AN EXPERIMENTAL INVESTIGATION OF MATERIAL HANDLING IN FLEXIBLE MANUFACTURING USING COMPUTER SIMULATION

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ABSTRACT

An important design issue for the automated factory of the future is the material handling function. Flexible manufacturing facilities demand an equally flexible material handling system. Material handling can have a significant impact on work-in-process inventory, and capacity requirements as well as material flow considerations. Since flexible manufacturing facilities are typically costly to design, install and maintain, direct experimentation is not feasible and analytical models give only an approximate solution at best. Due to the magnitude of the economics, even small errors of approximation can be significant.

Clearly, computer simulation can be a very effective design and analysis tool for the investigation of material handling processes. This paper presents the results of an experimental investigation of alternative control procedures for dispatching driverless (automated) vehicles to transport "move orders" between manufacturing cells or "islands". Dispatching methodologies examined include first-come-first-served, a dynamic adaptation of the assignment problem and a dynamic programming approach which seeks an optimal tour over the next two, three, etc. moves. Both the value of such optimum-seeking dispatching rules and the appropriateness of computer simulation as an effective design tool are discussed.

I. INTRODUCTION

Although it is somewhat of an over simplification, flexible manufacturing can be described as an attempt to bring flow shop (i.e., assembly line) technology to job shop production by recognizing and designing for the similarities in product and process structure. Functionally dissimilar production resources (typically machines) are grouped together into cells or "Islands" which can perform a limited number of distinct operations in a limited number of sequences. Unlike the assembly or transfer line, the manufacturing cell is not dedicated to a single product, but rather is used in the partial processing of a large number of similar products which share a commonality in design features and processing requirements. The manufacturing cell also differs from the job shop which is organized to group machines which perform the same function together. The high degree of automation and subsequent capital investment inherent in the design of flexible manufacturing facilities put strong pressures on the production planning and material handling functions to keep the utilization of equipment high and reduce work in process inventory. To do this, the methods of material handling need to be both flexible and responsive. Methods of material handling in industry can be loosely categorized by the type of equipment employed as either "fixed path" or "variable path." The prime example of fixed path methods is the conveyor which can be implemented in a variety of forms. Examples of variable path methods are the fork lift truck, the hand cart and the overhead crane system. With respect to flexible manufacturing, the limited paths which material can take within a manufacturing cell present strong arguments for the use of fixed path technology. Among manufacturing cells, the multiplicity of routes and the economics of transportation usually dictate the use of variable path techniques. There is considerable interest in exploring such options as automated "driverless" vehicles which can be routed under the control of a central computer (perhaps even a micro-processor).

A prerequisite to the effective and efficient implementation of computer controlled flexible material handling systems is

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the development of vehicle routing algorithms which perform well in the dynamic environment of discrete parts manufacture.

This paper documents preliminary efforts to study the vehicle routing problem, under dynamic demand for service, using computer simulation models as a test framework. Section II will review the more relevant literature concerned with the development and use of simulation models to analyze alternative manufacturing and/or material handling systems. Section III will discuss the choice of system performance measures used for this study. Two dynamic routing algorithms are presented in Sections IV. A simplistic example is presented in Section V with experimental results and a discussion of their implication. Finally, Section VI comments upon the use of computer simulation as a design and evaluation methodology with respect to flexible manufacturing systems, and directions for further research.

II. REVIEW OF THE LITERATURE

The use of computer simulation to study the operation of a job shop has received a fair amount of attention in the research literature over the past twenty-five years. The predominant focus of past studies, however, has been the evaluation of scheduling (or priority dispatching) rules to sequence job in queue into processing operations. Conway et. al (4) reported the first significant simulation experiment to study job shop priority dispatching rules with respect to such measures as mean job lateness, machine utilization and average dollar-days lost in holding work-in-process inventory. This work was extended by Conway (5, 6) to a more comprehensive analysis of work-in-process inventory and job lateness. Similar contemporary studies of job shop scheduling were performed by Baker and Dzielinski (2), LeGrande (16) and Brown (3). The model developed by LeGrande represented a real plant configuration and was driven by real operational data collected from the General Dynamics El Segundo facilities. Hottenstein (15) developed a GPSS model to extend the experimental analysis of two dispatching rules (first-come-first-served, and shortest-processing-time) to manufacturing systems consisting of small sub-assembly lines as processing centers within a job shop. Fryer (13) considered the concomitant decisions of job dispatching and labor allocation to machines. Adam and Surkis (1) have used simulation to evaluate dynamic dispatching rules which change the priority of queued jobs based on changes to the state of the system, and the interval length between priority re-evaluation.

The study of job shop material handling from a systems optimization perspective has received far less attention in the literature. An early paper by Fetter and Galliher (11) cited the potential of queueing theory and simple queueing models to evaluate cost, service and utilization issues with respect to variable path material handling equipment. Donaghey (9) proposed a general, but simplistic, descriptive simulation for material handling. Schwarz et. al. (18) used a simulation model to study scheduling and placement policies in an automated storage and retrieval system. Phillips (17) advocated the use of simulation modeling to design and analyze material handling systems making reference to two applications for fixed path systems.

Relevant related papers can be found in the more general literature of transportation research. Curry and Schuerman (8) proposed a simulation model for the transportation of aircraft parts requiring specially designed carriers, between contractors. Tillman and Cochran (19) developed a heuristic solution to optimal routing of delivery vehicles. Gavish and Schweitzer (14) developed an algorithm to route trucks so as to combine pick-ups and deliveries thereby reducing deadheading. Cook and Russell (7) developed a heuristic method to route vehicles with additional constraints on the time interval over which pick-up and deliveries may be made. They used a simulation model to test their methods.

III. MEASURES OF PERFORMANCE

In general, the mission of a material handling system is to support the manufacturing process. To this end, its objectives and performance measures should be closely aligned with those of the production organization. Two key goals of production management are cost reduction and schedule attainment.

Material handling can have a pronounced affect on manufacturing cost in two ways. First, the cost of providing material handling services is an indirect cost of production (i.e., overhead). More important, the material handling system has a major impact on the amount of work-in-process inventory (WIP) allowed to accumulate in the production system. The function of WIP is to act as a buffer between sequential manufacturing operations. This removes the need to synchronize operations closely in order to avoid delays and/or shutdowns. To be effective, WIP should be located in front of the next operation. This is the job of the material handling system, and the degree to which it performs this task determines the effectiveness of WIP. In addition, the material handling function is a major contributor to the lack of synchronization of sequential operations. An effective material handling system eliminates the need for a large WIP. For our analysis we will use average WIP as a key measure of performance for alternative deployment-routing procedures to be studied.

The second goal, schedule attainment, can often be of more importance to manufacturing management than cost, as future business success is heavily dependent upon meeting current obligations to its customers. To accurately measure schedule attainment requires a tracking of due dates and completion dates. Rather than deal directly with this additional demand for information and model complexity, we have chosen instead to use mean flowtime as a surrogate measure for schedule attainment. The flowtime for a job is the total time that the job spends in the system including both processing and delay periods. We are tacitly assuming that a low mean flowtime implies a low mean time spent in queues. This in turn, we assume, will result in an improved ability to meet scheduled due dates.

Finally, we will also measure the utilization of the driverless vehicles. Care needs to be taken in evaluating the significance of this measure. A high vehicle utilization does not necessarily indicate superior performance. Indeed, high utilization will result in larger move request queues, higher WIP and may significantly degrade the utilization of manufacturing resources.

IV. APPROACHES TO NEAR OPTIMAL ROUTING

In practice, there are two methods of organizing the deployment of variable path material handling equipment in a production facility. The most common method is to assign vehicles to organizational units such as departments or shops. The assigned vehicle then services the material handling needs of its department exclusively. While this scheme facilitates a tight control of material handling resources, it usually leads to significant cases of underutilization.

In plants which have a separate production control organization, it is possible to incorporate the material handling function under the control of a single centralized dispatching unit. The advantages are clear. Vehicles can be routed among departments in response to demand and priority, with resulting improvements in both utilization and service. The major disadvantages are in the increased importance of timely communication and the loss of direct control (out of sight, out of mind). Consequently, the centralized dispatching of vehicles is often given up as impractical.

The development of computer controlled automated driverless vehicles can overcome the aforementioned problems if effective and efficient routing algorithms can be created to perform the dispatching function. The easiest dispatching rule to implement would be to assign "moves" to vehicles on a first-come-first-served (FCFS) basis. Because of its simplicity, this method serves as a baseline against which other deployment-routing algorithms will be judged. The characteristic of the flexible manufacturing system which makes optimal routing a nontrivial problem is the dynamic manner in which move requests are generated. While a considerable amount of research has been done on vehicle routing, all work, which this author is aware of, deals with the deterministic case in which an optimal routing is constructed in full knowledge of a fixed set of move requirements. In the case of the flexible manufacturing facility (and the job shop) the optimality of a given routing assignment will possibly change as work orders complete processing at a given manufacturing cell and require transportation to the next operation. This has two implications for the design of a routing algorithm. First, the planning horizon is an important parameter in any routing procedure. Incremental gains in performance will diminish as the planning horizon is extended because of inherent change in the basic configuration of the routing problem. To be successful, a routing algorithm must be flexible, and easily re-evaluated as conditions change. Secondly, because of the dynamic environment in which a deployment-routing system must operate, it is not possible to build a sufficiently detailed analytically tractable model to evaluate performance. Computer simulation is the only feasible method of testing alternative routing algorithms short of constructing the real system itself.

A DYNAMIC PROGRAMMING APPROACH

One of the main deficiencies of the FCFS routing priority is the inability to couple "drop" trips with "pick-up" trips. To do so could greatly reduce the proportion of time that a vehicle is in transit without a load (termed "deadheading") and reduce the total time necessary to complete a given set of move requests. One approach to removing this inadequacy is to have each vehicle line up its pick-ups and drops so as to reduce the total travel time to execute the next n (n=1,2,3...) moves. This routing procedure is easily formulated as a dynamic programming problem as shown below. A dynamic program is described by the definition of its stages, state variable(s), reward function and decision variable. The reader is referred to Dreyfus and Law (10) for a comprehensive discussion of dynamic programming.

STAGES. The stages in this DP formulation are the sequential moves between departments. The first stage is always the next move to be made by the vehicle. The second stage is the move to be made after the next move, and so forth.

STATE VARIABLE. The value of the state variable is the present location (i.e., department) of the vehicle at the current stage.

DECISION VARIABLE. The decision variable at each stage is the location from which the vehicle was routed to arrive at the present state. Note that the recursion is performed backwards from the last stage in the time horizon to the first stage.

REWARD FUNCTION. The reward function at each stage is the sum of the travel time required to execute the move prescribed by the state at this stage plus the total travel time attributed to the optimal (i.e., minimum time) sequence of state realization (i.e., moves) at all subsequent stages (remember, we are using backwards recursions).

The objective of the DP formulation is to minimize the total travel time (or distance) necessary to execute a fixed number of move requests. This fixed number is the number of stages and is, in effect, a planning horizon which is set by the analyst. Clearly, a point of interest is the relationship between the number of stages and the system performance. Note that although the DP solution will dictate a tour consisting of n sequential moves, moves past the "next" move will not necessarily be optimal. This is due to the possible changes in the list of jobs to be moved.

It is also important to note that optimization is performed on a very localized basis as the case of each vehicle is considered separately and independently. It is reasonable to suspect that a DP routing algorithm will give good results when the volume of material handling activity is light or when only one vehicle is to be used. It will usually pick the closest available vehicle and will reduce deadheading. Under heavy traffic conditions its performance may degrade rapidly. A major advantage of the DP routing algorithm is the ease with which an implementation program can be programmed and the very modest requirements in computer memory and execution time.

AN ASSIGNMENT APPROACH

A second approach to optimum routing is an adaptation of the classical assignment problem in which vehicles are assigned to move requests so as to minimize the total time required for each vehicle to complete its current drop (if any) and execute the next move (to be assigned). The reader is referred to Wagner (20) for details of the assignment problem. Clearly, this method is optimal only in the sense of a single "stage." As each new move request is generated, the assignment of vehicles to moves should be re-evaluated.

There are several algorithms which have been developed to solve the assignment problem. We have chosen to use the "out-of-kilter" algorithm which formulates the problem as a flow network. Nodes are used to represent vehicles and move requests. Arcs run from vehicle nodes to move nodes and have a capacity of one. A solution in which an arc has a positive flow indicates an assignment of the source node (vehicle) to the sink node move). Reference Figure 1(a). The network formulation of the assignment problem is particularly convenient for our application, because of the ease with which new assignment problems can be reformulated and solved from the previous problem. As a new move request is generated it is represented as an additional node and arcs as shown in Figure 1(b). The out-of-kilter algorithm is an iterative procedure and must start from some initial set of positive flows. The set of arrays used to represent the network are easily updated to accommodate the added node and arcs and the previous (optimal) solution provides a good initial solution to the new assignment problem. This typically will facilitate a quick convergence to the new optimal solution. A FORTRAN code of the out-of-kilter algorithm is given in Wolsey and Swanson (21).

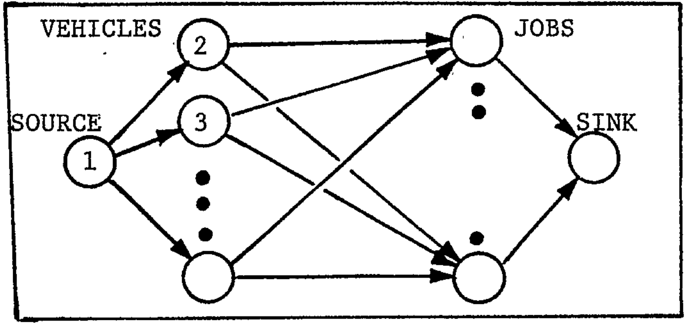

Figure 1(a) Network Representation of Assignment Problem

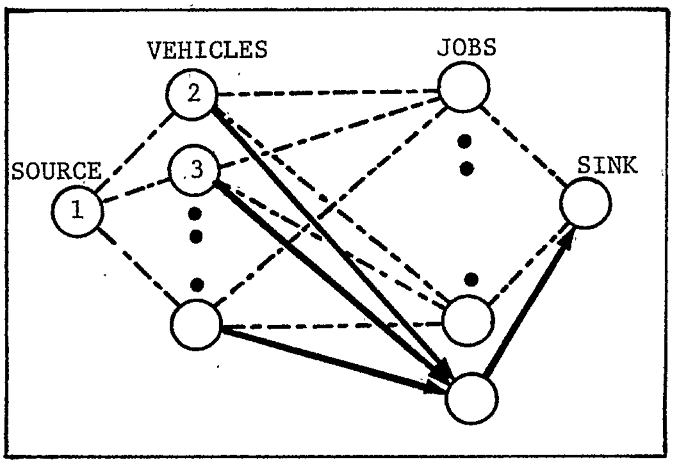

Figure 1(b) Addition of New Move Request to Network

V. AN EXAMPLE

The simulation models reported in this paper were developed with two objectives in mind. First they were designed to serve as a testbed in which to conduct empirical investigations of alternative algorithms for the automated deployment-routing of driverless vehicles in flexible manufacturing systems. Such research is definitely applied but generic in nature. Secondly, it is intended that these models be appropriate for the design and evaluation of real specific flexible manufacturing systems. To this end, the models and the conceptual context in which they are posed, have and will continue to evolve in structure and direction as more experience is gained in actual applications.

With respect to the first objective, we offer a simplified example which will both illustrate the method of application and offer some insight into the performance of the deployment-routing algorithms proposed in Section III.

Consider a small shop consisting of three manufacturing cells and a central stores shown schematically in Figure 2. For ease of exposition we will refer to the stores as the "fourth" department. Flow between departments is characterized by a transition matrix; refer to Table 1(a). Transport times are given in Table 1(b). Jobs (or work orders) are created and introduced into the system through the central stores. Each job consists of a number of unit loads determined from a binomial distribution with parameters n=5 and p=0.5. Each unit load will utilize the full capacity of the driverless vehicle. The time between job releases is exponential with a mean of 0.05 days (i.e., an average of 20 releases per day). Each department (or cell) is characterized by the capacity of its drop area (in unit loads) and the mean processing time per unit load; this information is summarized in Table 2. Processing time per unit load for each job is drawn from an exponential distribution. Set-up times are assumed to be zero.

SCHEMATIC OF JOB SHOP

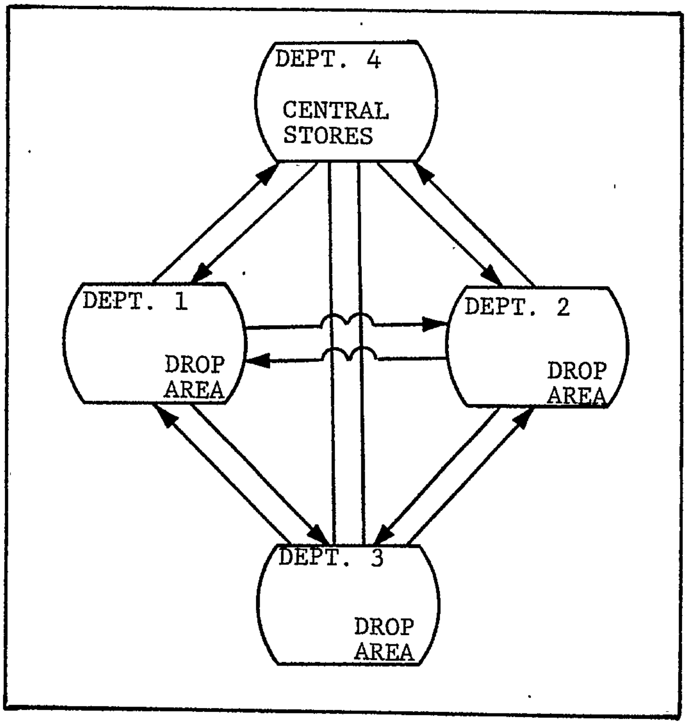

Figure 2 Example with Three Manufacturing Cells and a Central Stores

FROM DEPARTMENT	TO DEPARTMENT 1	2	3	4
1	0.00	0.40	0.40	0.20
2	0.10	0.00	0.70	0.20
3	0.10	0.10	0.00	0.80
4	0.50	0.40	0.10	0.00

Table 1(a) Product Flow Transition Probability Matrix

FROM DEPARTMENT	TO DEPARTMENT 1	2	3	4
1	0.00	3.00	5.00	6.00
2	3.00	0.00	3.00	4.00
3	5.00	3.00	0.00	3.00
4	6.00	4.00	3.00	0.00

Table 1(b) Transport Time Matrix All Values in Minutes

DEPARTMENT	MEAN PROCESSING TIME/UNIT LOAD	DROP AREA CAPACITY
1	0.75	150
2	0.50	70
3	0.25	70
4	-	∞

Table 2 Mean Processing Time Per Unit Load (Hours) and Drop Area Capacity (Unit Loads) for Each Department

To explore this exemplary scenario and other flexible manufacturing systems a set of simulation programs were coded in SIMSCRIPT II.5. All programs are copies of a basic prototype model with slight variations to implement the deployment-routing procedures as callable subroutines. This basic prototype models the jobs and vehicles as SIMSCRIPT processes and the manufacturing cell and associated drop area as SIMSCRIPT resources.

Simulation runs were made for the above scenario operating with five driverless vehicles, for each of the following deployment-routing algorithms:

(1a) Move requests are placed in a single move queue ordered on a first-come-first-served discipline (FCFS). All unit loads of a job are assigned to a single vehicle.

(1b) Move requests are placed in a FCFS que as in 1a. Any number of available vehicles are allowed to transport the unit loads of job.

(2) Move requests are placed in a move queue ordered on shortest transport time. Only one vehicle is allowed to transport a single job, as in 1a. This dispatching rule is similar to the "shortest operation" rule used to minimize makespan in single machine scheduling.

(3a) Unit loads of a move request are assigned to vehicles by the dynamic programming algorithm of Section IV with two stages.

(3b) Unit loads are assigned by the DP algorithm with five stages.

(4) Vehicles are assigned to move unit loads by the assignment algorithm of Section IV.

Each run was carried out for 40,000 job completions after the system had obtained stability. The results for all six runs are summarized in Table 3. The autoregressive analysis routines contained in Fishman (12) were used to compute 95% confidence intervals for the mean flow time.

Several interesting observations are immediately apparent from the data in Table 3. First, dispatching jobs (consisting of one or more unit loads) to a vehicle (1a) is clearly inferior to all other methods examined with respect to all three performance measures. This is the routing procedure most likely to be used in practice when, and if, centralized vehicle dispatching can be implemented in a job shop facility. The poor performance is mainly attributable to the assignment of one vehicle to one job at a time. Routing method 1b allows for the assignment of unit loads to vehicles (also FCFS) and results in a significant improvement in performance, cutting mean flow time

METHOD	MEAN FLOW TIME	95% CONFIDENCE INTERVAL FOR MEAN FLOW TIME LOWER	UPPER	UTILIZATION	QUEUE LENGTH
1a. FCFS (job)	1.39761	1.24862	1.54659	94.7%	12.2
1b. FCFS (unit load)	0.79627	0.76198	0.83056	83.2%	3.3
2. Shortest Transport Time (job)	0.98397	0.94730	1.02064	90.9%	4.6
3a. D.P., 2-Stage	0.69469	0.67345	0.71593	75.4%	2.8
3b. D.P., 5-Stage	0.69138	0.66741	0.71535	75.6%	2.4
4. "Assignment Problem"	0.70951	0.65804	0.76098	75.9%	2.9

Table 3 Experimental Results

approximately in half and reducing WIP by a factor of roughly three and one half. Splitting jobs up for transportation purposes also appears to be superior to ordering the queueing discipline by shortest transport time (method 2).

The results for methods 3a, 3b and 4 are strikingly similar. In all three cases, a significant improvement is evident. This lends strong support to the case for the development and application of optimum-seeking deployment-routing algorithms. An interesting result for this scenario is the lack of significant change induced by extending the time horizon from two to five moves in the DP algorithm. This may be due to the moderate activity level of this particular example, with average WIP of 2.8 and 2.4 unit loads, there is a small likelihood of having four or five moves for which to plan. For this example, there appears to be little difference in results between optimization strategies which focus on individual vehicle operation over a fixed number of stages (i.e., the DP algorithm) and those which focus on the allocation of all resources at a single stage (i.e., the assignment algorithm). One suspects that this will not be true in general.

V. CONCLUDING COMMENTS

The purpose of this paper is not to claim the superiority of one deployment-routing algorithm over others, but rather to advocate by discussion and example that there is much to be gained in the pursuit of such applied research and to argue that computer simulation is a very useful tool for this effort. The data in Table 3 clearly does more to raise questions than to provide answers. Future work should focus in two directions. First, there are other approaches to optimum-seeking algorithms of varying degrees of complexity which deserve consideration. This clearly can become an interesting research problem, even for those with a more theoretical bent.

Secondly, proposed deployment-routing methods need to be tested under a wide range of operating scenarios. Such scenarios should be tailored as closely as possible to correspond to <u>real</u> flexible manufacturing systems. Unfortunately, such data is hard to come by and usually can not be released for publication. Particular attention should be paid to identifying the system characteristics which tend to make one methodology perform better than others. It is reasonable to suspect that a given algorithm will not be superior under all operational circumstances. This hypothesis needs to be examined through valid experimentation. Computer simulation is the most effective and efficient methodology with which to perform this investigation.

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