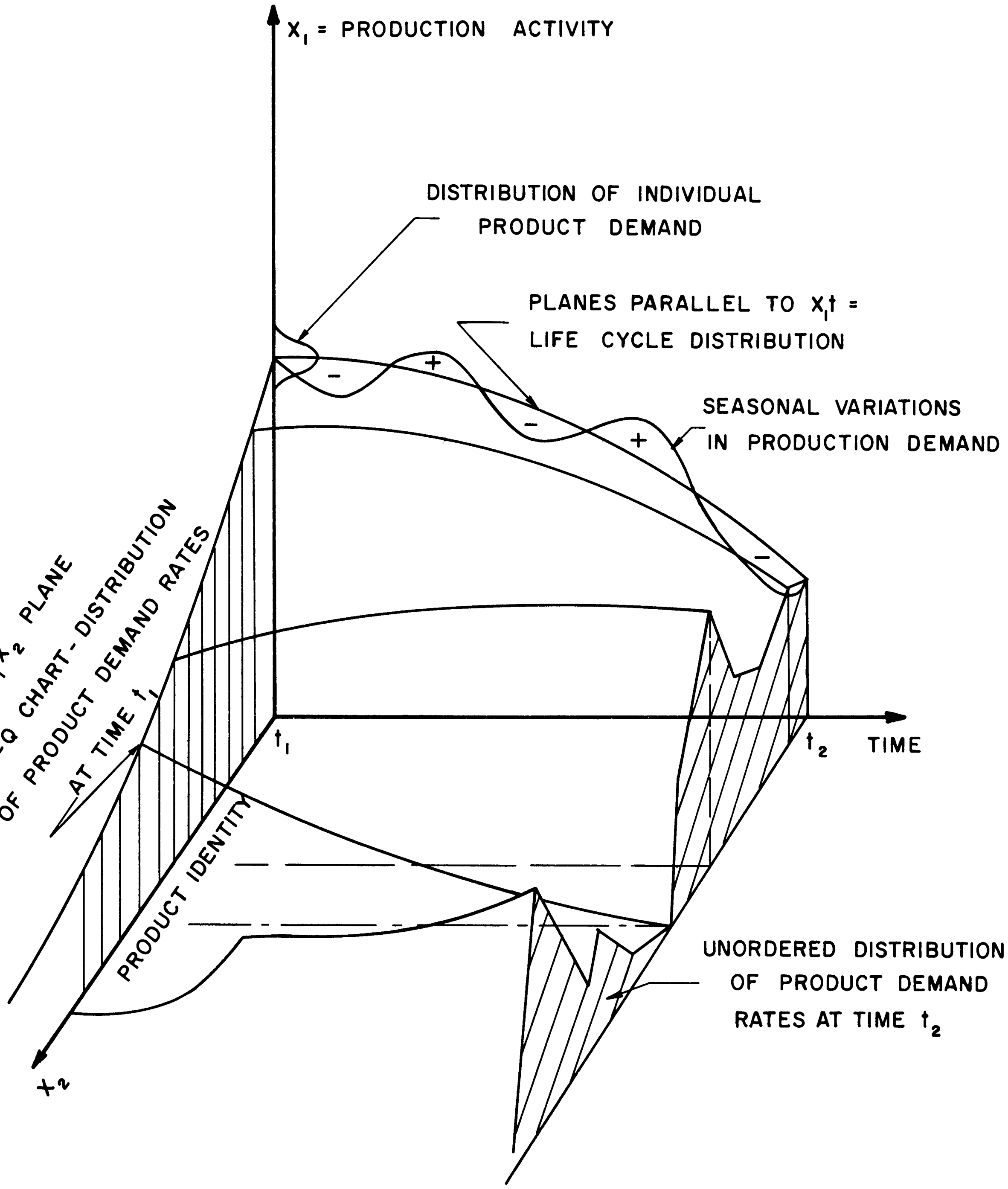

Figure 1. Section of Surface Generated by Independent Product Demand Variables Overtime.

based upon utilization of common facilities by products with peak demands at different seasons.

Product Life Cycle Demand Distribution and Variance. Because these parameters are a measure of the rate of product obsolescence, they are also out of the control of the designer.

### 2.2.2. Design Parameters

Individual Product Demand Distribution Variances. The day-to-day fluctuations in orders received causes short term variations in load on the production facilities. The distribution variance of the individual product demand is used to describe such fluctuations. Effective production management can reduce this variance by "smoothing" policies, i.e., by preplanning for adequate labor and materials, by preventive maintenance, and by systematic order dispatching. The plant layout designer also has considerable direct control over the variance of demand rates on later stages of production by his selection of facility arrangements, in-process-inventory storage, and labor utilization. Not all variance can be eliminated or controlled, however, because of "random" events such as rush orders, breakdowns, defective quality, etc.

Facility Service Level. The quantity of equipment of each type and the capacity of each equipment partially determine the mean time to process a product, the mean waiting time, and the number of units in process.

Labor Service Level. The quantity of each type of labor skill, both direct and indirect, and the man-machine-assignment utilization directly influence the mean process and waiting times.

Spatial Utilization. The physical location of process facilities, storage, and transport paths is a factor in determining the mean delay time of units in process, the area required, the equipment utilization, and the service level. In general, the more compact the process facility arrangement, the shorter the transport distance and time, and therefore, also the shorter the product lead times. The designer must balance his desire to minimize space against his desire to increase space for safety and for the in-process inventories required to achieve continuous operation in spite of variance in product demand.

Material Handling Facilities and Auxiliaries. The choice of material handling equipment affects the number of units which can be moved simultaneously, the utilization of space, the variance of individual product demand distributions, the utilization of labor, and the mean waiting time of units in process.

Lot Size or Run Frequency. If the designer groups the facilities by process, he must assume that products will be dispatched to the process groups by lots. Available machine time will be reduced because of the set-up time required for each lot. In contrast, the choice of line production assumes one initial set-up for the line with no subsequent loss of machine utilization due to set-up. Although subject to revision during operation, the feasible range of run frequencies is restricted by the designer's selection of equipment and its location.

Facility-Product Assignment Policies. The assignment of a product or set of products to unique facilities is initially a design decision, and affects in turn all other design parameters. Essentially the policies determine use of process or line type layout.

Risk of Shutdown. By his decisions regarding facility-product assignment policies and service levels, the designer applies different values for risk of shutdown to different facilities and related products. For example, where high risk of shutdown is assigned, standby facilities and process layouts may be selected.

Operating Policies. Decisions regarding number of shifts, overtime, days per week, and maintenance periods must be made by the designer.

### 2.2.3. Dependent Variables

Product cost is considered to be the usual dependent parameter measuring the effectiveness of plant design. A number of other measures, however, such as customer and worker satisfaction, are only partially related to immediate product costs. Rather than relying on one single measure, we suggest a number of dynamic measures of operating effectiveness, as well as static measures.

Dynamic Measures

Machine or capital utilization.--The lower the utilization for a specified production level, the more efficiently the selected capital assets are being worked. If capital investment is low as compared to direct costs, changes in operating policy can cause large changes in utilization without significant change in product unit cost.

Labor utilization.--The percent of labor utilization affects product unit cost in proportion to the labor cost component in product unit cost. Poor labor utilization can yield a reduction in mean process time without significant change in product unit cost.

Product cost.--Optimal product cost is often considered to be synonymous with optimal plant design.

Distribution and variance of elapsed completion time for each product.--In a sense, this measure is related to customer satisfaction, or the ability of the plant design to compete on a delivery basis. The shorter the mean completion time, the quicker the delivery possible. Variance is one measure of reliability of delivery promises and thus also of customer satisfaction.

Mean and variance of waiting time cost.--The unit product cost is only indirectly affected by waiting time. Some waiting time (in-process inventories, for example) may be needed for efficient capital or labor utilization, but excessive waiting time leads to high capital requirements for inventories and extension of mean completion time. The distribution of waiting time cost should be determined for the total plant, as well as for individual product groups and individual production facility groupings.

Maximum number of units delayed in process.--Parts or orders delayed in process require plant space for storage. Some in-process storage may be desirable in a process layout to assure efficient utilization of capital facilities. Required space costs and inventory costs must be balanced against idle machine costs.

Static measures. Traditionally, a number of measures of layout merit have been proposed.(17,36,52) In order to relate this investigation to previous work several of these measures are presented as dependent variables. Each of them is obtained by measurement made at a particular time, and none considers changes in value of the independent variables over time.

Total move volume distance.--Since the energy expended in material handling at time t is related to the product of the move-distance times the volume (or weight) of the items in the product-demand rate distribution at time t, this product is frequently proposed for layout evaluation.(52)

Number of material transfers by labor in the processing sequence of each product.--Usually, the layout designer attempts to minimize the amount of material handling by labor because of the expense and control problems which arise.

Cost of and percent of labor time devoted to material handling.--This measure is difficult to determine economically in an operating plant, but is frequently recommended as a practical indicator of the need for layout effort.(2)

# CHAPTER III

# SPATIAL ANALYSIS PROGRAM

After the plant layout designer has selected a particular arrangement of facilities, services, material handling equipment, storage, and labor, he must predict the effectiveness of his design in some set of quantitative and qualitative measures. A common method is to chart the flow(38) of each individual product through a proposed path in the design, measure each transfer distance, and to determine the transfer means from a drawing or 3-D model of the layout. Estimates of time for each transfer and estimates of production and equipment costs are also made. If the number of different products is large, and the number of different paths, or routings is also large, the computation of transfer estimates can be too time consuming and tedious to be accurately consummated. Because much of the work is not technical in content, performing the spatial measurements by means of computer would release the designer for more creative work. The feasibility of the idea has been explored through the preparation of a computer program, written in MAD for the IBM 704 at The University of Michigan Computing Center.

In developing the program, two particular restrictions were imposed:

1. The program must be capable of handling discrete product manufacturing plant layouts in general, not just the layout of a specific plant.

2. The program must be capable of handling a layout whose area, number of machines, and number of products are large enough to suggest that such a program would be more efficient than human evaluation.

A general description of the program follows. The independent variables (Section 3.1), the design parameters (Section 3.2), and the dependent variables (Section 3.3) are presented first. A brief description of the sequence of steps, together with a flow chart is given (Section 3.4); and finally, the results and conclusions (Section 3.5) are indicated.

## 3.1. Independent Variables

### 3.1.1. Service Requirements, Physical, and Operating Characteristics of Process Facilities

A set of IBM cards comprises a standard facility deck for use with any layout. Each card contains the information in Table I about a specific process or material handling facility. For a particular evaluation run, one card for each different facility used in the layout is selected from a master file and included in the data deck for that run. If no card is available, one must be prepared; otherwise the program user prepares no new facility information.

The ability of each facility to perform certain transfer movements and the type of materials which it can accomodate, are described by a coded number BON (k). The decimal digit code number used in BON (k) and later also in PBOO (p) is based on using the 35 binary digits of a word in storage as a qualitative taxonomy scheme (Table II). The decimal digit code number is equivalent to the binary number constructed in the following way:

## TABLE I

## PROCESS FACILITY INDEPENDENT VARIABLES

NUMP = Number of different process and material handling facilities in layout (< 50)

CALL(k) = Mnemonic alpha-numeric code name for process k

NCODE(k) = Numeric code number for process k

BON(k) = 10 digit decimal code number for Boolean characteristics of facility k

FIRC(k) = Packed word:
  - FCSUB(k) - subroutine code for first cost for k-th machine
  - FCF(k) - first cost, fixed component
  - FCV(k) - first cost, variable component

INSTC(k) = Packed word:
  - INCSUB(k) - subroutine code for installation cost function of facility k
  - INCF(k) - installation cost, fixed component of machine k
  - INCV(k) - installation cost, variable component, of machine k

MAINTC(k) = Packed word:
  - RC(k) - repair cost, % per year of first cost of machine k
  - LIF(k) - life in years of machine k

MISC(k) = Packed word:
  - MXLB(k) - maximum pounds on machine k
  - OPC(k) - operating cost $/hour on machine k

MCAP(k) = Packed word:
  - MXL(k) - maximum length 10's of inches of part which machine k can process
  - MXW(k) - maximum width in inches of part, etc.
  - MXH(k) - maximum height in inches of part, etc.

TABLE II

STRUCTURE OF BOOLEAN WORD USED TO DEFINE QUALITATIVE CAPABILITIES OF FACILITIES AND CHARACTERISTICS AND CONDITIONS OF MATERIAL

| Position of bit from right | Capability or Characteristic | |
|---|---|---|
| 1 | Not used | |
| 2 | Not used | |
| 3 | Not used | |
| 4 | Sticky | |
| 5 | Abrasive | |
| 6 | Corrosive | |
| 7 | Explosive | |
| 8 | Dirty | |
| 9 | Refrigerated | |
| 10 | Hot | |
| 11 | Noxious | |
| 12 | Radioactive | |
| 13 | Fragile | |
| 14 | Bulk solid | |
| 15 | Liquid | |
| 16 | Part | |
| 17 | Sheet | |
| 18 | Catch | C |
| 19 | Phase lap | PL |
| 20 | Grasp | G |
| 21 | Plan | P |
| 22 | Hold | H |
| 23 | Not used | |
| 24 | Select | S |
| 25 | Power | PR |
| 26 | Release | R |
| 27 | Not used | |
| 28 | Not used | |
| 29 | Not used | |
| 30 | Not used | |
| 31 | Not used | |
| 32 | Not used | |
| 33 | Not used | |
| 34 | Not used | |
| 35 | Not used | |

(a) if the process can treat or handle material with characteristics listed as 1 to 17 in Table II, the binary digit in the corresponding bit position of the binary number (counting from the right) is one,

(b) or if the process can perform transfers of the type listed as 18 to 26 in Table II, the corresponding bit is one,

(c) otherwise, the bit is zero.

For example, a human without auxiliary material handling equipment is capable of handling materials that are: 7-explosive, 8-dirty, 13-fragile, 16-parts, and 17-sheet. In addition, he is able to 20-grasp, 21-plan, 22-hold, 24-select, 25-furnish power, and 26-release. The binary number desired in storage is obtained by using the decimal equivalent for BON (k) $= 111011100110010000011000000_2 = 62492864_{10}$ on the data card. The purpose of this procedure is to conserve space on the card. The code number is used to detect gross errors in facility utilization. Mistakes in routing of material are detected by comparing the qualitative physical characteristics and conditions of the material to be processed with the material characteristics and conditions which the facility can accept. Rule one, the "material-facility compatibility rule" is used:

Let $M_{ik}$ = i-th Boolean qualitative property of the material prior to the k-th process,

$C_{ik}$ = i-th Boolean qualitative material capability of the k-th process, and

$M_{ik} \cap C_{ik} = 1$ when $M_{ik} = C_{ik}$ or when $M_{ik} = 0$.

Facility k is capable of handling material with property i(i=1,2,...,17), if and only if

$$\sum_{i=1}^{17} M_{ik} \cap C_{ik} = 17.$$

If $\sum_{i} M_{ik} \cap C_{ik} < 17$, use an auxiliary device (e.g., slings, pallet, tote pan) whose $C_{ik} = 1$ for all $M_{ik} \cap C_{ik} = 0$, for use with the k-th process.

Definitions of the qualitative capabilities listed as bits 18 to 26 inclusive follow. In many ways these capabilities are analagous to basic motions used in predetermined time systems, or to therbligs. For conciseness, we call them basic action patterns or "BAP's" for short.

| Bit | Capability | Definition |
|---|---|---|
| 18 | Catch - (C) | Facility has concave surface which enables it to restrict materials to a specific area when they fall onto the surface.<br>Examples: Hoppers, tote pans, barrels, bins. |
| 19 | Phase-Lap (PL) | Facility can begin processing subsequent parts before discharging those already in the process.<br>Examples: conveyors, storage racks. |
| 20 | Grasp - (G) | Facility is able to clamp onto the part without human assistance by means of jaws, magnets, or grapples and to lift the part in a vertical direction.<br>Examples: hoists, cranes |
| 21 | Plan - (P) | Facility has a fixed path or programmed procedure requiring no human attention after operation begins.<br>Examples: gravity conveyors, automatic screw machines. |

| | | |
|---|---|---|
| 22 | Hold - (H) | Facility supports the part from below only. No lateral restriction is furnished.<br>Examples: tables, flat car, flat belt conveyor. |
| 24 | Select - (S) | Facility is able to discriminate one particular class or individual parts among many.<br>Examples: lift truck, electromagnet crane. |
| 25 | Power - (PR) | Facility is supplied with integral means of mechanical power.<br>Example: Electric fork lift truck, tractor. |
| 26 | Release - (R) | Facility is able to disengage itself from the part to allow the part to fall vertically.<br>Example: clam shell bucket cranes, electromagnet cranes. |

By definition, the BAP's describe actions common to both processing facilities and material handling equipment. By comparing the loading and unloading requirements of a processing facility and the transfer capabilities of the available handling equipment, the feasibility of the transfer can be tested.

Rule two, the "facility transfer logic" rule results:

Let $k$ = the facility delivering the material and

$k + 1$ = the facility receiving the material from k-th facility.

Then, $k$ will transfer to $k + 1$ if and only if the following Boolean relation is true:

$$(R_k \cap (C_{k+1} \cup H_{k+1})) \cup ((G_{k+1} \cap PR_{k+1}) \cap (C_k \cup H_k)) = 1$$

(This rule says, the delivering facility must be able to release and the receiving facility must be able to catch or hold, or the receiving facility must be able to grasp and must be power driven and the delivering facility must be able to catch or hold.) An example satisfying the first condition is an electromagnet crane releasing scrap iron into a hopper car; and example satisfying the second half of the condition is that of an electromagnet crane unloading a hopper car of scrap iron.

These two rules are specifically utilized in the spatial analysis program. Two other rules follow which could be useful in refining the error detection effectiveness of the program during simulation.

Rule three, "equivalence of plan and power BAP's". Whenever a facility is equipped with its own power, a Plan BAP is needed for operation. The Plan BAP may be made available by a restricted move path as in a conveyor, by automatic limit switch control, by tape control, or by human operator. In any case the following Boolean relation must be satisfied by the n facilities being operated simultaneously

$$\sum_{k=1}^{n} P_k \cap PR_k = \sum_{k=1}^{n} PR_k \tag{3.1}$$

That is, a "plan" capability is necessary for each facility with its own power source.

Corollary to rule three

Whenever $\sum_{k=1}^{n} P_k \cap PR_k < \sum_{k=1}^{n} PR_k$ , where n = number of facilities operating, one unit of appropriate labor skill must be used at each k whose $P_k \cap PR_k = 0$, until (3.1) is true.

Rule four, "facility storage rule". A facility is capable of storing material if and only if it can phase-lap and grasp, catch, or hold. Thus storage capability of a facility k implies that

$$(G_k \cup C_k \cup H_k) \cap PL_k = 1 . \tag{3.2}$$

Both purchase cost and equipment cost are included as independent variables. A few cost estimates were based on studies by Zimmerman(55) and estimates were obtained from manufacturers and trade associations, but the majority are hypothetical to illustrate procedures.

### 3.1.2. Part Cards

Each part to be processed through the Spatial Analysis Program is described by a set of IBM cards, one card for each mechanical process or material handling facility used, in sequence. (See Table III)

A Boolean word constructed according to the method presented in 3.1.1 describes material characteristics. The length, width, height, and weight of the piece prior to the specified operation are tabulated and tested by the computer against the process capability. To test size compatibility, all orientations of the part are tested against the size restrictions of the process, as follows.

Let $P_i$ = dimension of part, (i = 1, 2, 3) and

$Q_j$ = dimension capability of process (j = 1, 2, 3).

If $P_i - Q_j \geq 0$, let $j^2 = H_{ij}$; otherwise $H_{ij} = 0$ (i = 1, 2, 3; j = 1, 2, 3).

Then, if $(H_{11} + H_{22} + H_{33}) \cup (H_{12} + H_{23} + H_{31}) \cup (H_{13} + H_{23} + H_{31}) = 14$, the part will fit into the process. The number of parts which can

## TABLE III

## PART CARD INDEPENDENT VARIABLES

(The following apply to one particular part only)

NUM2 = number of operations required on part

PRO(p) = packed word: machine group and dimension type used for operation p

INDX(p) = identification subscript of facility used for operation p

PTM(p) = packed word:
- LDT(p) = loading time in minutes/batch for operation p
- MUT(p) = service time in minutes/batch or ft/min for operation p
- ULDT(p) = unloading time, mins/batch for operation p

PWGT(p) = weight in pounds of part prior to operation p

PDIM(p) = packed word:
- LDIM = length
- WDIM = width
- HDIM = height

in inches of part before operation p

BATCH(p) = number of pieces which are to be processed simultaneously on operation p

PINC(p) = packed word = x, y, z coordinates of special load point required for this part only to operation p

POTC(p) = packed word = x, y, z coordinates of special unload point required for this part only to operation p

PBOO(p) = decimal code number for Boolean characteristics of part prior to operation p

AUX1(p) = NCODE number of auxiliary to be added to facility when performing operation p on this part

AUX2(p) = NCODE number of second auxiliary to be added to facility when performing operation p on this part simultaneously be fitted into the process is

$$\text{the minimum of} \quad \left\{ \begin{array}{l} \text{BATCH (p)} \\ \overset{3}{\underset{i}{\pi}} Q_i / \overset{3}{\underset{i}{\pi}} P_i \\ \text{MXLB(k)/PWGT(p)} \end{array} \right.$$

The type and sequence of process operations are determined by the sequence of cards in the particular part deck.

If the facility being utilized is a material handling facility k, the mean of the distribution of service time is given in feet/minute for operation p

$$\mu_p = MUT_p \times (\text{Distance }_k) + LDT_p + ULDT_p$$

If the facility being utilized is a process facility, the mean service time is given in minutes/batch thus:

$$\mu_p = MUT_p + LDT_p + ULDT_p$$

Throughout this investigation, each part is considered to be a complete product. Problems of identification of parts (see Reference 56) after assembly and disassembly are thereby avoided.

## 3.2. Design Parameters

### 3.2.1. Labor Service Level

The identification of labor classes is accomplished through straightforward use of the following design parameters:

NUML = number of different labor classes used in plant ($<$ 10)

LNAME(q) = mnemonic alpha-numeric code name for labor class q

LNUMB(q) = numeric code number for labor class q

LARATE(q) = labor rate $/hour for labor class q

### 3.2.2. Material Handling Facilities and Auxiliaries

The designer selects material handling facilities by including a card from the master facility file in the facility deck described in 3.1.1.

### 3.2.3. Facility Service Level

This is determined by selection of process cards (3.1.1) and spatial utilization (3.2.5).

### 3.2.4. Facility Product Assignment Policies

Each part card described in (3.1.2) includes the mnemonic code name for the facility and the unique number used to identify the facility group to which a part is to be routed. A part can be processed on any one of the $m (m < 10)$ machines in that group. If a part is always to be processed on a particular one of a number of like machines, the particular machine must be identified as constituting a distinct group by itself.

### 3.2.5. Spatial Utilization

The physical location of process facilities, of storage, and of transport paths is introduced into the program through a deck of location cards (Table IV). One, or several cards together, are used to describe the physical position of a facility or area with reference to a three-dimensional coordinate system $(0 \leq x \leq 99, 0 \leq y \leq 99, 0 \leq z \leq 99)$. To simplify the representation to the computer of the complex shapes of facilities, four types of shapes are defined according to their input-output flow characteristics. Within one of these four types of flow

## TABLE IV

## LOCATION DECK - SPATIAL UTILIZATION DESIGN PARAMETERS

NUM1 = number of cards in layout data description

NME(g) = alpha-numeric name of process facility in group g

NAME(g) = packed word: NCODE(k)
DM = dimension of group g
MGS = group number = g
MG(g) = number of machines in group g

LI(g) = number of "lines" needed to describe group g area ($\leq$ b)

NEQLB(g) = number of laborers/operating hour for each machine in group g

LBCL(g) = labor class used on facility group g

NESULB(g) = number of laborers required for set-up of each machine in group g

SETUP(g) = packed word = set up labor class on machine group g
elapsed set-up time in minutes on each
machine in group g

INTER1(g, b) = x, y, z coordinates of entry point of line b of group g

INTER2(g, b) = x, y, z coordinates of exit point of line b of group g

SPINT2(g) = x, y, z coordinates of special discharge point from group g

SPINT1(g) = x, y, z coordinates of special receiving point of group g

SPTLG1(g) = number of the line of the special receiving point of group g ( if any )

SPTLG2(g) = number of the line of the special discharge point of group g ( if any )

INP(g) = x, y, z coordinates of entry point to type 1 group g

OUTP(g) = x, y, z coordinates of exit point from type 1 group g patterns, it is possible to define most common process and material handling facilities (Figure 2).

Type I facilities are characterized by input at one unique spatial coordinate and output at one unique spatial coordinate, not necessarily different from the input coordinate. Travel is assumed to be on a straight line from input to output for calculations of distance moved by the part. Introduction or removal of parts between input and output points is assumed to be impossible, at least under normal operating conditions. Chutes, automatic transfer machines, and screw conveyors are examples of facilities meeting these restrictions.

Type II dimensions efficiently describe area coverage, characteristic of overhead cranes, derricks, mobile cranes, industrial trucks, and storage areas. Each area must be described by two space coordinates and a width measured perpendicular to the connecting line. Only one type II area can be assigned to a particular facility. If non-rectangular areas are to be assigned, type III or IV areas are needed. When measuring path distance moved, travel is assumed to be possible on the shortest line between any two points in the area. Input and output can occur at any point, unless specifically restricted at the option of the user.

Type III describes a one-directional path network representative of powered overhead chain-loops, chutes, and one-way aisles. Such paths are described as a collection of connected lines by a specific initial and ending point at the ends of each line, assigned in the direction of travel. If coverage perpendicular to the direction of travel is appreciable, it is specified by a width coordinate for each line. The ending x, y, z coordinates specified for one end of a line must coincide with the initial

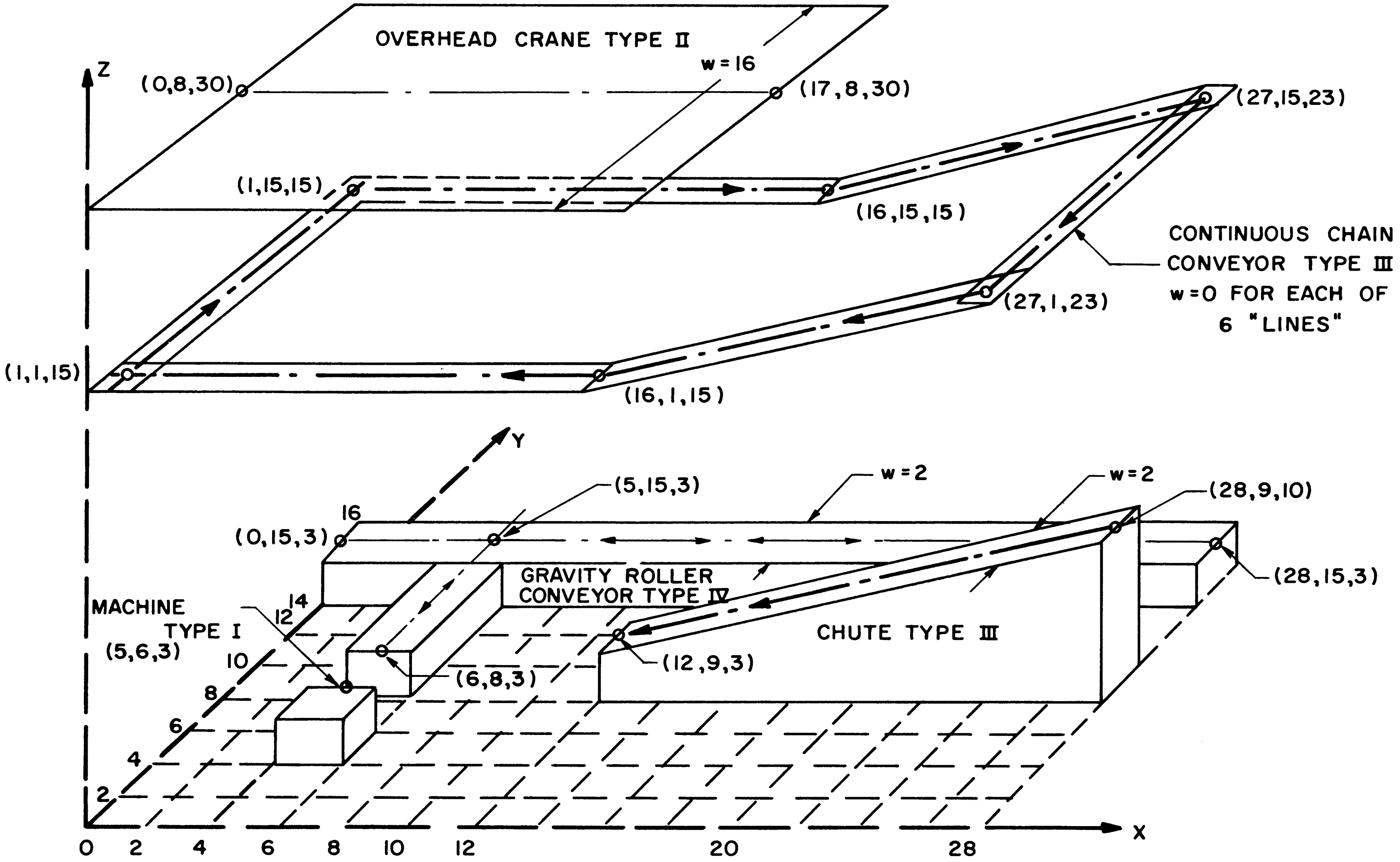

Figure 2. Examples of Process or Material Handling Facilities Showing Method of Spatial Description.

coordinates of the subsequent line if the same facility utilizes both lines. Move-distance for a part in a type III network is the sum of these components: (a) the straight-line distance between the entry point for the part and the ending coordinate of the line, (b) the straight-line distance from the exit point to the initial coordinate of the line in which the exit point is found, and (c) the minimum network centerline path-distance between the ending coordinate of the entry line and the initial coordinate of the exit line. When this procedure is used, only three coordinates are necessary to describe each line: the initial centerline coordinates, the ending centerline coordinates, and the line width. No restriction is made on the angles between lines. When one line ties into another at the midpoint, similar to the way the leg of a "T" connects to the cross-stroke, the cross-stroke must be described as two distinct lines, which happen to be co-linear. Loading and unloading may take place at any point along the network of lines, unless special points are specified at the option of the user.

Type IV is identical to type III facilities, except that it is used to apply to networks where travel is permitted in both directions. Examples of type IV facilities are tractor trains which travel only in aisle networks, monorail hoists, and non-powered horizontal roller conveyors.

## 3.3. Dependent Variables

The program evaluates the independent variables and design parameters by calculating the dependent variables listed in Table V. The results are produced in the form of a flow process chart for each part and a summary cost tabulation for the equipment utilized.

## TABLE V

## SPATIAL EVALUATOR DEPENDENT VARIABLES

MHC = purchase and installation cost ($) for facility type k

MHCST(k) = cost ($) per machine hour of operation for labor, maintenance and operating

The following are given for each part in sequence of operations on part

VOLUME(p) = maximum volume ($ft^3$) of load actually processed on operation p

MAXLOD(p) = maximum weight (#) of load actually processed on operation p

DISTAN(p) = number of feet moved from operation p-1 to p

XENTRY(p)
YENTRY(p) = coordinates of receiving point of facility for operation p

INFOO(p,1) = coordinates of discharge point of facility for operation p

MUT = standard time to perform operation p (does not include labor handling time)

The following error indications are printed:

100 = error in input location card deck

101 = error in input part card deck arrangement

103 = material not compatible with first facility specified

104 = first facility unable to handle size of raw material

105 = first facility unable to handle weight of raw material

106 = error in input part card deck content

"No material handling possible from operation __________ to ________"

This printout results whenever means of handling material between two processes has not been properly provided.

"Box Needed" This printout results when only labor has been provided for handling between two processes, and the parts are extremely small and light.

### 3.3.1. Capital Cost

Calculation of capital cost is based on the relation

$$MHC(k) = n_k(PSUBRT(i) + ISUBRT(i)),$$

where

$n_k$ = number of facilities of type k,

$PSUBRT(i)$ = i-th subroutine for purchase cost calculation, and

$ISUBRT(i)$ = i-th subroutine for installation cost calculation $(i = 1, \ldots, 9)$.

Users of the program can insert new subroutines if those available do not adequately describe the cost functions of the particular facility. The subroutines currently included in the program are similar in structure:

$$PSUBRT(1) = FCF_k + FT_k(FCV_k)$$

$$ISUBRT(1) = INCF_k + FT_k(INCV_k)$$

Both calculate costs as the sum of a fixed component plus a variable component which is a linear function of the number of feet of length of equipment (or other suitable factor such as load capacity). Total capital cost is thus the sum of all capital costs:

$$\sum_k MHC(k)$$

### 3.3.2. Operating Cost

Operating cost per facility hour is determined from

$$MHCST_k = \frac{RC_k(PSUBRT(i))}{2000\ LIF_k} + NOLB_k(LARATE_k) + OP_k$$

### 3.3.3. Other Dependent Variables

The method of determining values of other dependent variables (move distance, compatibility, transfer points, labor required for material handling, and service times) is best understood through the description of program operation which follows.

## 3.4. Program

The program consists of four machine core loads comprising the following program operations:

| | |
|---|---|
| Core No. 1. | Read and store facility card deck<br>Read and store labor card deck<br>Read and store location description deck<br>Calculate and print cost variables |
| Core No. 2. | Read and store part card deck<br>Analyze all part material-handling transfers<br>Print process chart of all manual transfers |
| Core No. 3. | Test coincident location, and determine minimum distance between facilities if not coincident |
| Core No. 4. | Determine minimum path through network developed in core 2 and 3 and print of results for each part |

The logic of the computations performed in cores 1 and 2 is described in 3.1.1 and 3.1.2, and the method of describing physical locations in 3.2.5. Procedures for analysis of transfers and methods of calculating path-distances follow. Flow charts are given in Figures 3 and 4.

### 3.4.1. Transfer Analysis

Transfer between two facilities is assumed to be possible if the two facilities meet the logic requirements of 3.1.1, if the two facilities have at least 1 location coordinate in common, and if the following restrictions are satisfied:

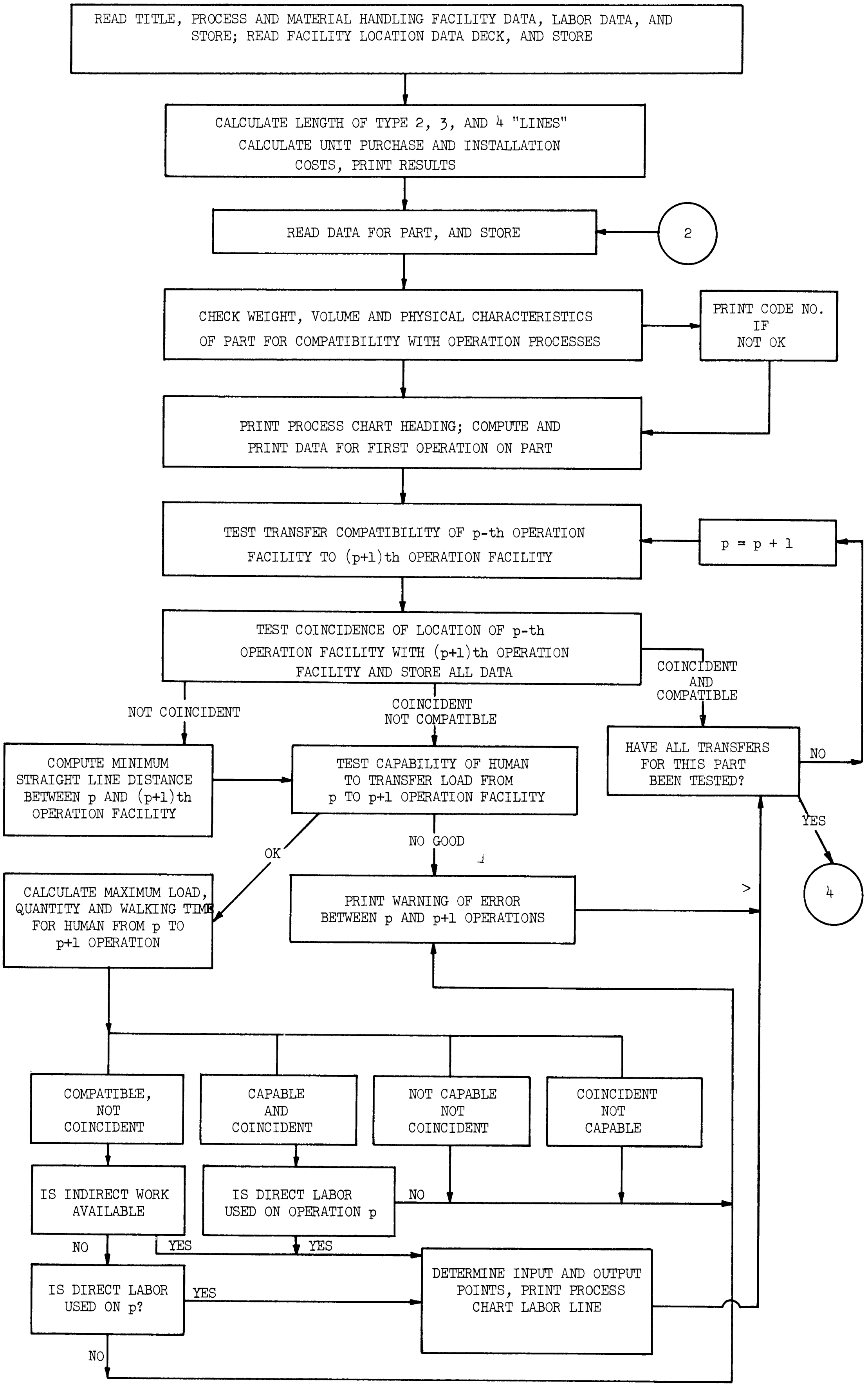

Figure 3. Spatial Analysis Program Flow Chart.

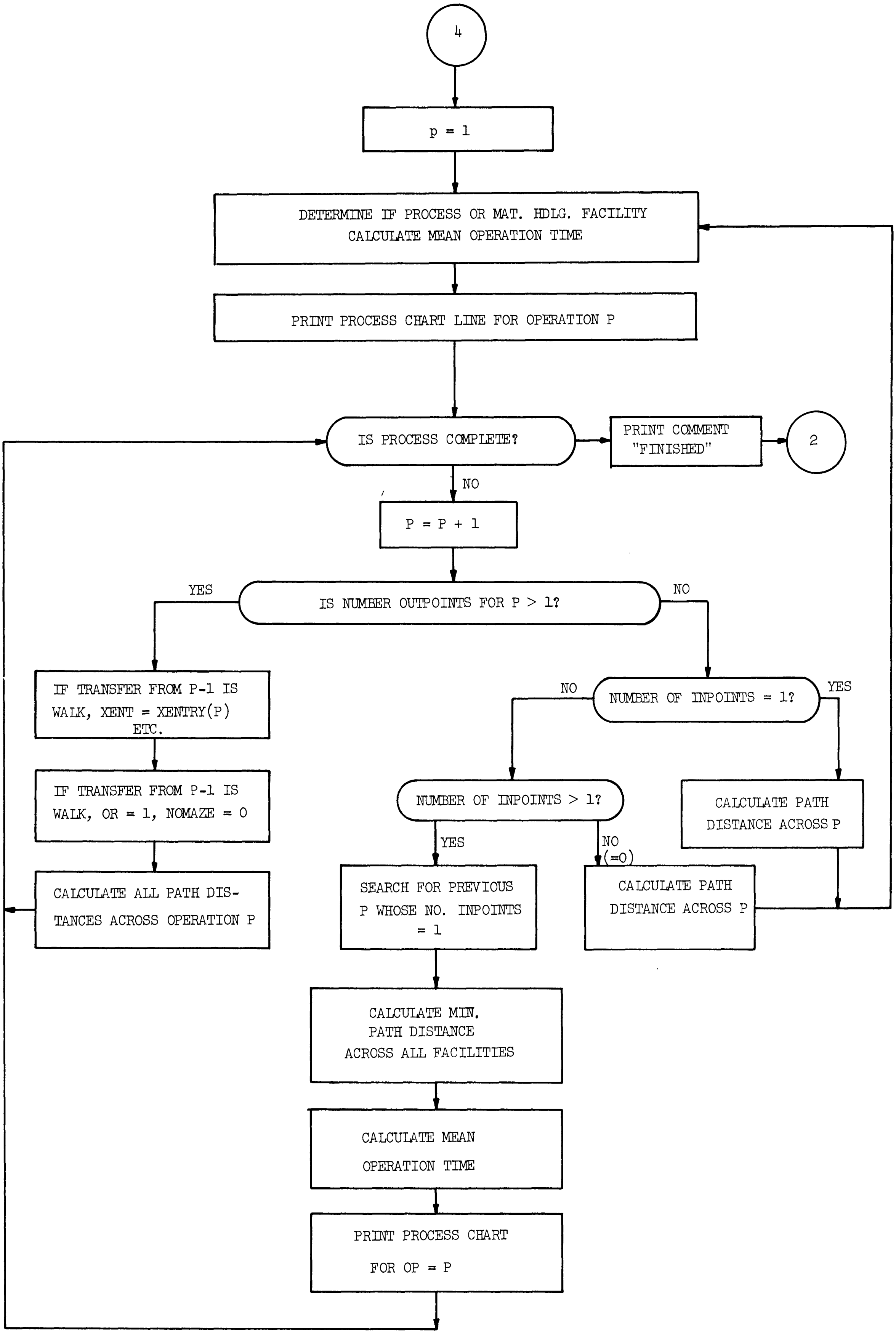

Figure 4. Spatial Analysis Program Flow Chart (Continued).

1. Transfer between two type I facilities is permitted if and only if the discharge point of the first operation coincides with the receiving point of the subsequent operation.
2. Transfer between a type I facility and any other type must take place at the receiving or discharge point of type I facility, but may take place anywhere on the type II, III or IV facility unless otherwise specified.
3. Specification of a particular receiving or delivery point or points on a type II, III, IV facility implies that transfer is permitted only if the point(s) is common to the respective delivery or receiving facility.

Transfers are tested in one of two ways, depending on the type of the facilities involved. For transfers between types I-II, I-III, and I-IV, a specific point in type I area must be found to be within the boundary of the other area. For transfers not involving a type I area, no point is specified, hence <u>any</u> point in one area which is also in the other will satisfy the location requirements for transfer.

We consider the first kind of transfers first. The test is initiated by transformation and rotation of the points describing the area or network line until they lie on an $x'$ axis. Let

$x_t, y_t$ = coordinates of specific point to be tested,

$x_a, y_a$ = coordinates of one end of line,

$x_b, y_b$ = coordinates of other end of line, and

$w$ = width of line.

Well-known concepts from analytic geometry can be used to obtain

$$\sin \theta = \frac{x_a - x_b}{\sqrt{(x_a - x_b)^2 + (y_a - y_b)^2}}$$

and

$$\cos \theta = \frac{y_a - y_b}{\sqrt{(x_a - x_b)^2 + (y_a - y_b)^2}}$$

Then rotation through the angle $\theta$, and translation so that the origin is at $x_b$, $y_b$ gives

$$x_a' = (y_a - y_b) \sin \theta + (x_a - x_b) \cos \theta,$$

$$x_t' = (y_t - y_b) \sin \theta + (x_t - x_b) \cos \theta,$$

and

$$y_t' = (y_t - y_b) \cos \theta + (x_t - x_b) \sin \theta.$$

The point $x_t$, $y_t$ is within the area of the "line" if

$$|x_t'| \leq |x_a'| \ , \quad |x_a' - x_t'| \leq |x_a'| \ , \text{ and } |y_t'| \leq w/2.$$

In the case where the point is to be tested for coincidence with a type III or IV network of lines, this test is iterated for each of the lines until it is satisfied, or all lines have been tested.

Where no specific point is indicated (as in the test of a type III with a type IV network), any of the infinite number of points in either of the two areas being tested, for example A and B, could be selected in the following arbitrary sequence:

1. All end coordinates of A are tested in each line of B
2. All end coordinates of B are tested in each line of A
3. Each line of A is tested for intersection with each line of B

If two networks overlap, one, two, or all three of the tests may disclose a number of transfer points in common. The list of points is stored for later use in the travel distance computation (3.4.2). It is possible to conceive of cases, for example, where two type II areas are contiguous for which the test would incorrectly indicate that no points were common. One method of reducing this possibility would be to test each extreme corner point of A in B and B in A. In the interests of saving computation time, this test was removed from the program. Additional tests for intersections also could lead to a longer list of points in common. Such a list would increase the choice of possible paths through the system but would not guarantee any improved paths.

Where the tests reveal no common points or overlaps between two sequential facilities, and handling by humans is compatible with the part to be transferred, a measurement of the minimum distance between the two facilities is made. The measurement is the minimum of (a) the perpendicular distances from any end point of the A network to any side of the B network, (b) the perpendicular distance from any end point of the B network to any side of the A network, or (c) the straight line distance between any two points of the A and B networks. The assumption is made that labor in the delivering facility (or indirect labor) will carry parts only to the closest point of the next facility. Where labor transfers are feasible and either indirect labor is available or direct labor is utilized with the delivering machine, the distance and time required for the transfer, at 90 feet per minute walking speed, are printed as a separate line of the flow process chart. A visual inspection of the chart then quickly reveals the number of times the part is handled by direct labor, the estimated time of the transfer based on distance moved, and the operation away from which the labor transfer is required.

### 3.4.2. Travel Distance Computation

The operations of the Spatial Analysis Program described thus far have resulted in lists (in computer storage) of:

(a) Points in common where material is transferred from one facility to the next with path distance of zero.

(b) Points of beginning and end of transfer by labor between facilities and the path distance of each.

All the paths and path distances across (or travelled by) any facility can be calculated from the points in the lists. For type III and IV facilities, several alternative paths across a facility may be found. The sequences of points from the first operation through the final operation therefore resemble a network. The initial operation (receiving) has a clearly specified origin and the final operation a specific destination. Between these two points may be a network of possible paths or, in the simplest case of all type I facilities linked by human transfers, a single path. In general, the sequence may be a number of smaller networks linked by single paths. Using the criterion of minimizing the move distance, the program examines the alternative feasible paths through the facilities network, and using Dantzig's algorithm(4,8) selects the "best" path. The path selected is then printed in the final process chart listing for each part, together with facility names, coordinates, and the operation sequence.

## 3.5. Results of Spatial Analysis Program

The feasibility of using computers to analyze and measure spatial as well as logical engineering principles of plant-layout materials-handling problems is conclusively established by the Spatial Analysis Program.

Appendix H shows a schematic representation of the $A_1$ layout spatial design. The design is transformed into punched-card information which, together with standard performance data on each of the seven types of machines, and the labor data and standard process data on each part, forms the input deck to the computer (Appendix G). The Spatial Analysis Program can accomodate an x, y, z coordinate system of 100 dimension units on each axis, up to 50 different facility groups, 9 machines per group, 9 labor groups, and an unlimited number of different parts with a maximum of 20 facility utilization steps in any part routing. This scope embraces the design of many processing departments of 10,000 square feet on a one-foot coordinate scale, or of larger processing plants on a coarser scale. The printout furnishes quick estimates of the number of times labor performs material handling, and of the amount of time required. Estimates of travel times, distances, and path sequences for each part are provided so that alternative layouts can be quickly compared in terms of these criteria. Total handling distances and times could be obtained by a slight program modification, or by specifying the results to be punched instead of printed, so that sorting and collating of the card output could be accomplished. Once a standard facility deck has been developed, the additional input information is readily prepared: less than one hour was required for complete preparation of the $A_1$ layout data from the design. A computer running time of approximately five minutes will evaluate the 2 parts specified. Each additional part requires from one to four minutes for evaluation depending on the complexity of the layout description and the number of facilities used in the part routing. The economics of computer time compared to engineering effort seem favorable if a large number of different paths must be evaluated. The detection of one gross error in a complex layout would be sufficient to justify the computer time required.

Development of the Evaluator Program highlighted a number of directions for further investigation of the engineering logic of material handling-plant layout systems design, and for improvement of the Evaluator Program itself.

1. A serious problem arose in attempting to define the service requirements, and physical and operating constraints of process equipment, both qualitative and quantitative, with sufficient precision to estimate performance, cost, and utilization feasibility. If the judgment, or "art", content of material-handling layout design is to be reduced, rigorous definitions of operational characteristics of facilities, rather than mere descriptions, must be developed. Qualitative characteristics may yield to a thorough study of transfer logic, as suggested by the rules in section 3.1. Individual facilities must be studied to discover more refined quantitative methods of concisely describing capacities, production rate functions, and cost functions, and the direction of change in these functions when accessories are employed with the facilities. It may be that the magnitude of this problem will postpone for a long time the practical application of the concepts of error analysis of layout design used in the Spatial Evaluator Program. The concept of

design automation as embodied in the Evaluator Program, however, has been accomplished by IBM in the development of computer logic diagrams,(59) and extension to plant layout hinges mainly on development of engineering operational definitions of process facilities.

2. Efficient programming would permit expansion of the Evaluator Program in two ways, both intended to improve the usefulness of the Program without much increase in operating cost over the present Program. First, the addition of the z dimension in evaluation of move distances would permit use of limitations in vertical move capability of facilities as another check on flow transfer logic. Second, by expanding the search capability of the Program a large improvement is possible in efficiency of use of the Program as well as in its attractiveness as a research tool. Currently, the Evaluator tests for feasible transfers between two specified facilities. If no direct transfer is possible due to violation of logic or contiguity requirements, a search for acceptable direct labor is carried out. If available and capable, direct labor is assigned the transfer task. By extension of this process, the program could be developed so that the part deck would specify only the sequence of processing steps required, thus eliminating the specification of material handling devices. The program would then search among all available and feasible material handling devices, or chains of devices, which could transfer

the part from one facility to the following. Since more than one available device may satisfy the feasibility requirements, some criterion must be chosen for the selection. Investigation of the effects of the use of different criteria in the selection of devices and paths should yield insight into the importance of such current empirical rules as "minimize transfer," "minimize move distance," etc.

# CHAPTER IV

# SIMULATION PROGRAM

## 4.1. Description of Simulation Program

The simulation program, written to test the line and process selection hypotheses, is similar in general concept to other simulation programs,(12,23,41V,55) but with two unique features to be described later. The flow chart for the general program is given in Figures 5 and 6. Independent design variables are listed in Table VI, and the simulation output, or dependent variables, is listed in Tables VII. The subscripts and ranges of subscripts are given in Table VIII. By proper interpretation of the subscripts it is seen that the simulation is capable of handling up to 20 machine groups (a machine group is one in which all machines have identical characteristics) with up to 9 identical machines in each group. Up to 20 different operations may be specified for process routing of each of the 20 different parts which may be processed. The number of orders which may be processed is unlimited except that no more than eighty may be in process at any one time. Nine different labor classes may be specified for assignment to machine groups as desired, and up to 9 laborers may be in each labor class. The number of laborers of each class working on each shift limits to 81 the number of labor-attended machines which can be operated simultaneously on any shift. Up to 99 more unattended machines can be in operation. By shifting labor from machine to machine, however, 180 different attended machines can be utilized during a shift. Machines may also be required to have more than one operator in simultaneous attendance.

## TABLE VI

## SIMULATION INDEPENDENT VARIABLES AND DESIGN PARAMETERS

PRT(n) = name of part n

OP(n) = number of different operations of part n

PRTINF(n, i) = packed word: $\left.\begin{array}{l}\text{Machine group}\\ \text{Quantity}\\ \text{Service time}\\ \text{Set-up time}\end{array}\right\}$ of part n, operation i

PRO(g) = name of process in group g

NUMCHS(g) = number of machines in group g

MHCST(g) = machine hour cost of machine in group g

NOLB(g) = number of laborers required to operate a machine in group g

LBCL(g) = labor class used with group g

LBSH(s, l) = number of laborers of class l working on shift
(Must be same all shifts, or 0)

PIECE(v) = name of part on order v

RELT(v) = packed word: Release time of order v, minutes after start, and order number

NUPCS(v) = quantity of parts on order v

CST(v) = raw material cost per/piece on order v

ORD(v) = order number on order v

PER = number of days per report period

STOP = number of periods per simulation

ENSF(s) = end time of shift in hours from start

## TABLE VII

## SIMULATION DEPENDENT VARIABLES

LQUE(l) = number of orders waiting to be processed by labor class l

LQ(l, k) = packed word: order number and operation number of order in labor class l queue, k-th position

LABT(l, m) = packed word: end time of operation currently being performed by laborer m, of labor class l ($\infty$ when idle) plus order number and operation number of part being processed

FIOT(g, p) = packed word: arrival time of first batch of order v, operation i, to end of conveyor machine group g, p-th order on conveyor

LBI(s, l) = number of laborers idle in labor class l, on shift s

LIOT(g, p) = packed word: arrival time of last batch of order v, operation i, to end of conveyor machine group g, p-th order on conveyor

P(g) = number of orders now on conveyor g

DCST(v) = direct cost of order v

SUTMUP(g) = set up time in hours, used on MCH(g) per period

LBHSP(l) = number of labor hours available in class l per period

MCHHUP(g) = machine hours utilized each period in group g

AVQT(g) = average length of time an order waits at g

AVQL(g) = average number of units waiting at g per period

AVQCST(g) = average number of dollars waiting at g per period

LABHRU(l) = labor hours used by class l per period

NUMW(g) = total number orders at g during period

## TABLE VII (CONT'D)

TOTW(g) = total time of waiting at g during period

MAXMQ(g) = maximum number of orders which wait before group g during period

MAXLQ(l) = maximum number of orders which wait before labor class l during period

TOCSTW(g) = total queue dollar hours

END(g, j) = packed word: end time of operation currently being performed on machine j of group g ($\infty$ when idle), order number v, and operation number i, being processed

MQUE(g) = number of orders waiting to be processed on machining group g

MQ(g, k) = packed word: order number v, and operation number i of order in machining group g queue, k-th position

## TABLE VIII

## SIMULATION SUBSCRIPT MEANINGS AND RANGES

$g$ = machine group identification number (1, ..., 20)

$i$ = number of operation performed on a part (1, ..., 20)

$j$ = machine identification number in group - (1, ..., 9)

$k$ = position of order in particular queue (1, ..., 20)

$l$ = number of labor classes (1, ..., 9)

$m$ = laborer identification number within class (1, ..., 9)

$n$ = part number identification (1, ..., 20)

$p$ = sequence number of order on conveyor (1, ..., 9)

$s$ = number of shift (1, 2, or 3)

$u$ = index of next event (1, ..., 7)

$v$ = order number (sequential queue) (1, ..., 80)

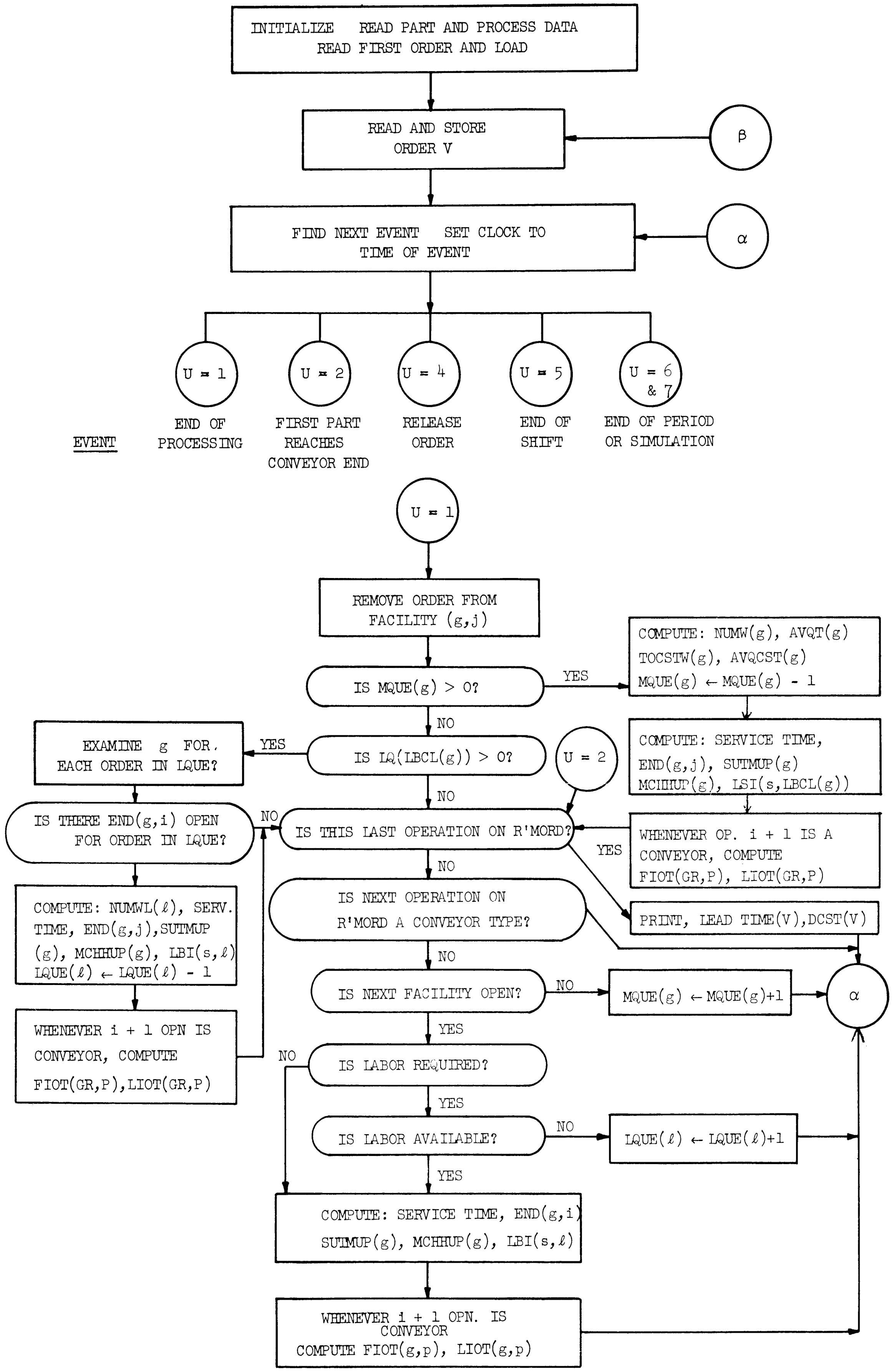

Figure 5. Simulation Program Flow Chart.

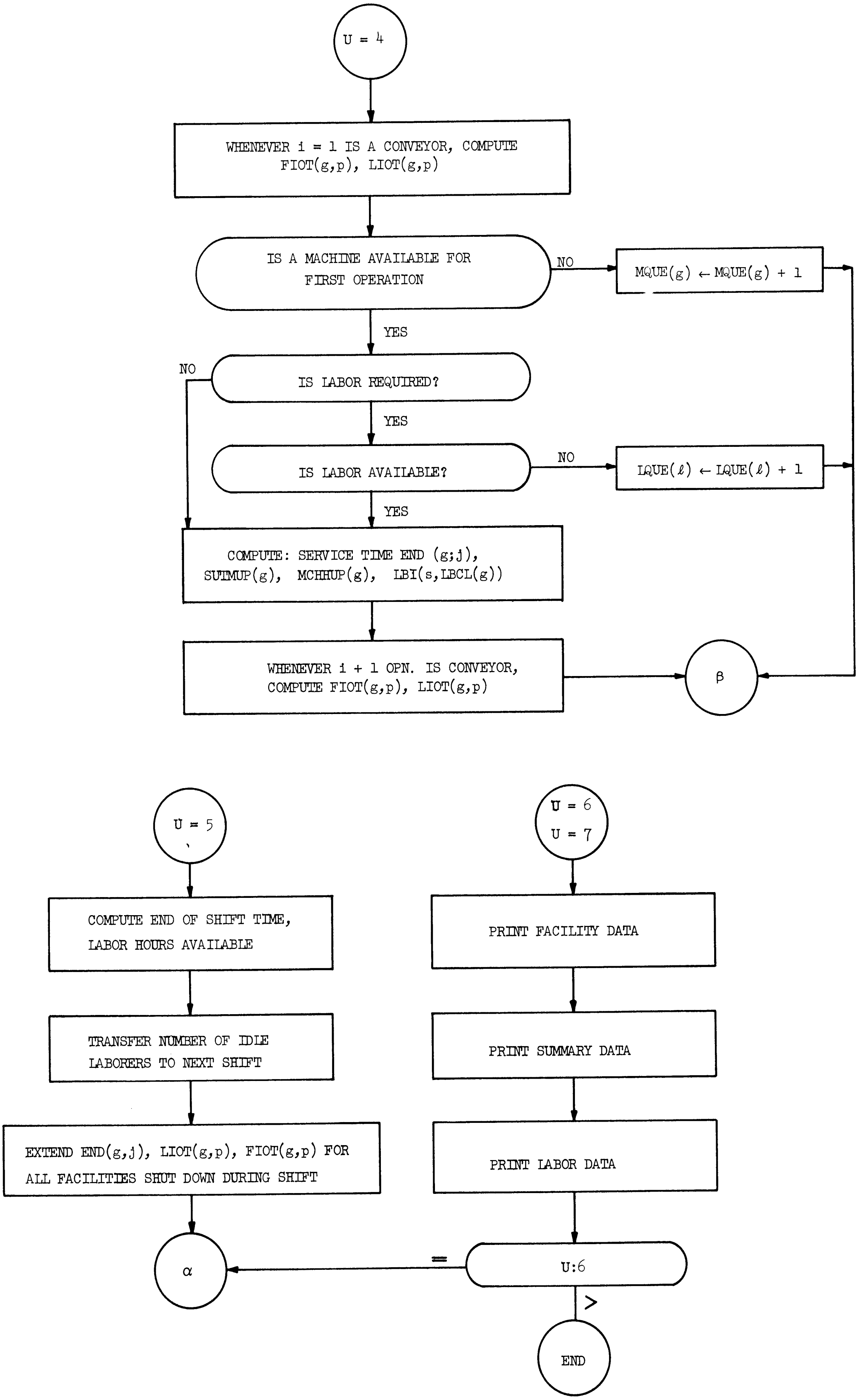

Figure 6. Simulation Program Flow Chart (Continued).

The operation of the simulation begins with the release of an order for a specified quantity of a stated part on a designated day. The simulation releases all orders at 9:00 a.m. of the designated day. The simulation searches for the machine group specified by the part routing as the first process on that part. If a machine is open in that group, and the required labor is also available, the open machine is set up for the part, labor is assigned, and the completion time for the order is calculated.

Throughout the simulation, it is assumed that set-up of a machine in a group begins only after a part has arrived for service. Part arrivals are not anticipated by prior machine set-up. If no machine is open, the order is added to the queue for that machine group. If required labor is not available, the machine remains idle, and the order is added to the queue for that labor class. The next event in time is then determined. It may be the release of the next order, the completion of an order on a machine, the end of a report period, the end of a shift, the time when the first part of batch reaches conveyor end, or the end of the simulation. If the event is completion of an order on a machine, the batch is moved to the next process and the loading or queueing operation is repeated. If a queue exists in front of the machine group, the now idle machine is loaded with the first order in the queue; otherwise it becomes idle. If no labor is available at any time to operate the machine, it becomes idle. If an end of shift occurs, and the labor class is reduced to zero for the following shift, all machines utilizing that labor class become idle until the next shift for which that labor class reports. The jobs remain in the machines and work resumes where it was previously stopped. At the completion of an order, the end of a report period, and the end of the simulation, data are computed and printed on in-process-time, order cost, in-process-inventory dollars, average queue lengths, average idle time, and average number in queue for each group.

One characteristic distinguishing this simulation from any other known simulations permits simulated phase lapping of operations where desired, in the following way:

Let

$\mu_g$ = mean service time of part on a machine in group g,

$t$ = release time of lot,

$E_g$ = ending time of process now on machine in group g,

$F_g$ = time of arrival of first part in lot to end of conveyor group g,

$L_g$ = time of arrival of last part in lot to end of conveyor group g,

$N$ = number of parts in lot, and

$S_g$ = set-up time of machine in group g.

Assume four machine groups in sequence, with $g = 3$ a conveyor. We wish to determine the time for completion of the lot, given a release time $t$ for the lot to the first machine in group $g = 1$.

Then

$$E_1 = t + S_1 + N\mu_1,$$

$$E_2 = E_1 + S_2 + N\mu_2,$$

$$F_3 = E_1 + \mu_2 + S_2 + \mu_3 + S_3,$$

$$L_3 = E_2 + \mu_3,$$

and

$$E_4 = \text{max of} \begin{cases} F_3 + S_4 + N\mu_4 \\ L_3 + \mu_4. \end{cases}$$

Hence, in general for the case of one conveyor, the ending time for the machine group g receiving parts from the conveyor is as follows:

$$E_g = \max \text{ of } \begin{cases} F_{g-1} + S_g + N\mu_g \\ L_{g-1} + \mu_g, \end{cases}$$

with

$$F_g = E_{g-2} + \mu_{g-1} + S_{g-1} + \mu_g + S_g$$

and

$$L_g = E_{g-1} + \mu_g.$$

A combination of process equipment such as a chain conveyor-hearth furnace, or a conveyorized paint booth, can be represented by combining a batch process g and phase-lap process g + 1 in the Simulation. The process service time $\mu_g$ should equal the time between trays, or hook availability; the process service time $\mu_{g+1}$ should equal the additional time for travel through the process so that the elapsed time for processing each part = $\mu_g + \mu_{g+1}$. The MHCST(g) must be selected so that the cost per piece on the process = $\mu_g$ x ($\text{MHCST}_g$). In this way, a part becomes available for the (g + 2)nd process only after it finishes the conveyor travel, phase-lapping is permitted, and queue and cost behavior can be determined from group g data.

In the case of two or more conveyors in series, a modification is necessary due to dependence of later questions on F and L rather than E. For example, assume six machine groups in sequence, with groups g = 3, 4, and 5 all conveyors.

Then

$$E_1 = t + S_1 + N\mu_1,$$

$$E_2 = E_1 + S_2 + N\mu_2,$$

$$F_3 = E_1 + \mu_2 + S_2 + \mu_3 + S_3$$

$$L_3 = E_2 + \mu_3$$

$$F_4 = F_3 + \mu_4 + S_4$$

$$L_4 = L_3 + \mu_4$$

$$F_5 = F_4 + \mu_5 + S_5$$

$$L_5 = L_4 + \mu_5$$

and

$$E_6 = \max \text{ of } \begin{cases} F_5 + S_6 + N\mu_6 \\ L_5 + \mu_m . \end{cases}$$

For each conveyor in series after the first therefore:

$$F_g = F_{g-1} + \mu_g + S_g$$

and

$$L_g = L_{g-1} + \mu_g .$$

Thus, it is possible to simulate production lines where parts on a given order are processed simultaneously, rather than in batches requiring completion of one operation before the next can begin. The process code number PRO(g) used to identify a phase-lapping facility must be $1999999999 < PRO(g) < 3000000000$, in agreement with the code system used in the Spatial Evaluator. The labor class assigned to a conveyor must be empty (0), because no simple service time calculations are provided.

We assume that each conveyor has capacity for all parts that may be placed on it at any given time; that is, the conveyor has infinite channels, hence never a queue. The conveyor service time is based on the travel time from loading to unloading point for the particular part. If the unloading point is busy so that a queue forms on the conveyor, adequate storage capacity is assumed to be available as, for example, by power and free sections, monorail switches, or belt conveyor back-ups. Set-up time for a conveyor could be required if special fixtures or hangers are necessary. In general, however, $S_g$ for conveyors is zero. If the last facility in the operation sequence on a part is a conveyor, the ending time listed for the order is the time at which the first part comes off the conveyor. Considerable additional time may elapse before the last part is completed.

The simulation uses machine groups as the basis for keeping track of queue build-ups. For this reason, an operation consisting of labor only must have a pseudo-machine group associated with it. In order to guarantee that labor utilization and not fictitious pseudo-machine utilization is the cause of queues, the number of machines in the pseudo-group should be given as nine, the maximum possible. The controlling processing service time used should be the labor time for the operation.

The simulation is also unique in that it provides for simultaneous servicing of one or more units on a particular facility, as specified by the user. Since the mean batch size can be adjusted for each facility, the total service time at a facility is not a function of the number of units to be processed, but of the number of batches. In this way, for example, the operation time of a lift truck which can move a complete batch in one or two trips is simulated, even though the adjoining facilities may service each part in the same batch individually.

The dependent variables are calculated by the simulator from the following relations:

If

$C_1$ = cost of raw material per part and

$C_g$ = cost per machine hour of operation in group g
(includes labor, maintenance, and services)

and additional notation is used as before,

$$\text{Direct cost of order } (v) = NC_1 + \sum_{g \in v} (S_g + N\mu_g)C_g$$

$$\text{Average queue time at } g = \frac{\sum_{v \in g} \text{wait times at } g}{\sum_{v} \text{number orders which wait at } g}$$

$$\text{Average queue length at } g = \frac{\sum_{v} \text{wait times at } g}{\text{Elapsed time per period}}$$

$$\text{Average queue cost at group } g = \frac{\sum_{v} (\text{elapsed time waiting})(\text{Direct cost of order } v \text{ waiting})}{\sum_{v \in g} \text{waiting time at } g}$$

$$\text{Elapsed time of order } v = \text{Completion time } (v) - \text{release time } (v)$$

$$\text{Average time of all orders} = \frac{\sum_{v} \text{elapsed time of order } v}{\text{number of orders}}$$

$$\text{Total storage requirements} = \sum_{g} \text{max queue length at group } g$$

$$\text{Total queue cost} = \sum_{g} \text{average queue cost at group } g$$

## 4.2. Order Tape Generator

Part processing sequences, part service and set-up times on each facility used, facility operating costs, labor classes, and labor number required are all design parameters which are constant for a particular layout and hence throughout a simulation run. The values for these parameters are specified to the simulation through the data cards. Orders to be run through the simulated layout require an order identification number, the part identification number (one part to an order), the release time in days after start of simulation, and the raw material cost. The release time of the orders is an independent variable to be altered by the experimenter in an effort to ascertain the performance of the particular layout design under hypothesized demands. If an existing shop is to be simulated, historical shop orders can be used as a basis for the order data deck information. Without such historical data an efficient method of specifying the order demand characteristics of hypothetical shop loads and producing the order input is desirable. The order tape generating program accomplishes these objectives for the particular experimental runs used for this study. Other sequences of shop loads would require a different order tape generating program.

By proper selection of order tape program parameters the user can control the level of three factors:

1. The distribution of product demand rate (Factor B) which corresponds to Muther's P-Q criterion.
2. Individual product demand distribution variances (Factor C).
3. Individual product mean demand rate (Factor D).

The use of an order tape generating program is optional; when used, it precedes the simulation as the first core load and generates an order tape which is then used as required by the second core load, the simulation itself. The user must supply the following program parameters:

| | |
|---|---|
| RUNWKS | the integer number of 5 day weeks of order releases which are to be generated for a given factor level. RUNWKS should be $\geq$ (PERIOD*STOP)/40 specified to the simulation. |
| PRCNT | a decimal number which describes the constant rate of change of the product demand rate distribution as described below. $0 < \text{PRCNT} < 1$ |

| | |
|---|---|
| NPRTS | the number of different parts specified to the simulator $0 < \mathrm{NPRTS} \leq 20$ |
| SEED | the odd integer number base to be used for random number generation |
| LACT | the low activity level of the shop; an integer determined from consideration of shop design $\mathrm{LACT} > 0$ |
| HACT | the "high" activity level of the shop $\mathrm{HACT} > \mathrm{LACT}$ |
| SVAR | the value of the small standard deviation of lot size distribution |
| LVAR | the value of the large standard deviation of the lot size distribution |
| LLOTLM | the minimum lot size to be used |

The program is designed specifically to generate orders which exhibit in sequence the characteristics of three different factors at two levels each, or a total of eight combinations. The number of simulated 5-day weeks of releases for each factor level is pre-established by the integer selected for the parameter RUNWKS. In order to condense the following presentation, the levels of the factors will be designated by (1) for the lower level and the corresponding small letter for the higher level. Thus the levels of factor B are designated by (1) and b.

Factor B, the distribution of product demand rate, or P-Q distribution, is defined as either (1) rectangular or (b) with negative slope changing at constant rate PRCNT from a maximum. The rectangular distribution is divided into a number of equal intervals, one for each of the parts to be processed. To determine which parts are to be released on a particular simulated day, the distribution is sampled by generating a random number. The part corresponding to the interval in which the random number falls becomes the part specified on the next order generated. In this way, the expected numbers of orders of each part to be released on a given day are equal. Since the mean lot size for all parts is identical, the expected number of all parts released in a day is equal. For level b, the samples are drawn from a geometric distribution, normalized to adjust for the varying number of parts which may be specified:

$$F(x) = \frac{\sum_{n=1}^{x} k(1-k)^{n-1}}{1 - (1-k)^{NPRTS}} ,$$

where k is the parameter PRCNT. The probability of "drawing" part 1 is seen to be largest, while the probability of drawing each higher numbered part decreases at a rate proportional to the factor k. The rate of change of the P-Q distribution is thus a function of k, the smaller values of k yielding flat P-Q or production demand rate distributions.

Factor C, the individual product demand variances, are the variances of a normally distributed lot size. Mean lot sizes and lot size variances are assumed to be the same for all parts in the simulation. The lot size variance levels are specified by (1) a small standard deviation SVAR, and (c) a larger standard deviation LVAR. To determine the lot size for a particular order, a sample is drawn from a normal distribution with mean lot size determined from the production level and the specified standard deviation. In order to prevent negative lot sizes, a lower bound for the lot size is specified by LLOTLM.

Factor D, the individual product mean demand rate, is arbitrarily established from the activity level of the facility and the product demand rate distribution. The activity level is an artificial index number used to indicate the general production activity, or level of shop load. Although the index is an abstraction, it should be selected by consideration of the layout design, the products to be processed, and the time demands on the facilities provided. The (l) lower activity index level is selected by considering the total number of all parts of specified product demand distribution which might be processed in five production days in the planned number of shifts, when operating with low capacity utilization. For example, if maximum ideal capacity, disregarding schedule interferences, for a given layout where each part is produced in the same quantity, is 1000 units total, then a lower activity index level, LACT, might be selected at 400. A (d) higher activity level index might be 900. It is clear that an index level over 1000 will overload the facilities, although it is conceivable that random fluctuations and scheduling interferences could either reduce or aggrevate the overload in the short run. One would expect that a low level (l), specified by LACT, would lead to short production lead time, but poor facility utilization. Increases in this index would be expected to increase the lead time and also to increase facility utilization. At some point, further increases in the index would result in critical increases in lead time and perhaps a sharp drop in utilization due to congestion factors.

The mean lot size is computed by dividing the lower activity level by the number of parts. The mean lot sizes are therefore identical for all parts, and the expected number of lots released per day at the lower activity level is equal to the number of different parts. When operating at a higher activity level, the mean lot size is not changed, but the expected number of lots is increased by the ratio of the higher to the lower activity level.

The order tape generator program produces a tape with the specified number of running weeks of orders arranged in the following sequence of combinations of factors and levels.

| Symbol for treatment combination | Level of factor B | C | D |
|---|---|---|---|
| (1) | - | - | - |
| d | - | - | + |
| cd | - | + | + |
| c | - | + | - |
| b | + | - | - |
| bd | + | - | + |
| bcd | + | + | + |
| bc | + | + | - |

# CHAPTER V

# THE PROBLEM AND EXPERIMENTS

## 5.1. The Problem of Process or Line Layout Selection

Although oversimplified, the problem of selecting between a line or process layout may be described in the following way, given

$H$ = number of production hours in period,

$[M_k]$ = integer number of machines of type $k$ in service,

$d_j$ = number of units demand for product $j$ during period,

$S_{jk_j}$ = set-up time of each lot of product $j$ on machine $k_j$,

$N_j$ = number of lots of product $j$ during period,

$k_j$ = machine $k$ used for product $j$ only, and

$t_{jk_j}$ = adjusted mean processing time of product $j$ on machine $k_j$ .

In practice the designer first estimates the effect of work pace, scheduling interferences, material shortages, and down time on standard times. A ratio based on his estimate is applied to the production time standards to compensate for these factors. If set-up time is long, a further adjustment may be made to $t_{jk}$ by first estimating the number of lots $N_j$ to be run over a period. Then, using

$$[M_k] \geq \frac{\sum\limits_j d_j\left(t_{jk} + \frac{N_j S_{jk}}{d_j}\right)}{H} ,$$

the designer determines the number of machines required for a process layout with joint utilization of machines.

The question of what, if any, products to select for production in a product line can be described, using the following restrictions:

1) If a machine is in a product line, $S_{jk_j} = 0$.
2) Any machine in a product line is used by one and only one product.
3) Any machine not in a product line is grouped with all similar machines in a process layout.
4) If a machine of type k is required more than once in the sequence of production operations in a line, each operation will be performed on a different type k machine and no back tracking is permitted.

The matrix B of machine time required is:

Process Number in Sequence of Operations

$$
\begin{array}{c|c|ccccccc}
 & & k_1 & & k_1 & & k_i & & k_n \\
 & 1 & T_{11_1} & \cdots & T_{1k_1} & \cdots & T_{1k_i} & \cdots & T_{iq_n} \\
 & \vdots & \vdots & & & & \vdots & & \vdots \\
\text{Product Number} & j & T_{j1_1} & & & \cdots & T_{jk_i} & \cdots & T_{jq_n} \\
 & \vdots & \vdots & & & & \vdots & & \vdots \\
 & p & T_{pl_1} & \cdots & \cdots & \cdots & T_{pk_i} & \cdots & T_{pq_n}
\end{array}
$$

where

$$T_{jk_i} = \frac{d_j(t_{jk_i} + \frac{N_j S_{jk_i}}{d_j})}{H}$$

An example of such a matrix for the hypothetical layout problem used in the simulation is shown in Table X. To find the number of machines required, the designer must first determine by some criterion which rows shall be designated for line layout, the remaining $k_i$ to be grouped by similar $k$'s for determination of the number of machines in the process portion of the layout. In selecting a line, or row, the $T_{jk_i}$ are adjusted by setting $S_{jk_i} = 0$; and the number of type $k$ machines needed in the line $= \sum_{i \in j} d_j t_{jk_i}$. Muther's criterion$^{(37)}$ for selecting the rows to be used in a line is to look at the $d_j$ and consider using line layouts for all $j$ where $d_j$ is appreciably greater than other $d_j$'s. Deming's criterion$^{(10)}$ is to select the set of rows for line production whose machine utilization is greater than machine utilization of the process layout alone. Some other criteria might be:

1. minimizing the number of machines required,
2. minimizing the capital required,
3. maximizing the number of product line layouts for a specified capital investment.

A solution could be obtained by direct enumeration of all combinations, but such enumeration is clearly impractical in a problem with a large number of products. For $p$ products, the number of combinations is $\sum_{j=1}^{p-2} \binom{p}{p-j}$. Moreover, there are a number of important dependent variables which are not included in the model. Salveson$^{(37)}$ describes some variables which are functions of lot size; for example,

"1) Material handling cost, because the smaller the lot, the more lots to be handled separately.

2) Capital equipment required, because as lots are smaller, more time is spent proportionately on set up, but smaller

lots are more 'scheduable', and as lots are made larger, the set-up time is proportionately smaller, but the larger lots are less scheduable into sequences which maintain high equipment utilization.

3) The longer the interval of time between changes in set-up, the more inventory must be stored to supply the continuous demand for parts."

Furthermore, solutions determined for one level of operation may lack sufficient flexibility to be satisfactory if the level fluctuates.

Because this analytic model for choosing line or process layout omits time dependent fluctuations and appears computationally intractable in practice, simulation will be used for the investigations of this study.

## 5.2. Hypotheses

In 1.6 a number of empirical rules for selection of a line vs. process layout are presented. We will use two as the basis of hypotheses and test their validity in a hypothetical layout situation by means of the simulation described in Chapter IV. . The method extends directly to practical layout problems.

Hypothesis I. (Muther's P-Q criterion) A pure process layout is operating at a specified aggregate activity level, with a specified P-Q demand distribution and lot size variance. The P-Q demand distribution clearly distinguishes two classes of products, those with high activity and those with low activity. If the layout is regrouped with line production for each product with high activity and process grouping for those with low activity, compared to the original pure process layout, the results listed below would be anticipated.

Hypothesis II. (Deming's criterion) A pure process layout is operating at a specified aggregate activity level, with a specified P-Q demand distribution and lot size variance. Machine utilization for the layout is calculated to be U % including set-up time. If the layout is regrouped with line production for each product whose machine utilization for the line is greater than U, and process grouping for all others, compared to the original process layout the results listed below would be anticipated.

For either hypothesis, the following results would be anticipated:

1. More available machine time, because of the reduction of set-up time. We define machine utilization as

$$U = \frac{\sum_g \sum_v (S_{gv} + n_v \mu_{gv})}{H \sum_g N_g}$$

where

$n_v$ = number of parts on order v

$\mu_{gv}$ = mean service time required by part on order v on machine group g

$N_g$ = number of machines in group g

$S_{gv}$ = set-up time for order v on g

and our hypothesis will not be rejected if $U$ decreases.

2. The mean completion time for each product will be smaller, for two reasons: (a) the products on line production will move directly through all operations without interference and setup delays, and (b) the products on process layout will encounter fewer queues. The mean completion time for product j is:

$$MUT(j) = \frac{\sum_{v=1}^{M} END(j, v) - RELT(j, v)}{M} .$$

3. The maximum in-process storage requirements will be smaller. The simulation keeps track of maximum length of queues at any time during a period. The maximum in-process storage required is the sum of the maximum numbers of orders in queues at any time during a period:

$$TOTSTO = \sum_g MAXMQ_g .$$

4. The average in-process inventory value will be reduced. We define the cost of an order waiting in a particular group's queue as the product of the time in the queue and the dollar value of the order in the queue. Then:

$$AVQCST = \frac{\sum_g TOCSTW(g)}{\text{Hours per period}} .$$

> Average in-process inventory can be reduced by providing balanced production flow through all facilities and also by designing layouts so that in-process inventories accumulate at early production sequences before appreciable value has been added to raw material, or by providing expeditions production flows for high cost products.

## 5.3. The Experiments

A hypothetical process layout (Figure 7) was first developed from an unpublished case problem called "The Lindon Company." Six parts are processed through the layout. The production data are given in Appendix B. For the process layout one fork-lift truck, facility group number 1, is utilized to move batches of parts between successive processing facilities. The same number of facilities is used for all layout revisions. The group numbers and parts assigned to a group are changed, however, in order to represent exclusive use of facilities by those parts in line production.

The experiment is designed as a four-factor factorial design with the three layouts designated as qualitative levels $A_1$, $A_2$, and $A_3$ for factor A. Factors B, C, and D, described in section 4.2, are each run at 2 levels. The process layout runs ($A_1$) were made first in order to discover whether the five-day period provided for loading the shop and for making changes in level was adequate time for the transition. Each level was run for two five-day report periods, providing a five-day transition period between report levels. A simulated 16 weeks of operation therefore were required for the eight factor-level combinations of the process layout

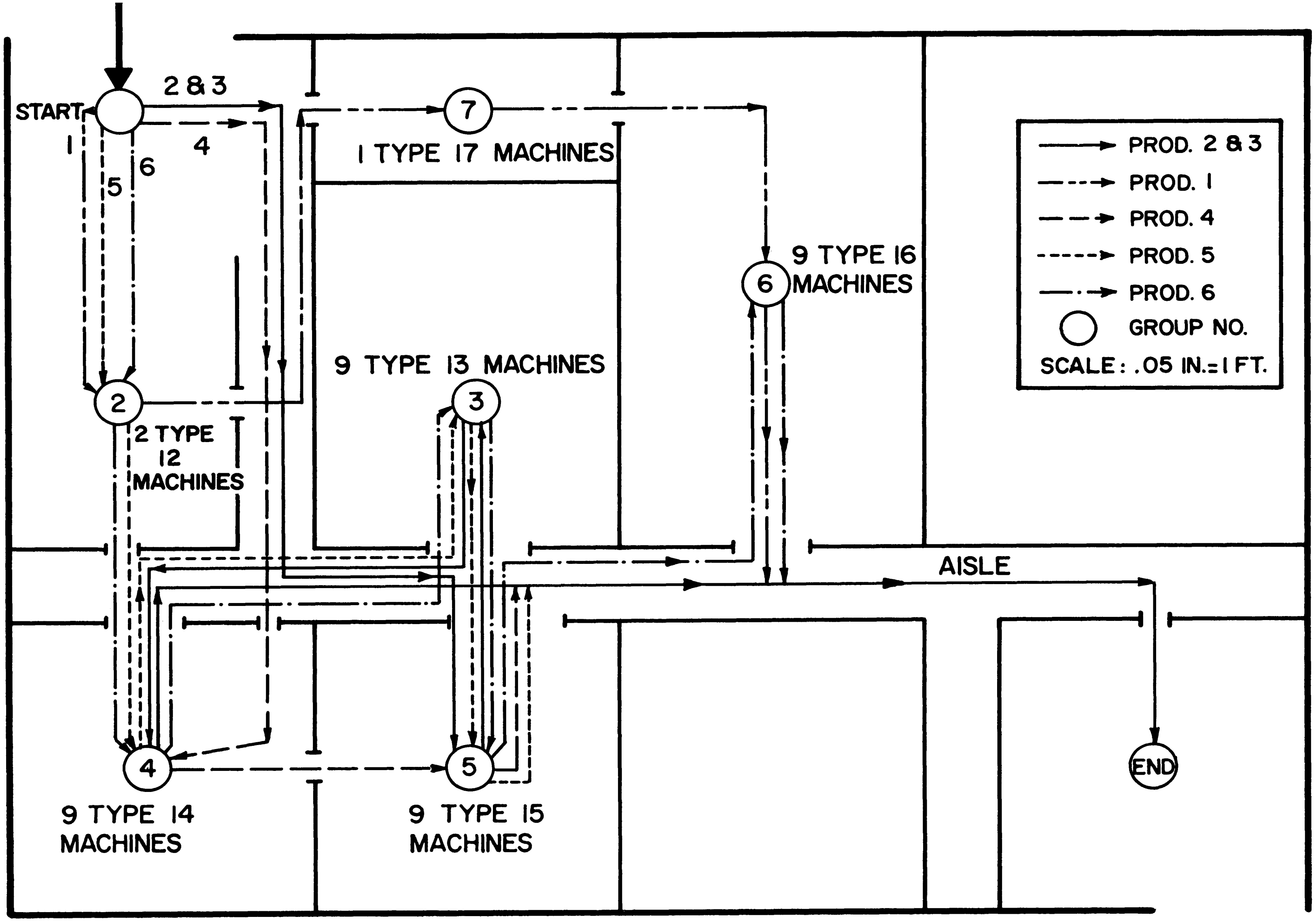

Figure 7. Pure Process Layout $A_1$ Flow Diagram.

simulation. Table IX gives the constants used in generating orders. The maximum total lead time for any part was 45 minutes for part number 6, or 3600 minutes for an order of 80 units. At the 4800 HACT level, therefore, it is not surprising that all orders clear the facilities in less than one week of 7200 minutes since the load at 4800 HACT level is only around 18% utilization.

Using Muther's P-Q criterion, the quantity of product 1 and product 2 accounts for 75% of the total and they are therefore selected for line production when designing layout $A_2$. The other 4 products continue to be processed in process groups. In arranging machines in line, excess machines were used where necessary to approximately balance production rates. The utilization percentages, machine type, and group assignments for layout design $A_2$ are tabulated in Table XII. Layout $A_3$ is designed on the basis of the upper diagonal entries in each row of matrix B, Table X. If these entries are appreciably higher than the 18% process layout utilization, the part of that row is set up in a production line. By this criterion, all operations on part 1, operations 15 and 14 of part 2, and operations 14, 13, and 15 of part 5 are selected for line production level $A_3$. Table XIII tabulates the resulting utilization and machine assignments. The physical orientation for each of the layout designs is shown in Figure 7, 8, and 9.

## 5.4. Results of Experiments

The results of the simulation experiments and the derived Analysis of Variance Tables are given in Appendix F. Statistically significant differences between means based on F tests are indicated by ** for

## TABLE IX

## CONSTANTS USED FOR ORDER TAPE GENERATION FOR ALL SIMULATION RUNS

RUNWKS = 2

PRCNT = .4

NPRTS = 6

397643627 for $A_1$
SEED = 987644627 for $A_2$
397645627 for $A_3$

LACT = 2400

HACT = 6400

SVAR = 1

LVAR = 25

LLOTLM = 10

## TABLE X

## MACHINE TIME UTILIZATION MATRIX B FOR SIMULATION ORDERS GENERATED WITH PRCNT = .4, HACT = 4800, SVAR = 1.0

| | Activity $d_j$ | | $k_j$ = machine type k and part processed j in sequence | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Prod. j | Quan. | Ord. | $12_1$ | $12_5$ | $12_6$ | $14_4$ | $14_5$ | $14_6$ | $17_1$ | $15_2$ | $15_3$ | $13_2$ | $13_3$ | $13_5$ | $13_6$ | $14_2$ | $14_3$ | $15_4$ | $15_5$ | $15_6$ | $16_1$ | $16_5$ |
| 1 | 2382 | 30 | .33/.37 | | | | | | .33/.83 | | | | | | | | | | | | 1.66/1.72 | |
| 2 | 1196 | 15 | | | | | | | | .83/.85 | | .17/.28 | | | | .83/.88 | | | | | | |
| 3 | 241 | 3 | | | | | | | | | .20/.21 | | .13/.17 | | | | .10/.11 | | | | | |
| 4 | 396 | 5 | | | | .11/.13 | | | | | | | | | | | | .39/.40 | | | | |
| 5 | 474 | 6 | | .13/.14 | | | .53/.55 | | | | | | | .59/.72 | | | | | .33/.33 | | | |
| 6 | 79 | 1 | | | .02/.02 | | | .02/.03 | | | | | | | .09/.11 | | | | | .10/.10 | | .13/.13 |

Numbers above the diagonal are utilization without set-up times

Numbers below the diagonal are utilization including set-up times

## TABLE XI

### MACHINE TIME UTILIZATION MATRIX B - LEVEL $A_1$

Arranged in a Process Layout for Simulation Orders
Generated with PRCNT = .4, HACT = 4800, SVAR = 1.0

| | | | Machine type k | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 12 | 13 | 14 | 15 | 16 | 17 |
| | | | Group Number | | | | | |
| Product j | Activity Quantity | $d_j$ Orders | 2 | 3 | 4 | 5 | 6 | 7 |
| 1 | 2382 | 30 | .37 | | | | 1.72 | .33 |
| 2 | 1196 | 15 | | .28 | .88 | .85 | | |
| 3 | 241 | 3 | | .17 | .11 | .21 | | |
| 4 | 396 | 5 | | | .13 | .40 | | |
| 5 | 474 | 6 | .14 | .72 | .55 | .33 | | |
| 6 | 79 | 1 | .02 | .11 | .03 | .10 | .13 | |
| Total no. type k machine required | 4768 | 60 | .53 | 1.28 | 1.70 | 1.89 | 1.85 | .33 |
| Total no. type k machine furnished | | | 2 | 8 | 7 | 8 | 9 | 1 |
| "Apparent" utilization | | | 27% | 16% | 24% | 24% | 21% | 33% |

## TABLE XII

## MACHINE TIME UTILIZATION MATRIX B - LEVEL $A_2$

Arranged for Line Production for Product 1 and Product 2 and Process for all Others
Based on P-Q Criterion. Simulation Orders Generated with
PRCNT = .4, HACT = 4800, SVAR = 1.0

| | | | Machine type k and product j | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $12_1$ | $17_1$ | $16_1$ | $15_2$ | $13_2$ | $14_2$ | 12 | 13 | 14 | 15 | 16 |
| | | | Group Number | | | | | | | | | | |
| Product j | Activity Quantity | No. Orders | 9 | 7 | 13 | 12 | 10 | 11 | 2 | 3 | 4 | 5 | 6 |
| 1 | 2382 | 30 | .33 | .33 | 1.66 | | | | | | | | |
| 2 | 1196 | 15 | | | | .83 | .17 | .83 | | | | | |
| 3 | 241 | 3 | | | | | | | | .17 | .11 | .21 | |
| 4 | 396 | 5 | | | | | | | | | .13 | .40 | |
| 5 | 494 | 6 | | | | | | | .14 | .72 | .55 | .33 | |
| 6 | 79 | 1 | | | | | | | .02 | .11 | .03 | .10 | .13 |
| Total no. type k machines req'd. | | | .33 | .33 | 1.66 | .83 | .17 | .83 | .16 | 1.00 | .82 | 1.04 | .13 |
| Total no. type k machines furnished | | | 1 | 1 | 5 | 4 | 1 | 4 | 1 | 7 | 3 | 4 | 4 |
| "Apparent" utilization per cent | | | 33 | 33 | 33 | 21 | 17 | 21 | 16 | 14 | 27 | 26 | 3 |

## TABLE XIII

### MACHINE TIME UTILIZATION MATRIX $B_1$ - LEVEL $A_3$

Arranged for Line Production for Product 1, and 5; Specific Type 5 and 4 Machines
for Product 2 Located in Department 3 to Reduce Handling;
Process Layout for 3, 4, and 6, Based on
Utilization Criterion,
PRCNT = .4, HACT = 4800, SVAR = 1.0

| | | | Machine type k and product j | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $12_1$ | $17_1$ | $16_1$ | $15_2$ | $14_2$ | $14_5$ | $13_5$ | $15_5$ | 12 | 13 | 14 | 15 | 16 |
| | | | Group Number | | | | | | | | | | | | |
| Product j | Activity Quantity | Orders | 9 | 7 | 13 | 12 | 11 | 14 | 15 | 10 | 2 | 3 | 4 | 5 | 6 |
| 1 | 2382 | 30 | .33 | .33 | 1.66 | | | | | | | | | | |
| 2 | 1196 | 15 | | | | .83 | .83 | | | | | .17 | | | |
| 3 | 241 | 3 | | | | | | | | | | .17 | .11 | .21 | |
| 4 | 396 | 5 | | | | | | | | | | | .13 | .40 | |
| 5 | 474 | 6 | | | | | | .53 | .59 | .33 | .14 | | | | |
| 6 | 79 | 1 | | | | | | | | | .02 | .11 | .03 | .10 | .13 |
| Total type k machines required | | | .33 | .33 | 1.66 | .83 | .83 | .53 | .59 | .33 | .16 | .45 | .27 | .71 | .13 |
| Total type k machines furnished | | | 1 | 1 | 5 | 1 | 1 | 1 | 1 | 1 | 1 | 7 | 5 | 6 | 4 |
| "Apparent" utilization per cent | | | 33 | 33 | 33 | 83 | 83 | 53 | 59 | 33 | 16 | 6 | 5 | 12 | 3 |

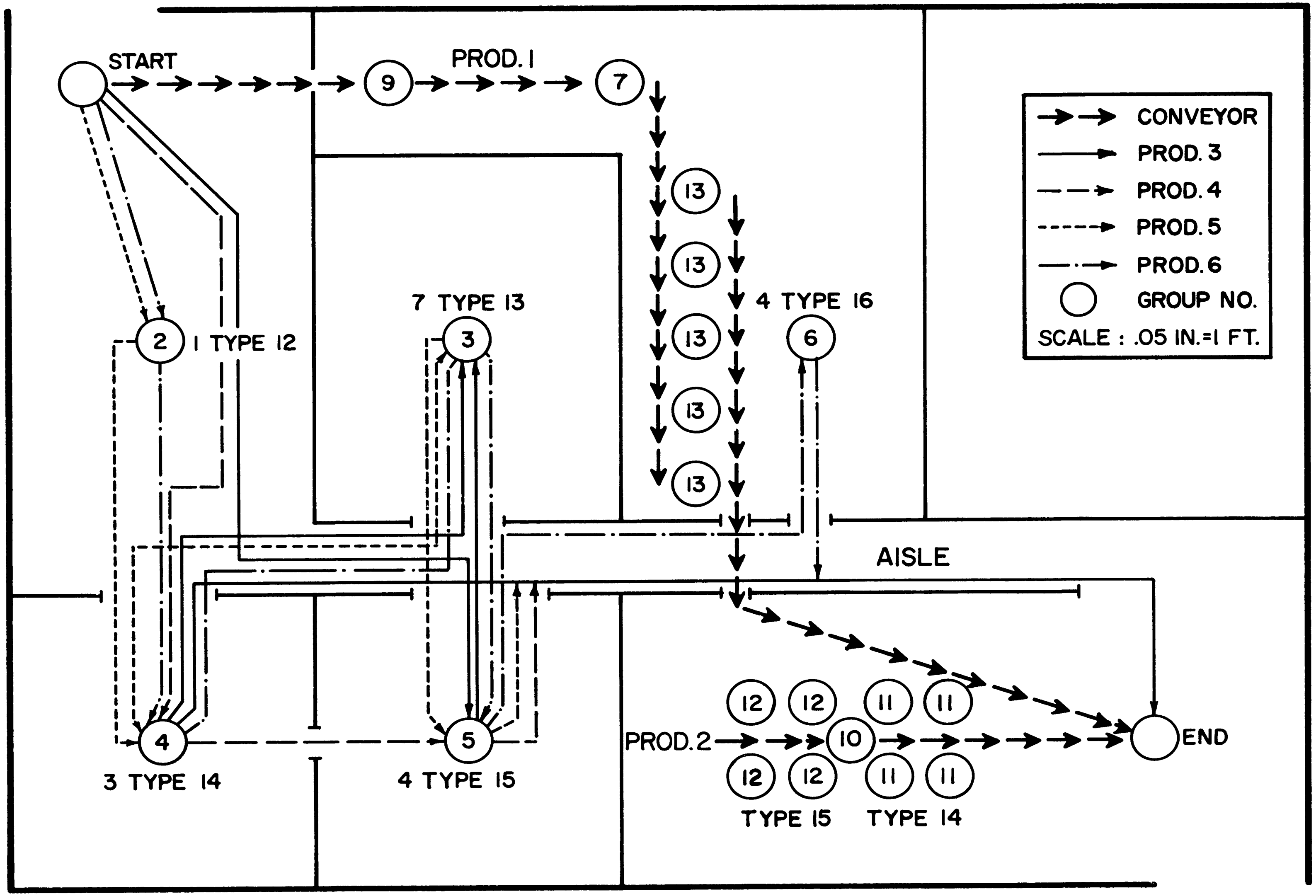

Figure 8. Layout A2 Flow Diagram Based on "P-Q" Distribution.

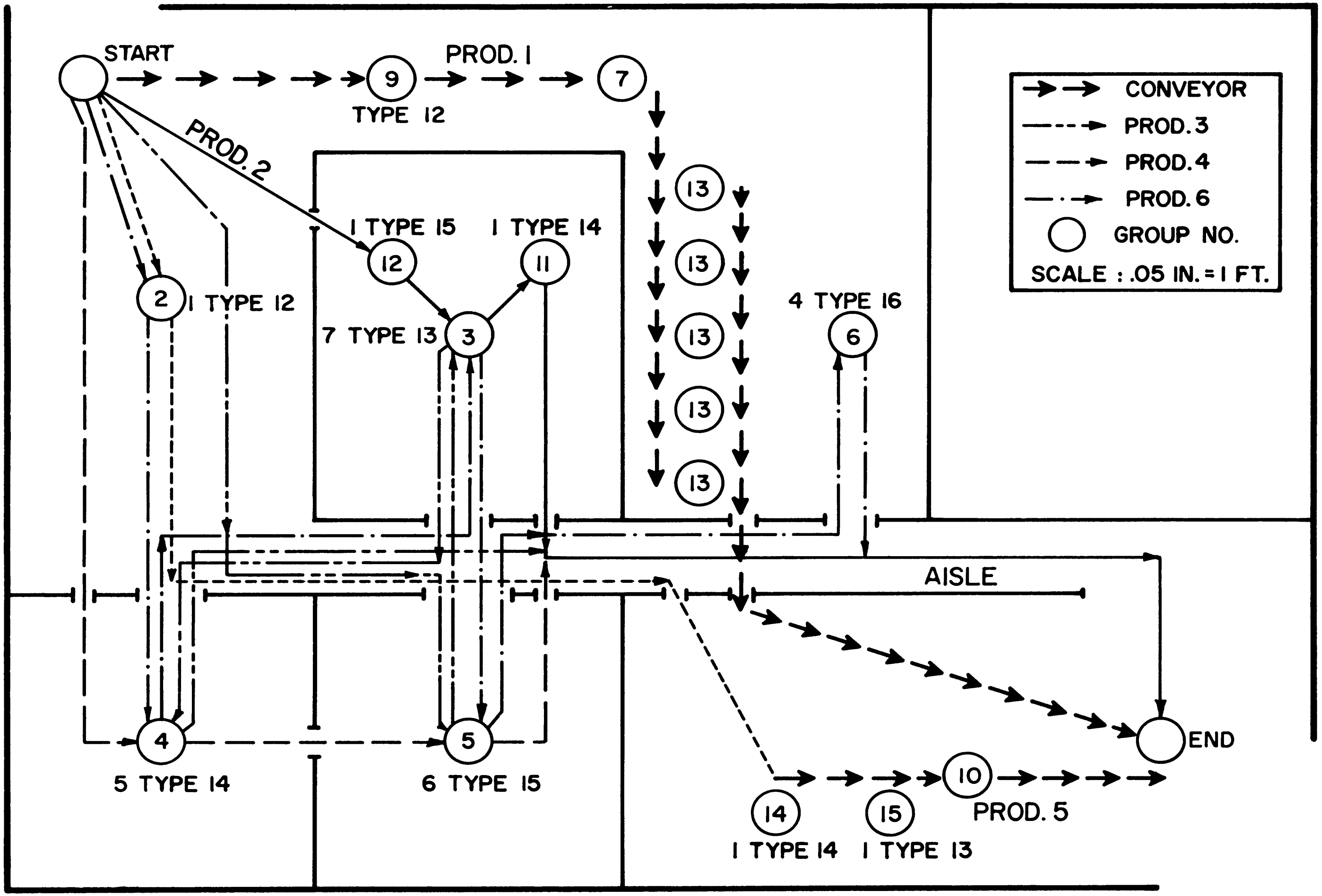

Figure 9. Layout $A_3$ Flow Diagram Based on Machine Utilization.

significance at the 1% level, * for significance at the 5% level, and + for significance at the 10% level.

We predicted that layouts $A_2$ and $A_3$, which were developed from the pure process layout $A_1$ using Muther's P-Q criterion and Deming's utilization criterion respectively, would result in more available facility time because of the reduction of set-up time. The Analysis of Variance Table 1.2 indicates that there is no significant difference in mean percent facility utilization, and therefore in available facility time resulting from the layout design. Because the set-up times used are small relative to the processing time for a lot with a mean quantity of 80 parts, this result is not surprising. We infer that one source of variation in available facility time, the reduction of set-up time for parts processed on a line, is not large enough to be detected by the sensitivity of our experiments. The activity level, the shape of the P-Q distribution, and the interactions between them are significant sources affecting available facility time. We conclude that the rate of production is more significant then layout as a source of variation in machine availability.

Our second prediction stated that layout designs $A_2$ and $A_3$ would permit significantly shorter completion times for each of the six products than would the pure process layout $A_1$. Appendix F, Tables 2.1 to 7.2 inclusive, shows the mean elapsed completion time for parts 1 to 6. For part 1, which is produced on a line in layouts $A_2$ and $A_3$, the reduction in completion time is statistically significant at the 5% level, and the hypothesis is supported. For part 2, which is also produced on a line in layouts $A_2$ and $A_3$, the layout factor similarly is a significant source of variation. Completion time for part 2 in layout $A_2$ is less than in layout $A_1$; in $A_3$, contrary to prediction, however, completion time for part 2 is greater than in $A_1$. Completion times for part 3 and part 4, produced on a process grouping on all layouts, are not significantly different, thus also contradicting the prediction. Part 5 completion time differences are significant at the 5% level, but the source of variation is the P-Q product demand distribution, and completion time is longer when the P-Q distribution is flat. The hypothesis is again rejected. For part 6, the layout factor, the P-Q demand distribution factor, and the activity level factor are all significant sources of variation in the mean completion times. The hypothesis is supported for this part.

According to our third prediction, the amount of in-process storage space required in layouts $A_2$ and $A_3$ should be smaller than in $A_1$ due to the difference in layout. The experiments show significant differences at the 10% level due to the layout (Appendix Table 8.1 and 8.2), but the in-process storage space in $A_2$ and $A_3$ is larger instead of smaller as predicted. The activity level is more significant (1/2% level) than the layout factor in determining in-process storage space requirements.

Our last prediction was that layouts $A_2$ and $A_3$ would reduce the average in-process inventory value below that of layout $A_1$. Statistical tests of the results in Tables 9.1 show no significant source of variation, and therefore contradict the hypothesis. The simulation calculates in-process-inventory dollars from the average number of dollars in queues during the report period of one week. If one unit of an order is in a machine, the other units on the order may be waiting to be processed or waiting to be moved to the next machine, but are not considered by the simulation to be in a queue. The in-process-inventory dollars therefore represent a time value weighting of the in-process storage requirements only, and not the total work in-process-inventory dollars. They do not reflect the value of reducing in-process inventories by phase-lapping production operations (an important reason for shifting from process to line layout). In future experiments we would redefine costs in two ways: first, the order cost would be defined as the direct cost of material and facility utilization plus the carrying charges arising from the value of in-process-inventory as the order travels through the layout; second, the average value of in-process inventory for each period would be computed. In view of the absence of statistical significance of the in-process-inventory dollars calculated by the simulation, no further analysis of the implication of this result will be attempted.

In summary, the experiments indicate the following results of statistical significance:

| | Factor Source of Variation | | | | |
|---|---|---|---|---|---|
| Hypothesis | Layout | P-Q Distribution | Lot Size Variance | Activity Level | |
| Layout design will affect: | A | B | C | D | BD |
| 1. Available machine time | | ** | | ** | * |
| 2. Elapsed completion time for part 1 | ** | | | * | |
| 3. Elapsed completion time for part 2 | * | | | | |
| 4. Elapsed completion time for part 5 | + | * | | | |
| 5. Elapsed completion time for part 6 | * | * | | * | |
| 6. In-process storage requirements | | | | * | |

**Significant at the 1% level; *Significant at the 5% level; +Significant at the 10% level.

Instead of making statistical comparisons of layout $A_1$ and $A_2$ or $A_1$ and $A_3$, the implications of observable differences of results will be interpreted by inspecting the results of each experiment and simultaneously considering the basis of each layout design used. Figure 10 compares the approximate P-Q demand distribution and activity level for each of six parts with the P-Q demand distribution used in designing layouts $A_2$ and $A_3$. The number of parts 3, 4, 5, and 6 released per week using the flat distribution, high-activity factor combination d is over twice as great as the design base. We would anticipate overloads to occur during these factor-level combination runs. The concave distribution, high-activity combination bd also exceeds the design base for parts 1, 2, 3, and 4; and overloads may be anticipated in these runs.

The use of Muther's Product-Quantity criterion resulted in layout design $A_2$ (Figure 8). Our experiments testing Hypothesis I on this layout gave no support to our prediction that layout $A_2$ would have more available facility time than layout $A_1$; activity level and product demand distribution factors, not the layout factor, contributed all statistically significant changes in machine time utilization. The production lines for product 1 and for product 2 in layout $A_2$ were well balanced (Table XII), so that no bottleneck facility restricted the utilization of other facilities in the line. Only if large blocks of facility time are held idle because of unbalance in a line would we expect a decrease in utilization of the line facilities. To achieve the balance in the line producing part 2, four of each of type 14 (group 12) and type 15 (group 11) machines were used. Consequently the three type 14 and four type 15 machines remaining in the process grouping were overloaded when the simulation was run with

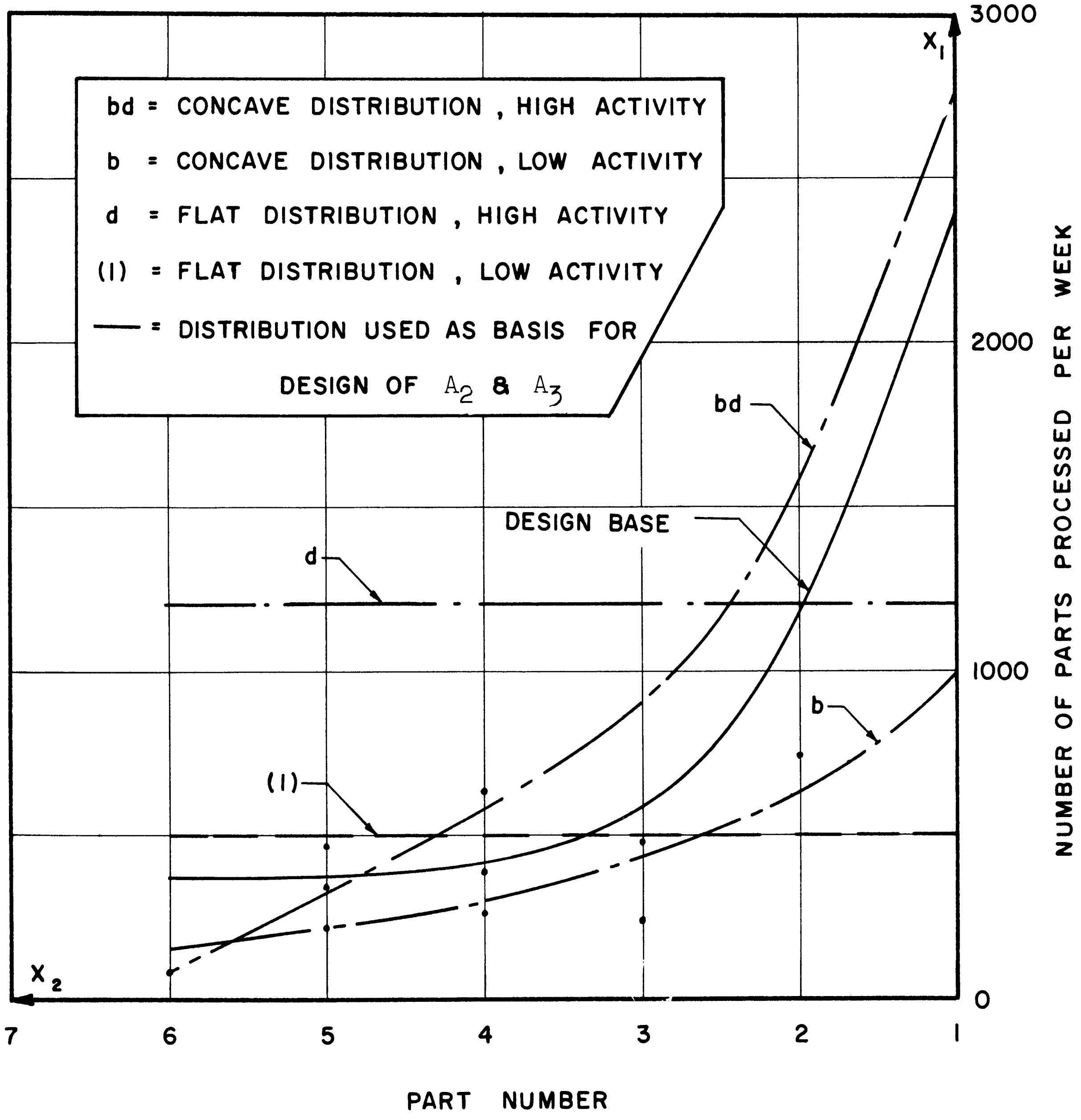

Figure 10. Approximate P - Q Demand Distributions Used for Experiments.

a flat P-Q distribution and high-activity level. The effects of this overload were dramatically revealed by the doubling of the completion time required for parts 3, 4, 5, and 6 under factor combination $A_2$cd. In contrast, the completion times for parts 1 and 2 when processed on the lines of layout $A_2$ dropped to one-half the completion times on layout $A_1$, as predicted by our hypothesis. The prediction however that $A_2$, as compared to $A_1$, would require less in-process-storage space is rejected. Storage space requirements increased for the improved layout $A_2$. The detailed source data (not included) showed that the aggregate storage-space requirements were closely proportional to the space requirements in front of facilities groups 14 and 15 in the process portion of the layout. We have already pointed out the overload which is placed on these groups under factor combination $A_2$cd.

Deming's Machine Utilization Criterion was used for the design of layout $A_3$ and formed the basis for Hypothesis II. In layout $A_3$, no attempt was made to balance the production rates of the facilities used on the line producing part 5; therefore at full production, 40% of facility $14_5$ (group 14) was unavailable for use. Machines assigned to the line of part 2 (groups 11 and 12) were loaded to 83% capacity on the design basis of 1200 units per week; therefore an overload should be expected on this line at the high activity level. As in the test of Hypothesis I, the test of Hypothesis II on layout $A_3$ indicated no support for the prediction of more available facility time due to the layout design factor. Elapsed completion times for part 1 were significantly reduced. For part 2, the completion time, as anticipated above, was greater on layout $A_3$ than on layout $A_1$ because of the overload on the first facility in the line (group 12) when operating at a high activity and concave P-Q factor combination. When operating with flat P-Q distribution, part 5 completion times were longer due to the overload on the production line for part 5 described above. The completion times for parts 3, 4, and 6, produced on process-grouped facilities, were unchanged. Our prediction of reduced completion times on layout $A_3$ is therefore correct for part 1 only because the demand level for other parts exceeded the capacity of the layout design. Activity level is the significant source of variation in in-process-storage requirements, the requirements for $A_3$ being larger than for $A_1$. The hypothesis that layout design is a significant source of in-process-storage variation is not supported.

In Reference 7, Conway points out some of the pitfalls of simulation experiments. The experiments reported here were not spared these pitfalls. During the $A_3$ experiments, an excessive backlog of orders accumulated during weeks 13 and 14 (factor level combination $A_3$bcd). The transition week 15 was not long enough to reduce this backlog to achieve the specified operating level for combination $A_3$bc to be observed during the 16th week. A separate 2 week run, starting the simulated plant empty and using identical order-release data, was used to obtain the $A_3$bc results. Table XII shows that facility group type 5 has an apparent utilization of 26% at the design activity level of 4800. The orders released during week 6 (Appendix B) indicate requirements exceeding the capacity available. During week 6, a queue exceeding the maximum queue storage occurred in front of facility group 5. Two orders were "lost" from the simulation, thus reducing the utilization, storage requirements, and queue inventory cost for this factor combination. For part 6 completion times, Table 7.1, observations from the week preceding the experimental run were required to obtain data for use in cell $A_2b$, and only one observation was available for cell $A_1bc$ and $A_3bc$. In general, this difficulty illustrates the extremes in number of observations which were used to compute the mean elapsed completion time for the six different parts during different runs.

Efforts to keep the computing time short led to the decision to conduct these experiments without replication. The penalty of this decision is evident in the paucity of observations for determining the mean process time for each cell in the Analysis of Variance Table for part 6, reported earlier. The use of only two levels of factors B, C, and D also prevented analysis of the shape of the functional relation between activity and completion time or in-process-storage requirements, for example. In spite of the minimal sample size, each layout design required 25 minutes of IBM 704 computing time, including about 4 minutes to generate the order arrivals. In retrospect, the absence of significant interactions between factors would have permitted running each experiment with an identical sequence of randomly generated orders and comparing the differences in means of the results for the various factor levels. Significant sample sizes would have been more easily obtained, since the transition weeks could also have been used as a source of behavior information and every order generated would have yielded a sample observation. Analysis of Variance models would not apply in such cases; however, the validity of the assumptions of the linear hypothesis model used in this experiment also is open to question. Because of carry-over from one week to the next, observations are not strictly independent in all weeks, nor is there basis for assuming factor effects are additive.

## 5.5. Conclusions

Early in this study we suggested that the dynamic characteristics of production demand might be of such a nature or magnitude as to make some current empirical rules of design limited or misleading in application. Our hypotheses were formulated to examine the relevance of some types of dynamic behavior on layouts designed from almost literal application of two empirical rules: Muther's Product-Quantity Distribution and Deming's Machine Utilization Criterion. Although our conjecture as to the nature of the impact of the dynamic behavior is now seen to be contrary to the experimental results, our intuition regarding its importance on plant performance is well supported. Factors of changing product-mix and demand level were seen to be the important sources of variation in plant performance. The following generalizations are inferred from the behavior of the particular hypothetical plant used as the subject:

1. Completion time is reduced by switching from process to line layout (batch to phase-lapped operation), but only if the demand level remains below the capacity of each line and each process grouping considered as a distinct entity.
2. In-process-storage requirements tend to increase as a plant is segmented into smaller line or process-centered production sequences.

3. In-process-storage requirements increase sharply with increase in demand levels above the design base.
4. Machine utilization is more responsive to demand level and product-mix than to the layout design (a truism).
5. The common layout design practice of ignoring lot size would have been satisfactory in this experiment. In none of the experiments does the lot-size variation contribute statistically significant variation. The set-up-time factor is not explicitly considered, however, since the mean number of lots per day in any factor level combination is constant.

In proceeding in basic research on layout design, we are confronted by the same question as is the layout designer himself: how can we define the characteristics of our particular plant so that they will indicate the rules of layout which must be adhered to and those rules which can be safely ignored? In our two mixed layouts, for example, completion time for part 2 was shorter for layout $A_2$ than $A_3$, whereas completion time for part 4 was longer for layout $A_2$ than for $A_3$. Which one of the layouts and empirical rule used for its design is to be perferred? In this instance, factors not considered in either rule, such as balanced processing time on sequential machines in line, and major shifts in demand from the design base, have overriden the more carefully considered factors. It is likely that only simultaneous consideration of multiple factors can avoid these pitfalls. Such considerations must therefore always be a part of plant layout design.

Meaningful research in plant layout must build on more explicit definitions than "job shop," "production line," "continuous manufacture," etc. The direct application of the results of the experiments reported here, statistical problems aside, would be foolish unless the plant in which the application was to be made had six products, six process machine groups, "negligible" set-up times, etc. For example, the simulation accepts orders with specified mean service times, order arrival times, set-up time, and sequence of operations. What statistics will describe these data so as to enable a designer to determine if his plant data are similar to the simulation data from which these experimental results were obtained? The independent variables defined in Chapter II are too general for successfully circumscribing classes of manufacturing plants with specific design properties. Rather than a study of individual part processing distributions, a study of aggregated plant or process operational distributions is needed.

For example, future investigations should look at the significance of these more explicit independent variables:

1. Degree of balance between operations on a part. Mathematically, this is the variance of percent utilization of machine time around its mean for all processes through which the part passes. We conjecture that the smaller this variance for a part, the "better" the layout balance.
2. Distribution of product lead times. Intuitively we believe that lead time for processing a part through the plant would affect dynamic plant behavior, because of the slow response of products with long lead time compared to products with quick response. We conjecture that different layout rules are appropriate depending on the applicable lead time

distribution. In our $A_1$ experiments, part 1 had a lead time of 600 minutes and a maximum completion time of 1300 minutes. Part 6 had a lead time of around 3000 minutes with a maximum completion time of 4500, a smaller range. On the line layouts the completion time of part 1 flucuated widely from 180 minutes to over 900. Comparable data for part 6 was not obtained.

3. Mean and variance of set-up times. A more explicit statement of these variables should be used in future experiments. The values used in the experiments reported in this study can at best be described only as "random".
4. Facility-product assignment policies. A statistic to describe these policies for general classes of plant design is not in common use. One method(55) is to use a matrix of transfer probabilities from each facility group to all other groups.
5. Life cycle distribution, seasonal variations, and individual product demand distributions. Future experiments should build more closely on current work in statistical forecasting. Description of plant demands in terms of statistically forecasted arrival distributions and variances may lead to more useful generalizations than specification of release dates alone.

Future investigations need to derive definitions and distributions from studies in operating plants. Nelson reports initial work on the study of arrival and service time distributions in a specific job shop.(39) Correlation analysis of independent design variables might reveal useful generalizations. There is immediate need for a clearing house to collect, interchange, and codify information for defining and classifying process facilities.

# CHAPTER VI

## SUMMARY AND CONCLUSIONS

The objectives of this investigation have been twofold: (a) to apply digital computers to routine measurement of plant layout spatial relations in order to reduce the drudgery of the design process, and (b) to improve the prediction of plant operating characteristics during the plant layout design stage.

The feasibility of using digital computers as an extension of the current use of templates and 3-D models in layout engineering has been demonstrated through preparation of a computer program which accepts engineering information about process facilities, costs, products, and spatial orientation of the layout design. The Spatial Analysis Program produces an error list for each part processed through the design if the part sequence is not feasible because of violation of capacity or transfer constraints, or a flow process chart if the flow sequence is feasible. The application of this concept of design automation to plant layout problems opens to the layout designer a method of reducing the tedium of checking layout designs and of efficiently making an exhaustive check of a large number of part flow sequences. Estimates of total move-distances on each transfer device, frequency of use of each transfer path, and the amount of labor effort expended in material transfer can be quickly obtained. Errors of omission or transfer logic, which heretofore were easily overlooked because of the great amount of detail checking required, are uncovered by the computer in routine fashion. The development of the Program suggests directions for further effort in plant layout research:

1. *Development of formal operational definitions of logical engineering capacity and transfer constraints useful in assembling systems of process equipment, material handling equipment, and auxiliaries into a unified production facility.* More precise analysis of errors in transfer flow paths and the discovery of misapplications of equipment would result.
2. *Further expansion of the internal "search" capability of the Analysis Program to permit using the computer to select path links of feasible material transfer systems for a specified process arrangement according to selected criterion such as minimum cost, minimum distance, least number of transfers, etc.* The problem may be compared to the problems of information retrieval. A large quantity of data about many different material handling equipments must be searched, either literally or by judgment based on accumulated experience, in order to narrow the choice to a few feasible or probable possibilities. The selection criterion can then be used the choose the "best" system from among those feasible without need for lengthy study by the designer.

The investigation to improve the prediction of plant layout operating characteristics began with a mathematical model of the problem of selecting a line or process layout. The combinatorial size of the model and the limitations in application introduced by the omission of time-dependence of product demand caused us to turn instead to two different empirical design criteria currently in use for selection of process or line layouts. A computer program was written to simulate the operating characteristics of alternative plant layout designs with dynamic product demands. The Simulation was used for a series of experiments in evaluating characteristics of delay, of storage space, and of completion time for three alternative layouts developed from empirical criteria. The tests disclosed that the layouts resulting from two criteria, the use of relative part activity or the use of relative machine utilization, had different operating characteristics. These differences, however, arose from different numbers of machines being allocated to particular part processing, because explicit rules for making the allocation were not a part of the two rules. Users of either of the rules need to observe at least two important restrictions when applying them:

1. Machine capacities in a production line must be "reasonably" balanced.
2. In-process storage requirements on a production line in-increase rapidly with increase in demand levels above the design base.

Simulation as a practical layout tool has been well described by others. Its usefulness can be further enhanced by the use of the Spatial Analysis Program described here to generate the mean processing and transport times, machine hour costs, labor and part routing data required for input to the Simulation. As a means of research in methods of layout design, the usefulness of simulation is documented by the explorations of this study. However, a basic dimension of the Simulation time, is missing from the Static Spatial Analysis Program, and a basic dimension of the Spatial Analysis Program, Cartesian Space, is missing from the Simulation. In general, we would expect interactions between these two parameters. For example, if a long run is set-up on the "closest" machine in a process group, transport times for other orders to that process group will be longer for the duration of the run. As another example, the sequence in which jobs are completed at different locations can establish the distances which a lift truck must travel, and hence the service time to perform a specific function. As presently written, the Spatial Analysis Program computes only a mean move-distance and move-time between any two facility groups. The Simulation, on the other hand, assumes that travel time between any two groups is a random variable with mean time determined by the loaded move distance only. No explicit consideration of empty or return travel time is included. Future plant-layout simulations therefore should be constructed by synthesizing the concepts of the Simulation and Static Analysis Programs into one program to permit the study of time and space interactions.* Such a program, developed and maintained in a firm's computing library for each plant operating unit, would furnish the plant layout designer a new tool as essential to proper layout engineering as process charts, 3-D models, and cross charting. A new dimension, time, could be explicitly incorporated into layout design.

The Simulator developed in this study dispatches jobs to facilities on a first-come, first-served queue discipline. The interactions between layout design, scheduling, and dispatching rules were not examined, although they may well be of key importance.(30) Given a foundation of

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*We are indebted to Frank J. Carr of the Westinghouse Electric Corporation for first suggesting this concept.

plant layout principles obtained from experimental research, additional research should certainly be made to discover what relations exist between facility design and production control systems.

# APPENDICES

# APPENDIX A

## ORDER DATA USED TO DESIGN LAYOUTS $A_2$ AND $A_3$
Orders Generated with PRCNT = 0.4,
HACT = 4800, LVAR = 1.0
and Mean Lot Size = 80 Units

| Order Number | Part Number | Release Day | Lot Size Units | Min. Lot Size Units |
|---|---|---|---|---|
| 481 | 1 | 56 | 79 | 10.0000 |
| 482 | 1 | 56 | 79 | 10.0000 |
| 483 | 5 | 56 | 81 | 10.0000 |
| 484 | 1 | 56 | 79 | 10.0000 |
| 485 | 1 | 56 | 78 | 10.0000 |
| 486 | 2 | 56 | 80 | 10.0000 |
| 487 | 2 | 56 | 79 | 10.0000 |
| 488 | 1 | 56 | 79 | 10.0000 |
| 489 | 1 | 56 | 78 | 10.0000 |
| 490 | 2 | 56 | 80 | 10.0000 |
| 491 | 1 | 56 | 78 | 10.0000 |
| 492 | 5 | 56 | 81 | 10.0000 |
| 493 | 2 | 57 | 80 | 10.0000 |
| 494 | 3 | 57 | 80 | 10.0000 |
| 495 | 1 | 57 | 79 | 10.0000 |
| 496 | 1 | 57 | 79 | 10.0000 |
| 497 | 1 | 57 | 79 | 10.0000 |
| 498 | 6 | 57 | 82 | 10.0000 |
| 499 | 4 | 57 | 81 | 10.0000 |
| 500 | 2 | 57 | 79 | 10.0000 |
| 501 | 5 | 57 | 81 | 10.0000 |
| 502 | 1 | 57 | 79 | 10.0000 |
| 503 | 4 | 57 | 81 | 10.0000 |
| 504 | 3 | 57 | 80 | 10.0000 |
| 505 | 2 | 58 | 80 | 10.0000 |
| 506 | 1 | 58 | 79 | 10.0000 |
| 507 | 2 | 58 | 79 | 10.0000 |
| 508 | 3 | 58 | 80 | 10.0000 |
| 509 | 4 | 58 | 81 | 10.0000 |
| 510 | 5 | 58 | 81 | 10.0000 |
| 511 | 2 | 58 | 79 | 10.0000 |
| 512 | 1 | 58 | 78 | 10.0000 |
| 513 | 2 | 58 | 79 | 10.0000 |
| 514 | 5 | 58 | 81 | 10.0000 |
| 515 | 1 | 58 | 79 | 10.0000 |
| 516 | 2 | 58 | 80 | 10.0000 |
| 517 | 4 | 59 | 81 | 10.0000 |
| 518 | 1 | 59 | 79 | 10.0000 |
| 519 | 4 | 59 | 81 | 10.0000 |
| 520 | 1 | 59 | 78 | 10.0000 |
| 521 | 1 | 59 | 78 | 10.0000 |
| 522 | 1 | 59 | 79 | 10.0000 |
| 523 | 1 | 59 | 78 | 10.0000 |
| 524 | 1 | 59 | 79 | 10.0000 |
| 525 | 2 | 59 | 80 | 10.0000 |
| 526 | 2 | 59 | 80 | 10.0000 |
| 527 | 1 | 59 | 79 | 10.0000 |
| 528 | 1 | 59 | 79 | 10.0000 |
| 529 | 1 | 60 | 79 | 10.0000 |
| 530 | 2 | 60 | 79 | 10.0000 |
| 531 | 1 | 60 | 79 | 10.0000 |
| 532 | 1 | 60 | 79 | 10.0000 |
| 533 | 1 | 60 | 79 | 10.0000 |
| 534 | 1 | 60 | 78 | 10.0000 |
| 535 | 2 | 60 | 79 | 10.0000 |
| 536 | 1 | 60 | 79 | 10.0000 |
| 537 | 1 | 60 | 79 | 10.0000 |
| 538 | 5 | 60 | 81 | 10.0000 |
| 539 | 1 | 60 | 79 | 10.0000 |
| 540 | 2 | 60 | 80 | 10.0000 |

# APPENDIX B

## TOTAL ORDERS AND PARTS GENERATED BY ORDER GENERATION PROGRAM USED AS INPUT TO INDICATED SIMULATION RUN

| | | NUMBER OF ORDERS RELEASED | | | | | | | | NUMBER OF PARTS RELEASED | | | | | | | | HACT = 4800 BASIS OF $A_2$ and $A_3$ DESIGN | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Part # | Layout | LACT Flat P-Q SVAR | HACT Flat P-Q SVAR | HACT Flat P-Q LVAR | LACT Flat P-Q LVAR | LACT Conc P-Q SVAR | * HACT Conc P-Q SVAR | HACT Conc P-Q LVAR | LACT Conc P-Q LVAR | LACT Flat P-Q SVAR | HACT Flat P-Q SVAR | HACT Flat LVAR | LACT FLAT LVAR | LACT CONC SVAR | * HACT CONC SVAR | HACT CONC LVAR | LACT CONC LVAR | Orders | Parts |
| | $A_1$ | 7 | 13 | 12 | 4 | 13 | 34 | 29 | 12 | 560 | 1040 | 885 | 380 | 1040 | 2720 | 2500 | 766 | | |
| 1 | $A_2$ | 5 | 16 | 12 | 6 | 13 | 32 | 33 | 10 | 400 | 1280 | 957 | 480 | 1040 | 2560 | 2901 | 824 | 30 | 2382 |
| | $A_3$ | 4 | 14 | 13 | 6 | 13 | 33 | 28 | 11 | 320 | 1120 | 1095 | 465 | 1040 | 2640 | 2114 | 833 | | |
| | $A_1$ | 3 | 13 | 10 | 3 | 7 | 20 | 22 | 6 | 240 | 1040 | 707 | 299 | 560 | 1600 | 1577 | 390 | | |
| 2 | $A_2$ | 5 | 11 | 17 | 5 | 9 | 15 | 14 | 11 | 400 | 880 | 1197 | 441 | 720 | 1200 | 1150 | 868 | 15 | 1196 |
| | $A_3$ | 4 | 16 | 14 | 7 | 10 | 23 | 25 | 6 | 320 | 1280 | 1003 | 622 | 880 | 1880 | 1825 | 476 | | |
| | $A_1$ | 3 | 13 | 9 | 6 | 6 | 11 | 9 | 6 | 240 | 1040 | 576 | 579 | 480 | 880 | 672 | 475 | | |
| 3 | $A_2$ | 8 | 13 | 13 | 12 | 4 | 12 | 19 | 7 | 640 | 1040 | 889 | 940 | 320 | 960 | 1412 | 571 | 3 | 241 |
| | $A_3$ | 6 | 11 | 16 | 2 | 2 | 10 | 12 | 7 | 480 | 880 | 1213 | 153 | 160 | 880 | 1015 | 491 | | |
| | $A_1$ | 4 | 16 | 12 | 3 | 3 | 12 | 12 | - | 320 | 1280 | 811 | 237 | 240 | 960 | 900 | - | | |
| 4 | $A_2$ | 2 | 12 | 18 | 2 | 3 | 11 | 6 | 2 | 160 | 960 | 1385 | 74 | 240 | 880 | 591 | 209 | 5 | 396 |
| | $A_3$ | 6 | 11 | 17 | 4 | 1 | 6 | 6 | 5 | 480 | 880 | 1212 | 311 | 80 | 480 | 474 | 463 | | |
| | $A_1$ | 7 | 11 | 15 | 4 | 2 | 2 | 5 | 4 | 560 | 880 | 1239 | 395 | 160 | 160 | 367 | 316 | | |
| 5 | $A_2$ | 2 | 15 | 7 | 1 | 1 | 6 | 5 | - | 160 | 1200 | 484 | 102 | 80 | 480 | 379 | - | 6 | 474 |
| | $A_3$ | 5 | 13 | 12 | 7 | 3 | 5 | 7 | 2 | 400 | 1040 | 956 | 619 | 240 | 400 | 591 | 229 | | |
| | $A_1$ | 6 | 14 | 22 | 10 | 1 | 1 | 3 | 2 | 480 | 1120 | 1764 | 776 | 80 | 80 | 247 | 183 | | |
| 6 | $A_2$ | 8 | 13 | 13 | 4 | - | 1 | 2 | - | 640 | 1040 | 1125 | 348 | - | 80 | 123 | - | 1 | 79 |
| | $A_3$ | 5 | 15 | 12 | 4 | 1 | 3 | 2 | 1 | 400 | 1200 | 958 | 255 | 80 | 240 | 170 | 63 | | |

# APPENDIX C

## PART, FACILITY, AND LABOR CONSTANTS USED FOR FACILITY DESIGN $A_1$

```
*DATA
      RUNWKS     FACTOR B
                 PERCNT
        2        .40
                             FACTOR D             FACTOR C
    NUMBER OF  RN SEED     LOW        HIGH        SMALL     LARGE       LOWLIMIT
      PARTS              ACTIVITY  ACTIVITY  STD.DEV.  STD.DEV.    LOT SIZE
          6   397643627       2400         6400         1.0      25.00             10

SIMULATION EXPERIMENT DATA FOR LAYOUT DESIGN FACTOR A1
   LEVEL 1   PURE PROCESS LAYOUT


   NUMBER OF DIFFERENT PARTS
         6

      PART       OPERATION   MACHINE    BATCH      SERVICE     SET UP
       NO.        NUMBER      GROUP      SIZE        TIME        TIME
        1           1           1         99          1           0
        1           2           2          1          1          10
        1           3           1         99          2           0
        1           4           7          1          1           0
        1           5           1         99          2           0
        1           6           6          1          5          15
        1           7           1         99          3           0

        2           1           1         99          3           0
        2           2           5          1          5          10
        2           3           1         99          2           0
        2           4           3          1          1          53
        2           5           1         99          2           0
        2           6           4          1          5          26
        2           7           1         99          4           0

        3           1           1         99          3           0
        3           2           5          1          6          12
        3           3           1         99          2           0
        3           4           3          1          4          78
        3           5           1         99          2           0
        3           6           4          1          3          20
        3           7           1         99          4           0

        4           1           1         99          3           0
        4           2           4          1          2          25
        4           3           1         99          1           0
        4           4           5          1          7          10
        4           5           1         99          4           0

        5           1           1         99          1           0
        5           2           2          1          2          10
        5           3           1         99          2           0
        5           4           4          1          8          30
        5           5           1         99          2           0
        5           6           3          1          9         145
        5           7           1         99          2           0
        5           8           5          1          5           5
        5           9           1         99          4           0

        6           1           1         99          1           0
```

```
      6         2         2         1         2        10
      6         3         1        99         2         0
      6         4         4         1         2        40
      6         5         1        99         2         0
      6         6         3         1         8       170
      6         7         1        99         2         0
      6         8         5         1         9         7
      6         9         1        99         2         0
      6        10         6         1        12        36
      6        11         1        99         3         0

NUMBER OF DIFFERENT FACILITY GROUPS
      7

   FACILITY   GROUP     NUMBER     LABOR    NUMBER OF  DOLLARS
  NUMBER     NUMBER   IN GROUP  CLASS USED LABORERS   PER MACH.
                                            NEEDED     HOUR
     11         1         1         1         1      4.50
     12         2         2         2         1      4.00
     13         3         8         3         1      9.00
     14         4         7         4         1      7.00
     15         5         8         5         1      5.50
     16         6         9         6         1     6.500
     17         7         1         7         1    11.000

NUMBER OF LABOR CLASSES
      7

   LABOR     NUMBER    NUMBER    NUMBER
   CLASS     ON 1ST    ON 2ND    ON 3RD
              SHIFT     SHIFT     SHIFT
      1         1         1         1
      2         2         2         2
      3         8         8         8
      4         7         7         7
      5         8         8         8
      6         9         9         9
      7         1         1         1

   DAYS PER   NUMBER
    PERIOD   OF PERIODS
      5        16
```

# APPENDIX D

## PART, FACILITY, AND LABOR CONSTANTS USED FOR FACILITY DESIGN $A_2$

```
*DATA
     RUNWKS     FACTOR B
                PERCNT
       2        .40
                             FACTOR D            FACTOR C
   NUMBER OF  RN SEED     LOW      HIGH       SMALL     LARGE      LOWLIMIT
     PARTS               ACTIVITY  ACTIVITY  STD.DEV.  STD.DEV.   LOT SIZE
         6  397644627      2400        6400       1.0     25.00          10

SIMULATION EXPERIMENT DATA FOR LAYOUT DESIGN FACTOR A2

   LEVEL 2  P-Q CRITERION
  NUMBER OF DIFFERENT PARTS
       6

     PART     OPERATION  MACHINE   BATCH   SERVICE    SET UP
      NO.       NUMBER    GROUP     SIZE     TIME      TIME
       1          1         1        99        3         0
       1          2         9         1        1         0
       1          3         8         1        1         0
       1          4         7         1        1         0
       1          5        16         1        1         0
       1          6        13         5        5         0

       2          1         1        99        3         0
       2          2        12         4        5         0
       2          3        14         1        1         0
       2          4        10         1        1         0
       2          5        15         1        1         0
       2          6        11         4        5         0

       3          1         1        99        3         0
       3          2         5         1        6        12
       3          3         1        99        2         0
       3          4         3         1        4        78
       3          5         1        99        2         0
       3          6         4         1        3        20
       3          7         1        99        4         0

       4          1         1        99        3         0
       4          2         4         1        2        25
       4          3         1        99        1         0
       4          4         5         1        7        10
       4          5         1        99        4         0

       5          1         1        99        1         0
       5          2         2         1        2        10
       5          3         1        99        2         0
       5          4         4         1        8        30
       5          5         1        99        2         0
       5          6         3         1        9       145
       5          7         1        99        2         0
       5          8         5         1        5         5
       5          9         1        99        4         0

       6          1         1        99        1         0
       6          2         2         1        2        10
       6          3         1        99        2         0
       6          4         4         1        2        40
```

```
         6         5         1        99         2         0
         6         6         3         1         8       170
         6         7         1        99         2         0
         6         8         5         1         9         7
         6         9         1        99         2         0
         6        10         6         1        12         0
         6        11         1        99         3         0


   NUMBER OF DIFFERENT FACILITY GROUPS
        16
      FACILITY   GROUP     NUMBER    LABOR    NUMBER OF  DOLLARS
     NUMBER     NUMBER   IN GROUP  CLASS USED LABORERS  PER MACH.
                                               NEEDED     HOUR
        11         1         1         1         1      4.50
        12         2         1         2         1      4.00
        13         3         7         3         1      9.00
        14         4         3         4         1      7.00
        15         5         4         5         1      5.50
        16         6         4         6         1      6.50
        17         7         1         7         1     11.00
2500000000         8         1         0         0       .50
        12         9         1         2         1      4.00
        13        10         1         3         1      9.00
        14        11         1         4         4     28.00
        15        12         1         5         4     22.00
        16        13         1         6         5     32.50
2500000000        14         1         0         0         0
2500000000        15         1         0         0         0
2500000000        16         1         0         0         0

   NUMBER OF LABOR CLASSES
         7

      LABOR     NUMBER    NUMBER    NUMBER
      CLASS     ON 1ST    ON 2ND    ON 3RD
                 SHIFT     SHIFT     SHIFT
         1         1         1         1
         2         2         2         2
         3         8         8         8
         4         7         7         7
         5         8         8         8
         6         9         9         9
         7         1         1         1

      DAYS PER   NUMBER
       PERIOD   OF PERIODS
         5        16
```

# APPENDIX E

## PART, FACILITY, AND LABOR CONSTANTS
## USED FOR FACILITY DESIGN $A_3$

```
SIMULATION EXPERIMENT DATA FOR LAYOUT DESIGN FACTOR A3

      LEVEL 3 UTILIZATION CRITERION
   NUMBER OF DIFFERENT PARTS
      6          1

     PART      OPERATION   MACHINE    BATCH     SERVICE      SET UP
      NO.       NUMBER      GROUP      SIZE       TIME         TIME
      1           1           1         99         3            0
      1           2           9          1         1            0
      1           3           8          1         1            0
      1           4           7          1         1            0
      1           5          16          1         1            0
      1           6          13          5         5            0

      2           1           1         99         3            0
      2           2          12          1         5            0
      2           3           3          1         1           53
      2           4          11          1         5            0
      2           5           1         99         2            0

      3           1           1         99         3            0
      3           2           5          1         6           12
      3           3           1         99         2            0
      3           4           3          1         4           78
      3           5           1         99         2            0
      3           6           4          1         3           20
      3           7           1         99         4            0

      4           1           1         99         3            0
      4           2           4          1         2           25
      4           3           1         99         1            0
      4           4           5          1         7           10
      4           5           1         99         4            0

      5           1           1         99         1            0
      5           2           2          1         2           10
      5           3           1         99         2            0
      5           4          14          1         8            0
      5           5          17          1         1            0
      5           6          15          1         9            0
      5           7          18          1         1            0
      5           8          10          1         5            0

      6           1           1         99         1            0
      6           2           2          1         2           10
      6           3           1         99         2            0
      6           4           4          1         2           40
      6           5           1         99         2            0
      6           6           3          1         8          170
      6           7           1         99         2            0
      6           8           5          1         9            7
      6           9           1         99         2            0
      6          10           6          1        12            0
      6          11           1         99         3            0

   NUMBER OF DIFFERENT FACILITY GROUPS
      18
```

```
      FACILITY   GROUP     NUMBER    LABOR    NUMBER OF  DOLLARS
     NUMBER     NUMBER   IN GROUP  CLASS USED LABORERS  PER MACH.
                                               NEEDED     HOUR
        11         1         1         1         1      4.50
        12         2         1         2         1      4.00
        13         3         7         3         1      9.00
        14         4         5         4         1      7.00
        15         5         6         5         1      5.50
        16         6         4         6         1      6.50
        17         7         1         7         1     11.00
2500000000         8         1         0         0       .50
        12         9         1         2         1      4.00
        15        10         1         5         1      5.50
        14        11         1         4         1      7.00
        15        12         1         5         1      5.50
        16        13         1         6         5     32.50
        14        14         1         4         1      7.00
        13        15         1         3         1      9.00
2500000000        16         1         0         0         0
2500000000        17         1         0         0         0
2500000000        18         1         0         0         0


   NUMBER OF LABOR CLASSES
         7

      LABOR     NUMBER    NUMBER    NUMBER
      CLASS     ON 1ST    ON 2ND    ON 3RD
                 SHIFT     SHIFT     SHIFT
         1         1         1         1
         2         2         2         2
         3         8         8         8
         4         7         7         7
         5         8         8         8
         6         9         9         9
         7         1         1         1

      DAYS PER   NUMBER
       PERIOD   OF PERIODS
         5        16
```

# APPENDIX F

# RESULTS OF SIMULATION RUNS AND ANALYSIS OF VARIANCE TABLES

## MEAN PERCENT FACILITY UTILIZATION

### TABLE 1.1

### SIMULATION RESULTS

| | | Low Activity Level | | High Activity Level | |
|---|---|---|---|---|---|
| | | Flat P-Q | Concave P-Q | Flat P-Q | Concave P-Q |
| Layout $A_1$ | Small Lot Size Variance | .1778 | .1139 | .4191 | .2671 |
| | Large Lot Size Variance | .1980 | .1091 | .4701 | .2697 |
| Layout $A_2$ | Small Lot Size Variance | .1847 | .1107 | .4409 | .3021 |
| | Large Lot Size Variance | .1778 | .1134 | .4160 | .3170 |
| Layout $A_3$ | Small Lot Size Variance | .1675 | .1221 | .4336 | .2799 |
| | Large Lot Size Variance | .1956 | .1221 | .3921 | .2850 |

# TABLE 1.2

## ANALYSIS OF VARIANCE

| Source of Variation | Sums of Squares x 1000 | Degrees of Freedom | Variance Estimate x 1000 |
|---|---|---|---|
| A | 5.45 | 2. | 2.73 |
| B | 574.97 | 1. | 574.97** |
| C | 3.60 | 1. | 3.60 |
| D | 2508.19 | 1. | 2508.19** |
| AB | 24.22 | 2. | 12.11 |
| AC | 3.36 | 2. | 1.68 |
| AD | 11.14 | 2. | 5.57 |
| BC | 3.52 | 1. | 3.52 |
| BD | 52.36 | 1. | 52.36* |
| CD | 0.08 | 1. | 0.08 |
| ABC | 4.32 | 2. | 2.16 |
| ABD | 13.23 | 2. | 6.62 |
| ACD | 2.75 | 2. | 1.37 |
| BCD | 0.01 | 1. | 0.01 |
| RESIDUAL | 1.78 | 2. | 0.89 |
| TOTAL | 3208.97 | 23. | |

**Significant at the 1% level

*Significant at the 5% level

MEAN ELAPSED COMPLETION TIME FOR PART 1

TABLE 2.1

SIMULATION RESULTS

| | | Low Activity Level | | High Activity Level | |
|---|---|---|---|---|---|
| | | Flat P-Q | Concave P-Q | Flat P-Q | Concave P-Q |
| Layout $A_1$ | Small Lot Size Variance | 684 | 658 | 792 | 857 |
| | Large Lot Size Variance | 808 | 602 | 729 | 869 |
| Layout $A_2$ | Small Lot Size Variance | 205 | 248 | 300 | 406 |
| | Large Lot Size Variance | 192 | 191 | 222 | 428 |
| Layout $A_3$ | Small Lot Size Variance | 177 | 251 | 267 | 439 |
| | Large Lot Size Variance | 165 | 258 | 226 | 362 |

## TABLE 2.2

## ANALYSIS OF VARIANCE

| Source of Variation | Sums of Squares | Degrees of Freedom | Variance Estimate |
|---|---|---|---|
| A | 1222865.58 | 2. | 611432.79** |
| B | 26800.17 | 1. | 26800.17 |
| C | 2242.67 | 1. | 2242.67 |
| D | 88573.50 | 1. | 88573.50* |
| AB | 17158.58 | 2. | 8579.29 |
| AC | 1669.08 | 2. | 834.54 |
| AD | 385.75 | 2. | 192.87 |
| BC | 181.50 | 1. | 181.50 |
| BD | 29962.67 | 1. | 29962.67 |
| CD | 1980.17 | 1. | 1980.17 |
| ABC | 1624.75 | 2. | 812.38 |
| ABD | 5506.08 | 2. | 2753.04 |
| ACD | 1410.58 | 2. | 705.29 |
| BCD | 4930.67 | 1. | 4930.67 |
| RESIDUAL | 6167.58 | 2. | 3083.79 |
| TOTAL | 1411459.37 | 23. | |

**Significant at the 1% level

*Significant at the 5% level

## MEAN ELAPSED COMPLETION TIME FOR PART 2

### TABLE 3.1

### SIMULATION RESULTS

| | | Low Activity Level | | High Activity Level | |
|---|---|---|---|---|---|
| | | Flat P-Q | Concave P-Q | Flat P-Q | Concave P-Q |
| Layout $A_1$ | Small Lot Size Variance | 975 | 991 | 998 | 1012 |
| | Large Lot Size Variance | 948 | 880 | 1180 | 991 |
| Layout $A_2$ | Small Lot Size Variance | 185 | 271 | 345 | 315 |
| | Large Lot Size Variance | 451 | 232 | 307 | 298 |
| Layout $A_3$ | Small Lot Size Variance | 940 | 1319 | 1559 | 2541 |
| | Large Lot Size Variance | 1502 | 1543 | 1326 | 4113* |

*Possibly overloaded from previous weeks

## TABLE 3.2

## ANALYSIS OF VARIANCE

| Source of Variation | Sums of Squares | Degrees of Freedom | Variance Estimate |
|---|---|---|---|
| A | 9705591.00 | 2. | 4852795.50* |
| B | 598504.33 | 1. | 598504.33 |
| C | 224266.67 | 1. | 224266.67 |
| D | 939312.66 | 1. | 939312.66 |
| AB | 1605099.92 | 2. | 802549.96 |
| AC | 343950.59 | 2. | 171975.29 |
| AD | 1323296.34 | 2. | 661648.17 |
| BC | 33450.67 | 1. | 33450.67 |
| BD | 459266.66 | 1. | 459266.66 |
| CD | 13537.67 | 1. | 13537.67 |
| ABC | 255938.85 | 2. | 127969.43 |
| ABD | 945704.15 | 2. | 472852.07 |
| ACD | 45804.09 | 2. | 22902.05 |
| BCD | 230104.01 | 1. | 230104.01 |
| RESIDUAL | 359006.55 | 2. | 179503.27 |
| TOTAL | 7082834.00 | 23. | |

*Significant at the 5% level

## MEAN ELAPSED COMPLETION TIME FOR PART 3

## TABLE 4.1

## SIMULATION RESULTS

| | | Low Activity Level | | High Activity Level | |
|---|---|---|---|---|---|
| | | Flat P-Q | Concave P-Q | Flat P-Q | Concave P-Q |
| Layout $A_3$ | Small Lot Size Variance | 1153 | 1150 | 1205 | 1174 |
| | Large Lot Size Variance | 1318 | 1155 | 1052 | 1035 |
| Layout $A_2$ | Small Lot Size Variance | 1218 | 1170 | 1965 | 1247 |
| | Large Lot Size Variance | 1147 | 1277 | 3309 | 1195 |
| Layout $A_3$ | Small Lot Size Variance | 1162 | 1163 | 1174 | 1177 |
| | Large Lot Size Variance | 1121 | 1040 | 1266 | 1278 |

## TABLE 4.2

## ANALYSIS OF VARIANCE

| Source of Variation | Sums of Squares | Degrees of Freedom | Variance Estimate |
|---|---|---|---|
| A | 863363.33 | 2. | 431681.66 |
| B | 382285.00 | 1. | 382285.00 |
| C | 63551.00 | 1. | 63551.00 |
| D | 375750.33 | 1. | 375750.33 |
| AB | 569280.00 | 2. | 284640.00 |
| AC | 158862.67 | 2. | 79431.34 |
| AD | 711324.34 | 2. | 355662.17 |
| BC | 86040.33 | 1. | 86040.33 |
| BD | 303975.00 | 1. | 303975.00 |
| CD | 55200.00 | 1. | 55200.00 |
| ABC | 102730.98 | 2. | 51365.49 |
| ABD | 760318.35 | 2. | 380159.18 |
| ACD | 184603.64 | 2. | 92301.82 |
| BCD | 71395.34 | 1. | 71395.34 |
| RESIDUAL | 243108.37 | 2. | 121554.18 |
| TOTAL | 4931789.00 | 23. | |

## MEAN ELAPSED COMPLETION TIME FOR PART 4

## TABLE 5.1

## SIMULATION RESULTS

| | | Low Activity Level | | High Activity Level | |
|---|---|---|---|---|---|
| | | Flat P-Q | Concave P-Q | Flat P-Q | Concave P-Q |
| Layout $A_1$ | Small Lot Size Variance | 768 | 759 | 974 | 906 |
| | Large Lot Size Variance | 806 | 843 | 800 | 805 |
| Layout $A_2$ | Small Lot Size Variance | 769 | 766 | 1665 | 976 |
| | Large Lot Size Variance | 673 | 995 | 3248 | 1049 |
| Layout $A_3$ | Small Lot Size Variance | 763 | 764 | 905 | 774 |
| | Large Lot Size Variance | 750 | 792 | 800 | 705 |

## TABLE 5.2

## ANALYSIS OF VARIANCE

| Source of Variation | Sums of Squares | Degrees of Freedom | Variance Estimate |
|---|---|---|---|
| A | 1141391.66 | 2. | 570695.83 |
| B | 323640.33 | 1. | 323640.33 |
| C | 90897.00 | 1. | 90897.00 |
| D | 720720.00 | 1. | 720720.00 |
| AB | 505669.34 | 2. | 252834.67 |
| AC | 315254.67 | 2. | 157627.34 |
| AD | 1036646.06 | 2. | 518323.33 |
| BC | 40755.00 | 1. | 40755.00 |
| BD | 530145.33 | 1. | 530145.33 |
| CD | 36582.00 | 1. | 36582.00 |
| ABC | 137284.00 | 2. | 68642.00 |
| ABD | 765540.73 | 2. | 382770.37 |
| ACD | 277525.02 | 2. | 138762.51 |
| BCD | 136957.34 | 1. | 136957.34 |
| RESIDUAL | 284040.64 | 2. | 142020.32 |
| TOTAL | 6343049.75 | 23. | |

## MEAN ELAPSED COMPLETION TIME FOR PART 5

## TABLE 6.1

## SIMULATION RESULTS

| | | Low Activity Level | | High Activity Level | |
|---|---|---|---|---|---|
| | | Flat P-Q | Concave P-Q | Flat P-Q | Concave P-Q |
| Layout $A_1$ | Small Lot Size Variance | 2225 | 2185 | 2494 | 2323 |
| | Large Lot Size Variance | 2362 | 2104 | 2527 | 2188 |
| Layout $A_2$ | Small Lot Size Variance | 2260 | 2121 | 3255 | 2499 |
| | Large Lot Size Variance | 2559 | 2202 | 4683 | 2245 |
| Layout $A_3$ | Small Lot Size Variance | 1354 | 1326 | 3144 | 1530 |
| | Large Lot Size Variance | 5290 | 1437 | 5252 | 1591 |

## TABLE 6.2

## ANALYSIS OF VARIANCE

| Source of Variation | Sums of Squares | Degrees of Freedom | Variance Estimate |
|---|---|---|---|
| A | 776832.00 | 2. | 388416.00 |
| B | 7826125.31 | 1. | 7826125.31* |
| C | 2454400.00 | 1. | 2454400.00 |
| D | 1631252.00 | 1. | 1631252.00 |
| AB | 4552219.94 | 2. | 2276109.97 |
| AC | 2600561.31 | 2. | 1300280.66 |
| AD | 520324.00 | 2. | 260162.00 |
| BC | 2806453.31 | 1. | 2806453.31 |
| BD | 789523.94 | 1. | 789523.94 |
| CD | 69661.31 | 1. | 69661.31 |
| ABC | 2046708.19 | 2. | 1023354.09 |
| ABD | 385964.06 | 2. | 192982.03 |
| ACD | 476713.37 | 2. | 238356.69 |
| BCD | 4081.37 | 1. | 4081.37 |
| RESIDUAL | 637754.50 | 2. | 318877.25 |
| TOTAL | 7578576.00 | 23. | |

*Significant at the 5% level

## MEAN ELAPSED COMPLETION TIME FOR PART 6

## TABLE 7.1

## SIMULATION RESULTS

| | | Low Activity Level | | High Activity Level | |
|---|---|---|---|---|---|
| | | Flat P-Q | Concave P-Q | Flat P-Q | Concave P-Q |
| Layout $A_1$ | Small Lot Size Variance | 2986 | 2975 | 3318 | 3007 |
| | Large Lot Size Variance | 2828 | 2189[+] | 3105 | 3139 |
| Layout $A_2$ | Small Lot Size Variance | 3006 | 3229* | 4211 | 2958 |
| | Large Lot Size Variance | 3263 | 2618 | 5936 | 3729 |
| Layout $A_3$ | Small Lot Size Variance | 2956 | 2849 | 3380 | 2991 |
| | Large Lot Size Variance | 3010 | 2003[+] | 3220 | 2663 |

*Data from previous week (9) since no parts No. 6 were processed during week 10.

[+] Only one order (observation) of small size processed.

## TABLE 7.2

## ANALYSIS OF VARIANCE

| Source of Variation | Sums of Squares | Degrees of Freedom | Variance Estimate |
|---|---|---|---|
| A | 2665370.66 | 2. | 1332685.33* |
| B | 1965965.33 | 1. | 1965965.33* |
| C | 1106.67 | 1. | 1106.67 |
| D | 2499376.00 | 1. | 2499376.00* |
| AB | 555637.33 | 2. | 277818.66 |
| AC | 908543.99 | 2. | 454272.00 |
| AD | 857234.66 | 2. | 428617.33 |
| BC | 419496.01 | 1. | 419496.01 |
| BD | 259792.00 | 1. | 259792.00 |
| CD | 672346.66 | 1. | 672346.66 |
| ABC | 148053.34 | 2. | 74026.67 |
| ABD | 914813.33 | 2. | 457406.66 |
| ACD | 447610.77 | 2. | 223805.38 |
| BCD | 109213.37 | 1. | 109213.37 |
| RESIDUAL | 77026.66 | 2. | 38513.33 |
| TOTAL | 2501588.00 | 23. | |

*Significant at the 5% level

TOTAL IN-PROCESS STORAGE REQUIREMENTS

TABLE 8.1

SIMULATION RESULTS

| | | Low Activity Level | | High Activity Level | |
|---|---|---|---|---|---|
| | | Flat P-Q | Concave P-Q | Flat P-Q | Concave P-Q |
| Layout $A_1$ | Small Lot Size Variance | 9 | 9 | 37 | 35 |
| | Large Lot Size Variance | 8 | 9 | 34 | 30 |
| Layout $A_2$ | Small Lot Size Variance | 13 | 14 | 54 | 42 |
| | Large Lot Size Variance | 16 | 13 | 68* | 40 |
| Layout $A_3$ | Small Lot Size Variance | 10 | 14 | 48 | 46 |
| | Large Lot Size Variance | 22 | 14 | 45 | 49 |

*Two orders lost from queue to group 5.

TABLE 8.2

ANALYSIS OF VARIANCE

| Source of Variation | Sums of Squares | Degrees of Freedom | Variance Estimate |
|---|---|---|---|
| A | 583.08 | 2. | 291.54$^{+}$ |
| B | 100.04 | 1. | 100.04 |
| C | 12.04 | 1. | 12.04 |
| D | 5922.04 | 1. | 5922.04* |
| AB | 124.08 | 2. | 62.04 |
| AC | 40.58 | 2. | 20.29 |
| AD | 139.08 | 2. | 69.54 |
| BC | 30.37 | 1. | 30.37 |
| BD | 63.38 | 1. | 63.38 |
| CD | 3.38 | 1. | 3.38 |
| ABC | 24.25 | 2. | 12.13 |
| ABD | 127.75 | 2. | 63.87 |
| ACD | 33.25 | 2. | 16.62 |
| BCD | 0.38 | 1. | 0.38 |
| RESIDUAL | 59.25 | 2. | 29.63 |
| TOTAL | 7262.96 | 23. | |

*Significant at the 5% level

$^{+}$Significant at the 10% level

AVERAGE DOLLARS IN PROCESS INVENTORY (QUEUES ONLY)

TABLE 9.1

SIMULATION RESULTS

| | | Low Activity Level | | High Activity Level | |
|---|---|---|---|---|---|
| | | Flat P-Q | Concave P-Q | Flat P-Q | Concave P-Q |
| Layout $A_1$ | Small Lot Size Variance | 214 | 140 | 2004 | 1397 |
| | Large Lot Size Variance | 272 | 122 | 2072 | 1077 |
| Layout $A_2$ | Small Lot Size Variance | 254 | 355 | 7262 | 2234 |
| | Large Lot Size Variance | 251 | 275 | 12495* | 2096 |
| Layout $A_3$ | Small Lot Size Variance | 291 | 580 | 6469 | 5192 |
| | Large Lot Size Variance | 5247 | 487 | 8177 | 8572 |

*Two orders lost in queue to group 5.

TABLE 9.2

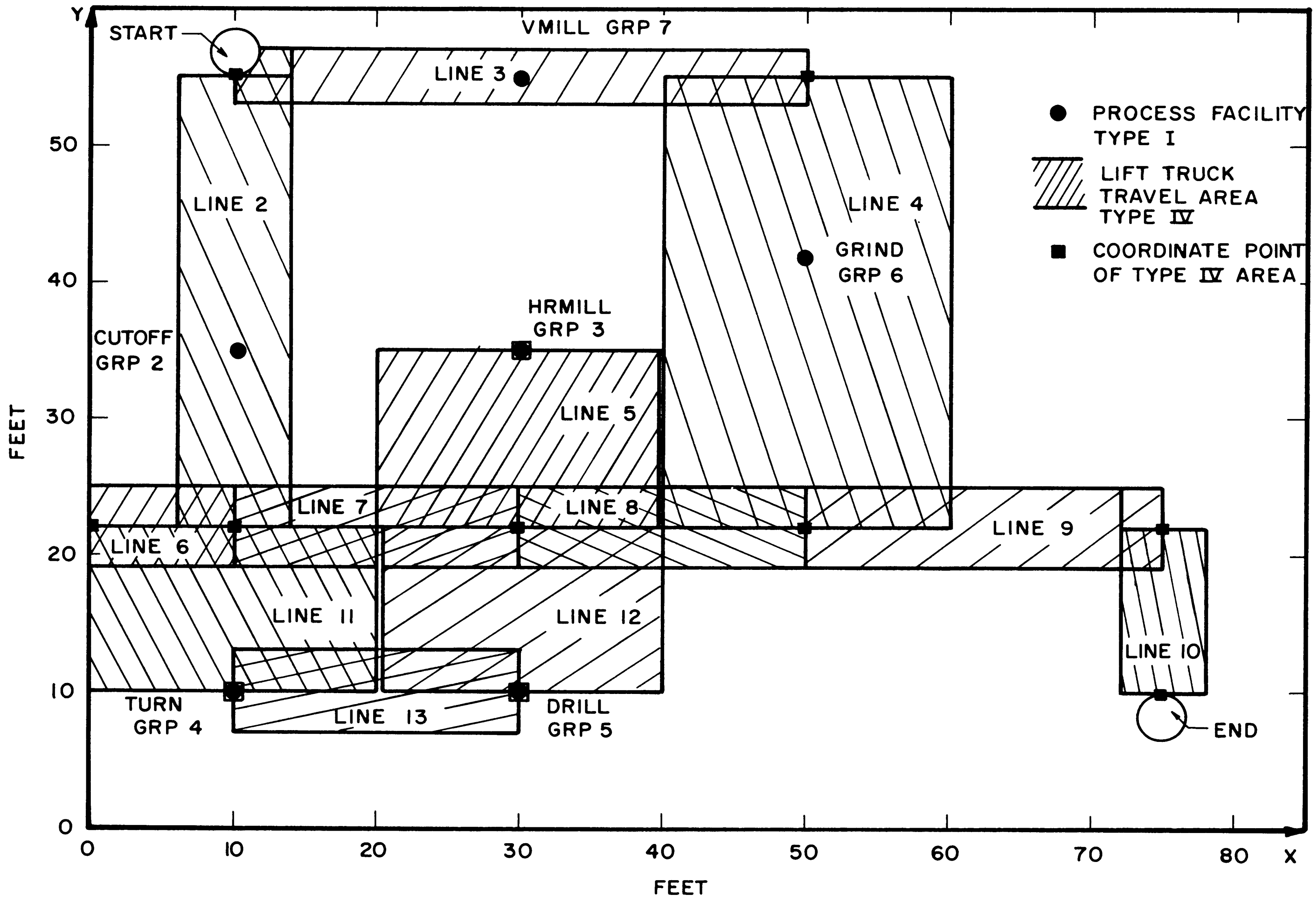
ANALYSIS OF VARIANCE

| Source of Variation | Sums of Squares | Degrees of Freedom | Variance Estimate |
|---|---|---|---|
| A | 8219780.00 | 2. | 4109890.00 |
| B | 6641676.00 | 1. | 6641676.00 |
| C | 6257708.00 | 1. | 6257708.00 |
| D | 6252164.00 | 1. | 6252164.00 |
| AB | 7856140.00 | 2. | 3928070.00 |
| AC | 6916993.00 | 2. | 3458496.50 |
| AD | 19693980.00 | 2. | 9846990.00 |
| BC | 1922700.00 | 1. | 1922700.00 |
| BD | 4900585.00 | 1. | 4900585.00 |
| CD | 284926.00 | 1. | 284926.00 |
| ABC | 619015.00 | 2. | 309507.50 |
| ABD | 18254279.00 | 2. | 9127139.50 |
| ACD | 631199.00 | 2. | 315599.50 |
| BCD | 543306.00 | 1. | 543306.00 |
| RESIDUAL | 6093945.00 | 2. | 3046972.50 |
| TOTAL | 7544200.00 | 23. | |

# APPENDIX G

## LAYOUT A$_1$ FOR INPUT TO SPATIAL EVALUATOR PROGRAM

```
*DATA
     HYPOTHETICAL PURE PROCESS LAYOUT A1
         9
LIFTRK343000  27362448                  1720000010000000000028100004000100484848
START     11   2396288                  100000001000000000000000   9999   999999
END       18   2396288                  10000000100  00000000000   9999   999999
CUTOFF    12  52461568                  1350000010100000000005200001000100961810
HRMILL    13  52461568                  1900000011100000000005200001000500301010
TURN      14  52461568                  1500000010270000000005250001000300300808
DRILL     15  52461568                  1180000010100        520   1000200303005
GRIND     16  52461568                  13500   10175        520   10003  301010
VMILL     17  52461568                  17600   11350        520   10007  301010
         7
TRKDVR     1 1.70
DILBR1     2 1.75
DILBR2     3 2.50
DILBR3     4 2.10
DILBR4     5 1.80
DILBR5     6 2.00
DILBR6     7 2.75
         9
LIFTRK4011    3022    203010  12   1     1
LIFTRK4011    1022    201010  11
LIFTRK4011    7522     67510  10
LIFTRK4011    5022     67522   9
LIFTRK4011    3022     65022   8
LIFTRK4011    1022     63022   7
LIFTRK4011    0022     61022   6
LIFTRK4011    3035    203022   5
LIFTRK4011    5055    205022   4
LIFTRK4011    1055     45055   3
LIFTRK4011    1055     81022   2
LIFTRK4011    1010     63010   1
CUTOFF1022    1035      1035   1   1     2
HRMILL1039    3035      3035   1   1     3
TURN  1049    1010      1010   1   1     4
DRILL 1 59    3010      3010   1   1     5
GRIND 1069    5042      5042   1   1     6
VMILL 1071    3055      3055   1   1     7
START 1081    1055      1055   1
END   1091    7510      7510   1
         9
START 1081     101              500 481210     32896 99
LIFTRK4011     102     100101   500 481210     32896 99
CUTOFF1022     1 3          1   500 481210     32896  1
LIFTRK4 11     1 4     100101    20  21210     32896 99
VMILL 1071     1 5          1    20  21210     32896  1
LIFTRK4011     1 6     100101    20  21210     32896 99
GRIND 1 69     1 7          5    20  21210     32896  1
LIFTRK4011     1 8     100101    20  21210     32896 99
END   1091     109               20 21210      32896 99
         9
START 1081     201               10  4 4 4     32768 99
LIFTRK4011     2 2     100101    10  4 4 4     32768 99
DRILL 1059     2 3          5    10  4 4 4     32768  1
LIFTRK4011     2 4     100101    10  4 4 4     32768 99
HRMILL1039     2 5          1    10  4 4 4     32768  1
LIFTRK4011     2 6     100101    10  4 4 4     32768 99
TURN  1049     2 7          5    10  4 4 4     32768  1
LIFTRK4011     2 8     100101    10  4 4 4     32768 99
END   1091     209     100101    10  4 4 4     32768 99
```



APPENDIX H. Layout $A_1$ for Input to Spatial Evaluator Program.

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