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SOME OBSERVATIONS ON FACILITY DESIGN

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SOME OBSERVATIONS ON FACILITY DESIGN

Expenditures for industrial plant construction in the United States are about $3 billion annually. An equal amount is committed for school structures, and still more for transportation and service facilities. Engineers responsible for wise use of these important capital funds draw upon a rich background of research and experience in the architectural and engineering sciences to aid in selecting materials and equipment suitable for the service desired. In spite of the most careful planning, costly errors arise from the limitations of an empirical approach to combining separate equipment into a complex system: a prominent new hotel finds it necessary to add another passenger elevator shortly after opening; a close-coupled automatic machine line is found to give greater capacity by breaking the line into segments separated by in-process inventory; a power-and-free conveyor installation is unable to handle the planned production rate and must be supplemented by fork-lift-truck material-handling between some stations. The occurrence of these errors is not a criticism of the facility designer's skill or care. On the contrary, in view of the limited tools for analysis at the designer's disposal, he is to be complimented that such gross errors arise infrequently. Methods for arriving at superior configurations of physical components and for predicting the performance characteristics of proposed designs under dynamic operating loads have been conceived only recently.

In this paper, we will briefly review recent developments which seem to be the most relevant to the problems of the facility designer. Our intent is to familiarize the designer with concepts usually omitted from the literature of facility design; to suggest a useful but abstract structure for conceptualizing operating systems independently of particular physical equipment; to present a number of open questions amenable to investigation; and to stimulate more open exchange of experience in this complex area. For purposes of this presentation we define facility planning as:

> "The synthesis of physical equipment and structures, human elements, and communication means, into an integrated system for efficiently furnishing designated services, or manufacturing specified products."

Unlike the usual treatment of facility design, we emphasize the abstract aspects of the analysis of material flow systems and facility layout. As we shall see, a major reason for such abstract representation lies in the hope of thereby discovering general concepts and principles useful for narrowing the seemingly infinite number of choices of equipment and arrangements facing the facility designer. We propose to describe facilities by networks, of three types: material flow networks, communication networks, and fixed-facility configurations. Each of the several material flow and communication networks has arrival rates, service times, and service-priority disciplines for the class of materials or messages flowing in its particular links. Other links, of specified capability, permit the flow of certain units between the networks so that a complex of interconnections exists in both time and space. At some of the nodes or fixed facilities, processing equipment may perform transformations on the flow units, thus permitting transfer to a different network via a link or alternatively, continued movement in the same network. The flow parameters (cost, time, distance, etc.) in the links may be a function of the location of the fixed nodes, thus giving rise to a problem typical of plant layout: locate departments and machines in space so as to optimize some network flow function.

The simplest form of a flow network consists of a single commodity and can be represented by a set of nodes A, B, C, ..., G, and links connecting the nodes in a specified fashion (Figure 1). Associated with each link may be deterministic cost, time, or capacity functions. The flow of the single commodity in the network may be directed from one particular node to another, or may travel in either direction depending upon the application. A rapidly developing theory of network flows(1)* is finding application to a number of industrial problems. Critical Path Scheduling is a currently well-known application of network methods. Other useful applications of this subclass of linear programming are: finding the maximal capacity of a railroad between two points, such as A and G in the network of Figure 1(2); finding the shortest route through a city for transportation studies(3); and finding the flow capacity of water mains. More complex procedures have been developed to aid in the optimal allocation of a fixed budget to the links to obtain the maximum increase in the capacity of the network(4),

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[*] Numbers in brackets refer to bibliography at end of paper.

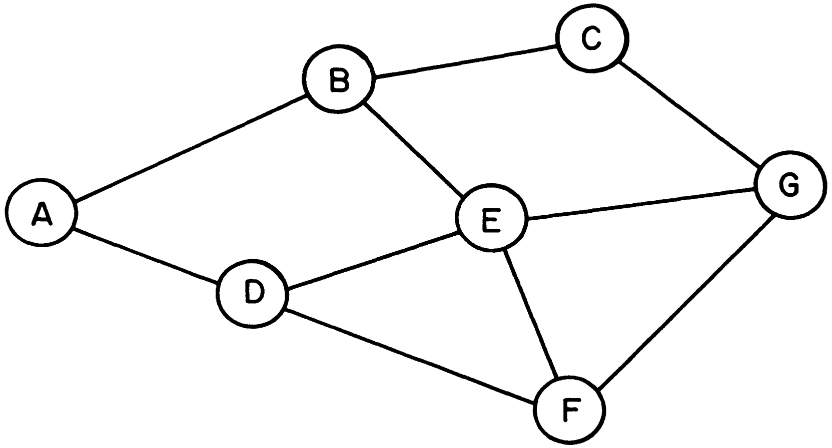


Figure 1. Single Commodity Network Flow.

and to determine the maximum dynamic flow possible over a specified number of time periods when each link has associated with it a maximum flow capacity and the number of time periods required to traverse the link(5).

Multi-commodity flow has also been studied through network flow methods(6). Figure 2 is a simplified diagram of the type of problem considered. Product 1 can flow through the sequence of nodes (or facilities) 11-12-24-14-15 or 11-12'-22-14'-15, each with known fixed maximum capacity. Product 2 must flow through sequence 21-22-23-24-25, also with known capacity for each node. What is the maximum total flow of both products, and how is it obtained?

The transportation algorithm of linear programming has the network flow structure shown in Figure 3. A known number of homogenous units is located at the sources (A, B) and a known number of the units is required at each of the sinks, or destinations. If a cost or other linear penalty function is associated with a unit shipped from any source to any sink, we seek that shipping plan which has minimum total cost. This algorithm probably enjoys the widest application of any in the linear programming family and details of its use in distribution problems of a broad class are unnecessary. Interesting variations are under development. The inclusion of capacity restrictions on the transportation routes(7), or the use of non-linear cost functions(8,9,10,11) open new areas to application of the transportation-type algorithm.

A network flow problem of increasing difficulty arises when the requirement for cyclic flow is added. In contrast to the previously

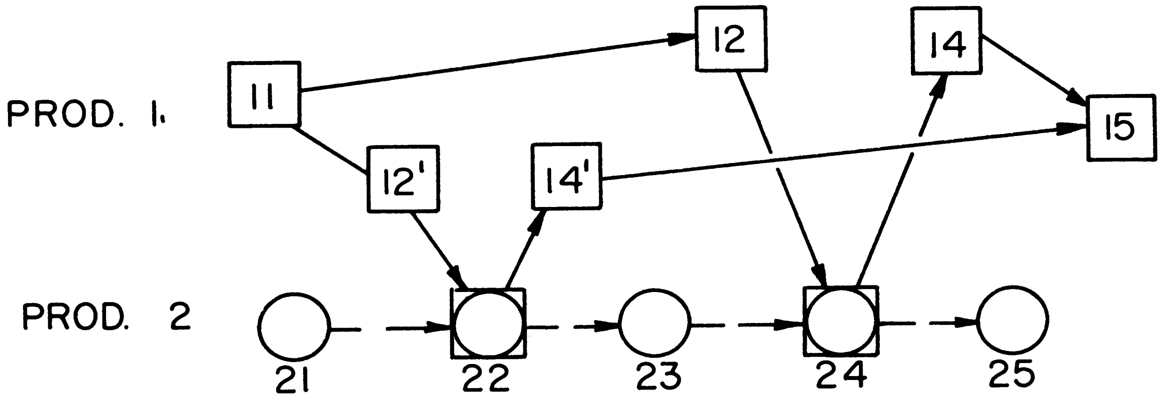


Figure 2. Multi-Product Network Flow.

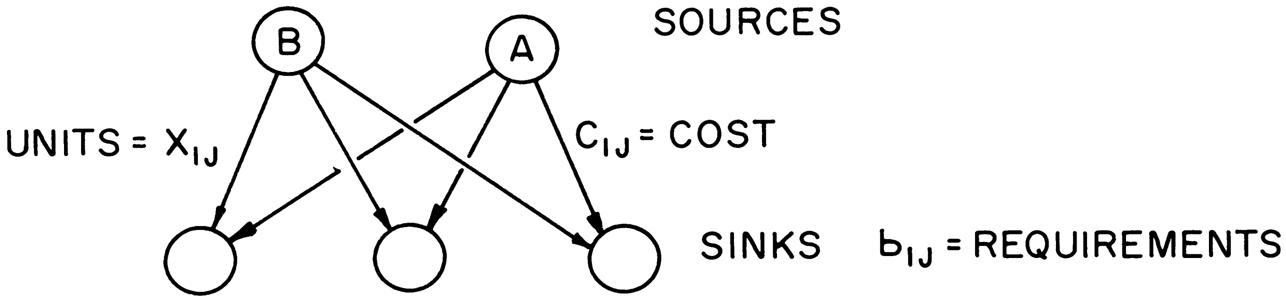


Figure 3. Transportations Flow.

described flow problems in which flow originated at one or more sources and ended at one or more different sinks, cyclic flow begins and ends at the same node. The travelling salesman problem (Figure 4) is a classical example of this kind of problem. In this example, a unit is to travel from node A, visit each of the other nodes, B, C, D, and E once and conclude the circuit at the origin node A with minimum total travel distance. A practical application of this problem arises in truck dispatching(12). Assume that node A is a loading station for fuel trucks and nodes B, C, D, E, are customers to be served with requirements r_b, r_c, r_d, and r_e. Assume that the capacity of the fuel-truck is less than the total requirements of all customers, thus compelling the truck to make two or more tours from the loading station A. What sequence of tours should the truck make in order to serve all customers with minimum travel distance?

The broad generality of network flow models is illustrated by the representation of a material-handling equipment-selection problem as a network(13). In Figure 5, any connected path from the left node to the right node is an admissible sequence of material-handling devices which can be used to accomplish a particular task. Associated with each link is a unit cost per unit of material handled (C1, ..., C7), and, in addition, a fixed cost C_t when purchase of some classes of equipment such as a truck is necessary. The objective is to find that path through the network (e.g. the material-handling sequence) with minimum total cost. Such problems, on a limited scale, are yielding to recent developments in integer programming(14).

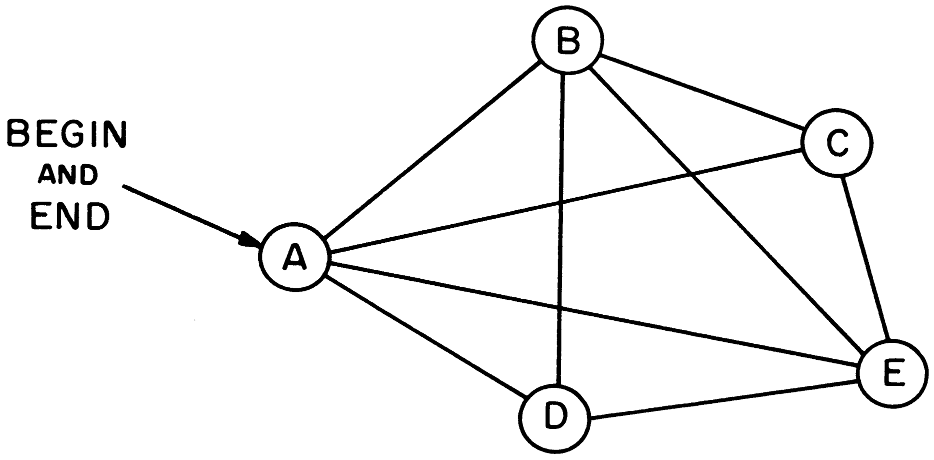
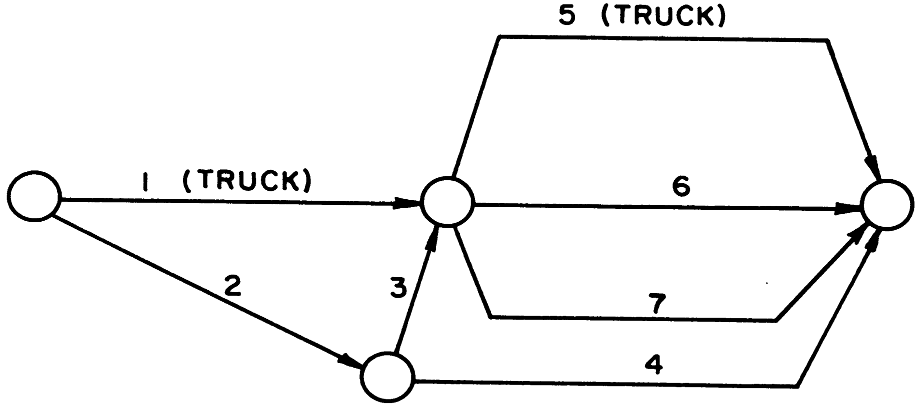


Figure 4. Cyclic Flow.



$$X_1 + X_2 = 1$$

$$X_3 + X_4 = X_2$$

$$X_1 + X_3 = X_7 + X_8 + X_9$$

$$X = X_T$$

$$X_5 = X_T$$

$$\text{MIN}: C_T X_T + C_1 X_1 + \ldots + C_7 X_7$$

Figure 5. Equipment Selection Network.

In contrast to these prescriptive solutions obtained from analysis of deterministic network flow problems, only descriptive solutions of random flow in networks are obtained from analysis by queueing theory. Nevertheless, significant understanding of random flow processes often follows from the concepts of queueing theory. Figure 6 illustrates the possibilities for considering (a) job-shop flow processes as queueing networks, and (b) conveyor systems as queueing stations in series. In the queueing network, the assumption of infinite in-process inventories before work stations which have exponentially distributed service times permits analysis of the most complex networks as a system of independent stations(15). The ability of in-process inventory to dramatically increase the total capacity of a series of work stations which have random service times has been effectively studied through queueing theory(16). One excellent case study of the application of queueing theory to an airport transportation problem is given in Reference 17. The handling of cargo from ship to dock has been named a "shuttle process" and is a special case of queueing, if the service times for each shuttle are random. As shown in Figure 7a, the shuttle process consists of a series of material-handling devices, each of which is constrained to travel between a point of material pick-up P_n and delivery node P_{n+1}. Storage is permitted at the node and multiple shuttles may operate in any link. Of special interest is the abstract analogy between operational characteristics of shuttle processes and sequential processing lines (Figure 7b). If the multiple shuttles in each stage are thought of as machines

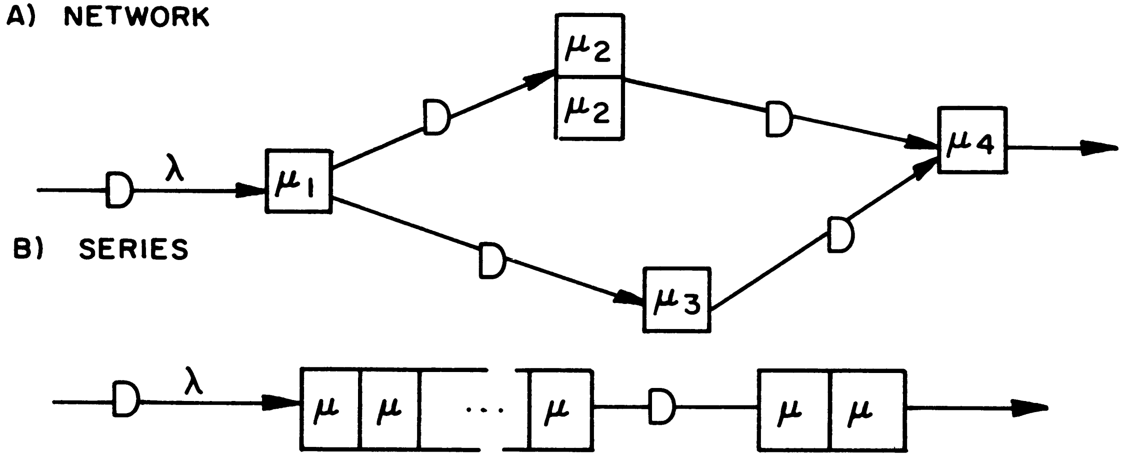


Figure 6. Random Flow (Queueing) Systems.

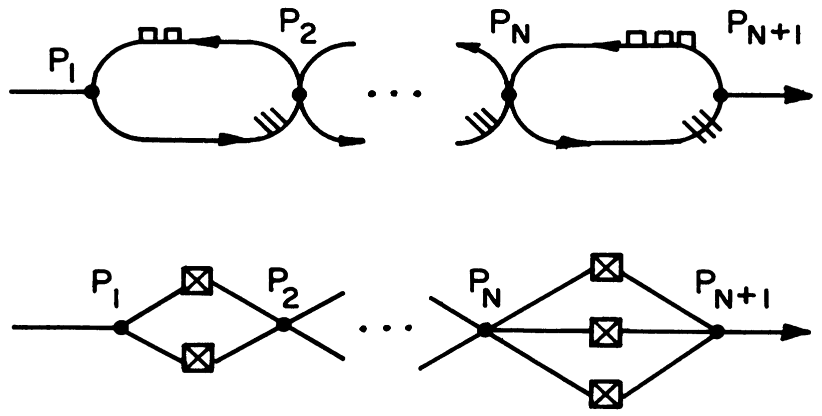


Figure 7. Random Flow Processes.

in parallel, with the restriction that the first job into the machine group is also the first out, if the empty shuttle return-line is considered the machine set-up time, and if the shuttle travel-time is the machine process time, the two systems have identical operating characteristics. The operational structure of the abstract model of the system thus permits immediate generalizations regarding behavior of a class of flow systems, independent of hardware considerations.(18)

Figure 8 introduces a random flow process with cyclic features: the hook storage-delivery conveyor system. Material arrives at random for loading at station A and is unloaded at station B, also at random and perhaps with a different shift schedule. Analytic studies of the effect of conveyor speeds and capacity for specified flow rates are appearing(15,19,20) but they are still restricted to the simplest of configurations, the single loop.

The performance of any material flow network will be directly influenced by the design and operating policies of the communication system. The truck dispatching problem mentioned earlier assumed that a central dispatching procedure could be devised because demands were completely known and deterministic. In many instances, however, complete information is not available at any one time because of the dynamic and perhaps random nature of the system, or because of the high cost of equipment (such as radios) to collect and transmit complete information. In such cases, rules are needed to guide operators in making immediate decisions based on information available to them locally. Figure 9 shows the shuttle system described earlier with the added restrictions that inventory cannot be stored at nodes.

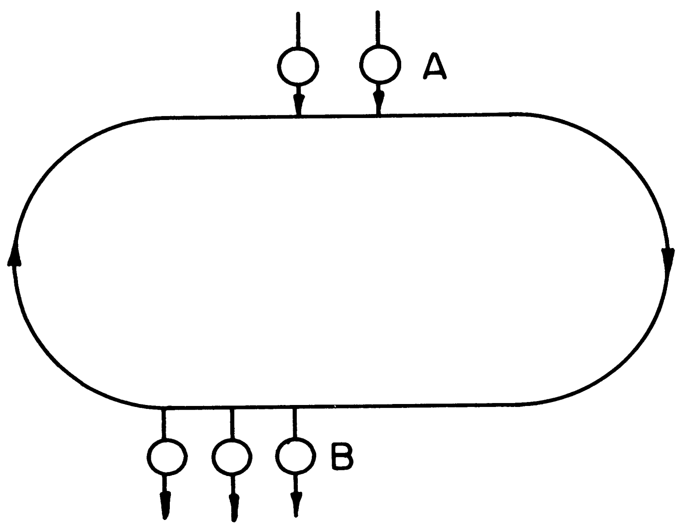


Figure 8. Hook Storage-Delivery Conveyor System.

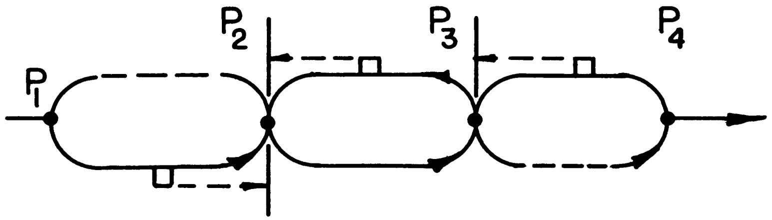
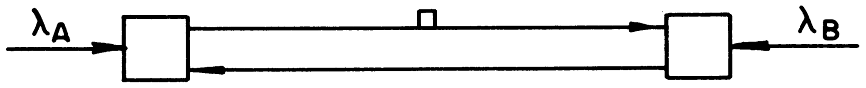


Figure 9. Shuttle Process With Communication.

Each carrier waits until the adjoining carrier arrives at their junction node to transfer material. On the portion of the path shown solid in Figure 9, a shuttle speeds up when it sees the adjoining carrier waiting. Will the system flow capacity be greater than without the visual communication? Contrary to expectation, investigations failed to show any significant improvement(21). A planning problem typical of shuttles serving random arrivals at multiple points is illustrated by Figure 10. If customers arrive randomly at two spatially separated points with mean rates λ_a and λ_b, which of two policies should the shuttle follow: remain where it becomes free, or return to the busier point(22)? Finding a policy for police patrol-car crusing which minimizes incidence of crime with known probability density, and the location of postal sorting-centers to optimally serve areas originating mail with spatially uniform probability are similar problems.

A criterion frequently proposed for use in arranging manufacturing facilities is to minimize the move-volume distance product of the flows between the fixed nodes of the material flow network. Figure 11 contains the essence of this problem for a simple case. Assume that four machines A, B, C, and D, with know volume of flow between each of the six pairs, are to be located in the areas 1, 2, 3, and 4, which are at known distances apart, so that the total move-volume distance is a minimum. Except for some observations on heuristic approaches to the solution(23), no formal practical algorithms are known to this quadratic programming problem.



POLICY A : SHUTTLE REMAINS WHERE IT BECOMES FREE

POLICY B: SHUTTLE RETURNS TO BUSIER POINT

Figure 10. Random Arrival Shuttle Process.

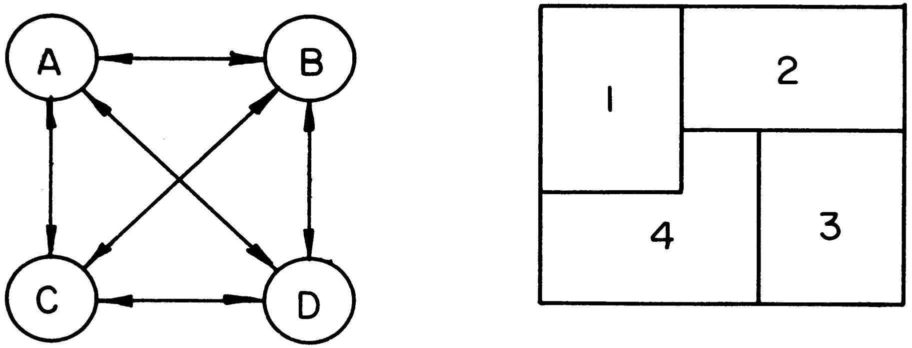


Figure 11. Static, Deterministic, Facility Location Problem.

The concept of service continuity is a key consideration in another (largely unexplored) location problem of considerable practical importance. In Figure 12, the circles represent independent facilities which can operate if and only if one or more of the connected support facilities (the squares) are operable. If one or more of the squares are removed by some random event, what is the probability that service can be maintained at all circles(24,25,26)? The analogy to problems of electrical service reliability in the face of possible failure of key transmission interconnections or generating stations is clear. The optimal location of food distribution centers relative to produce suppliers having some probability of crop failure is a problem with similar structure.

Having no explicit means of handling simultaneously all the variables typical of most facility design problems, we resort to the schematic diagram of Figure 13 which shows the relationship among the several sequences of sub-steps in a typical facility design process. The broad engineering and physical characteristics of the materials, processes, and handling equipment to be employed, are independent variables serving as hardware constraints on design feasibility. These constraints are analyzed in conjunction with forecasts of operating policies (the desired productive capacity, the manpower availability, shift utilization, for example), and the production and inventory communication systems and action rules. In the process of establishing the engineering and physical feasibility of the design, the designer will also compute the capacity and space requirements of

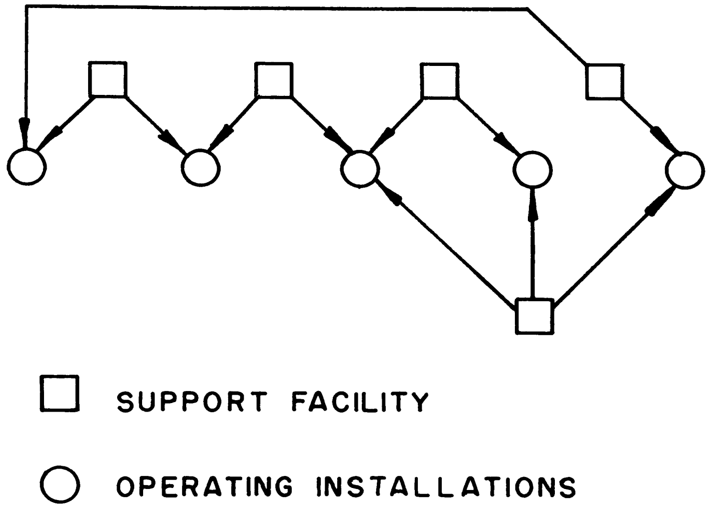


Figure 12. Multiple Correspondence Facility Service Probability.

the facilities, and locate major areas based perhaps on gross material flow links and capacities. Analysis of detailed machine locations and local handling methods follows. These analyses are based, for the most part, on assumptions that the parameters are constant in time. In most design practice in fact, the system behavior is examined at one projected point in time, and the merits of the design are evaluated by a jury of experts on this basis. The evaluation is followed by a return to those phases found to need readjustment, until the design is considered acceptable. In this process of converging on the final design, changes may be required in operating policy and/or the communication system, or different materials, processes or handling equipment may be selected or created from the stored knowledge of experience and the engineering sciences. Any particular block of the sequence in Figure 13 may need to be repeated many times because of the multiplicity of products, processes, or handling devices.

Early in this paper, several examples were given of costly modifications made to facility designs thought to be satisfactory at time of installation. The difficulties and the need for subsequent modifications arose because the dynamic behavior of various installations was understood and accepted only from results from the performance of the facilities themselves _after_ the installation was completed. Figure 13 is seen therefore to be more than a schematic for pre-installation facility design. The recurring cycle of facility adaptation or reconstruction during utilization as well as during design is included. A change in demand forecast for example, initiates a new cycle of adjustment or modification to the facility design. Although

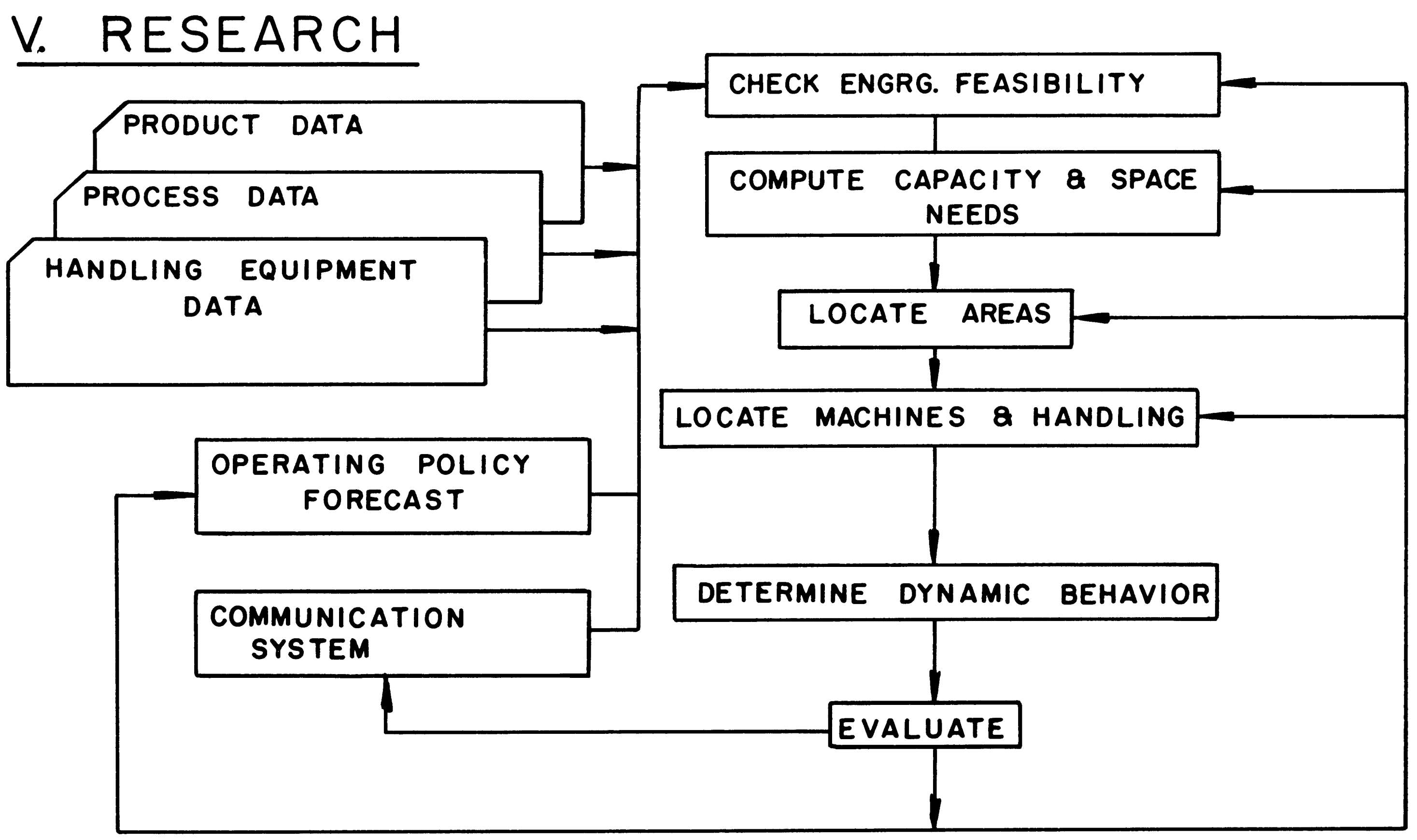


Figure 13. Facility Design Inputs and Sequence.

the visible symptoms of facility design deficiencies have been described in the literature, the study of facility adaptation as a process is virtually unknown. The potential savings from analysis of dynamic behavior during the design phases are evident and present a strong argument for more extensive use of simulation.

This recommendation for using simulation to study the dynamic behavior of facility designs is not to be accepted blindly however. An effective simulation will incorporate those variables most significant in influencing or altering the behavior characteristics under study. In most cases, flow simulations are generalizations of a queue network model in which the system behavior is studied with reference to a time dimension. A typical set of input variables for such a simulation(27) are listed in Figure 14, together with the parameters of system performance resulting as output. The appropriateness of such a simulation is studying production and inventory control is apparent, but its effectiveness in studying facility design is open to question. The following are typical of some criteria suggested for evaluating plant layout designs(28):

a) Proportion of distance materials move mechanically
b) Total distance moved
c) Proportion of machines movable in one shift to total number of machines
d) Proportion of total area used for aisles
e) Proportion of cubic volume utilized.

Admittedly these criteria are primarily static in nature, but they do not clearly indicate the need to recognize the spatial dimension in facility

IV. EVALUATION

2. SIMULATION

INPUT:

1. SCHEDULE POLICIES
2. PART OPERATION SEQUENCE, SET UP & OPERATION TIMES
3. NUMBER OF GROUPS, MACHINES PER GROUP, LABOR ASSIGNMENT
4. DISPATCH RULES
5. TRANSIT TIMES
6. ORDERS

OUTPUT:

1. GROUP LOAD
2. GROUP UTILIZATION
3. QUEUE BEHAVIOR
4. LABOR UTILIZATION
5. COMPLETIONS VS. DUE-DATES

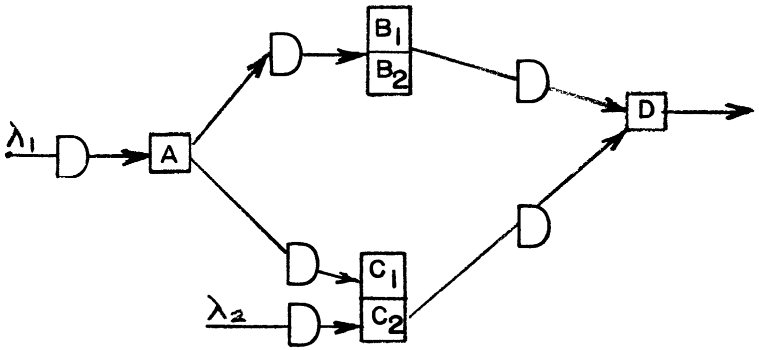
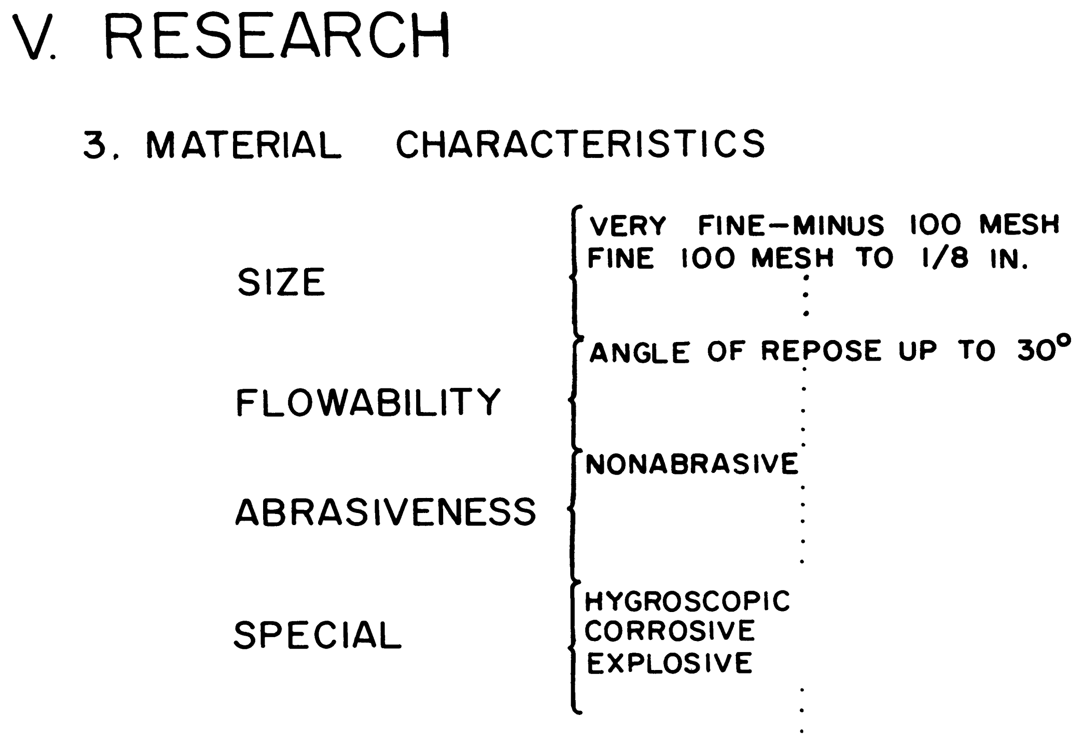


Figure 14. Flow Simulation Inputs and Output.

design. Dynamic spatial utilization criteria would not be directly obtainable from current simulations. A conspicuous exception is a simulation used to study efficient warehouse storage-block configuration and inventory control interaction(29). A more critical examination of criteria for facility design evaluation is feasible and needed now that dynamic interactions at a simple level can be observed through simulation.

Figure 13 also serves as a framework for relating current progress toward automating segments of the design process itself. The trend toward abstract representation and simulation of facility designs, and the prospect of automation of the design process imply that the operational characteristics of processes and materials can be studied and easily abstracted. In fact, of course, considerable research remains to be accomplished. Two examples suffice. First, the properties of a material most useful to describe its "conveyability" are not yet well defined. Research underway(30) is attempting to find the fundamental properties of bulk materials most significant in the selection of bulk conveyors. Some suggested properties are given in Figure 15. Many questions such as how to measure abrasiveness, are unanswered. Second, if we are to use probability distribution in a simulation in order that it may exhibit some of the randomness which seems to characterize flow systems, what distributions should we use? Few measurement studies of shop flow-characteristics appear in the literature even though knowledge of the general properties of arrival and service time distributions for plants and facilities is a necessary



V. RESEARCH

3. MATERIAL CHARACTERISTICS

SIZE	VERY FINE—MINUS 100 MESH FINE 100 MESH TO 1/8 IN. ⋮
FLOWABILITY	ANGLE OF REPOSE UP TO 30° ⋮
ABRASIVENESS	NONABRASIVE ⋮
SPECIAL	HYGROSCOPIC CORROSIVE EXPLOSIVE ⋮

Figure 15. Flow Characteristics of Bulk Materials.

prerequisite to meaningful simulation. A broad study of these properties might serve to usefully classify equipment and facilities by operational characteristics.(31)

Abstract mathematical modelling and system simulation has contributed to the efforts of the facility designer in many instances. The difficulty of achieving inexpensive and yet clear communication between operating personnel and system simulation specialists should motivate the development of compilers for design simulation and ultimately the automation of much of layout design practice.(35,36,37) Another impressive accomplishment would be the development of a general abstract structure, or theory of facility design, including theorems for spatial configuration and for the interaction between scheduling policies and design. With such a theory, designers will be provided with means to learn the effects of decisions before they become expensive errors.

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