

TECHNICAL RESEARCH REPORT

Current Research on Manufacturing Shop and Material Handling System Design

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T.R. 95-102



*Sponsored by
the National Science Foundation
Engineering Research Center Program,
the University of Maryland,
Harvard University,
and Industry*

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Abstract

The importance of the manufacturing shop design in the successful operation of a production system is well known and as a result, significant research has been devoted to this area. This paper reviews important literature in various aspects of manufacturing shop design including layout, material flow path design, and transporter fleet sizing and routing. In addition, the paper focuses on contributions to integration issues, such as the design for operation of material handling systems, and the concurrent design of the shop layout and the transportation system. Research studies in these areas are critically examined, and emerging opportunities for research are identified.

Keywords: Facility Layout, Material Handling Systems, Manufacturing Systems, Material Flow Network Design, Vehicle Routing, Integrated Shop Design

1 Introduction

Manufacturing facility design is a key factor for the successful operation of a manufacturing firm. A well designed facility results in efficient material handling and short transportation times between resources, leading to decreased production cycles and manufacturing costs (Francis *et al.* 1992; Jajodia *et al.* 1992; Sims 1991). In such facilities the flow of material and sub-assemblies between operations is simplified, and the tracking of jobs is easier, since their movement is continuous and visible (Eastman 1987). Thus, production management becomes more effective, and on-time delivery performance is improved, consistent with *Just-in-time* manufacturing practices (Schonberger 1984). The quality of the products is also enhanced, since the amount of material lost or misplaced on the shop floor is reduced, and handling, which usually degrades the product quality, is decreased (Eastman 1987). Finally, through well-planned material handling, queues in resource input and output stations remain small, since material is transferred in a just-in-time manner between resources (Eastman 1987); thus, work-in-process levels are kept low and inventory holding costs are decreased (Proth and Souilah 1992).

Due to the importance of the facility design problem, significant research has been devoted to its constituent subproblems, i.e., the physical placement of the resources on the available area of the shop floor, and the design of the material handling system (MHS). Apple and McGinnis (1987) underline the need for *close cooperation and continuous interface* between facility layout and MHS design and planning, since the layout of the facility influences greatly the design and control of the material handling system.

Figure 1 provides an overview of a commonly used framework for manufacturing facility design. The major components of this framework are:

- *Department/cell formation.* This stage organizes the set of production resources into groups. Each of these groups may comprise functionally similar machines as in traditional job-shop arrangements, or functionally dissimilar machines that are dedicated to the production of part families or parts that share common operations, as in cellular arrangements or flexible manufacturing systems. Departments can be formed in a straightforward manner based on the characteristics of the production resources (Ang

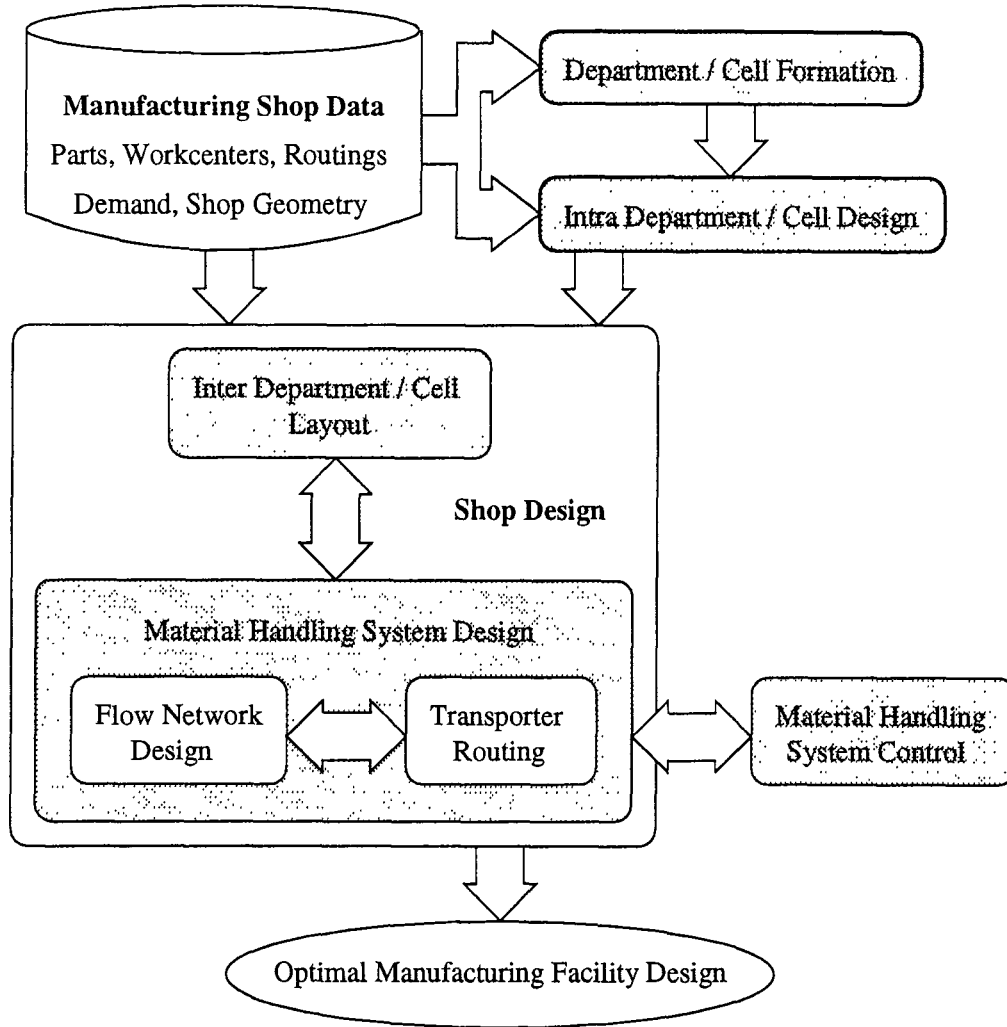


Figure 1: Manufacturing facility design framework

and Willey 1984). For formulations and solution approaches to the cell formation problem, see (Harhalakis *et al.* 1990; Harhalakis *et al.* 1994; Jajodia *et al.* 1992).

- *Intra-department/cell design.* It comprises the physical layout of the manufacturing resources within each department/cell. The relative arrangement of the resources depends upon their interactions and the type of intra-cell material handling system employed (Hamann 1992). The particular characteristics of the intra-cell MHS lead to different layout configurations such as linear single row, double row, circular etc. (Kusiak and Heragu 1987). For efficient methods of intra-cell design see (Delaney *et al.* 1995; Minis *et al.* 1990; Lu 1993).

- *Shop design.* This stage addresses the placement of the resource groups on the available area of the shop floor and the design of the inter-group material handling system.

The focus of this paper is this last stage, i.e., the design of the manufacturing shop and its two major subproblems. In the context of manufacturing facilities, MHS design includes two highly inter-related subproblems, as shown in Figure 1: i) Design of the topology of the flow network that provides the resource inter-connections, and ii) determination of the number of transporters necessary to transfer parts/batches between resources as well as allocation of the inter-resource moves to these transporters. Subproblem (ii) is referred to as *transporter routing* both in Figure 1 and throughout this paper to be analogous to the vehicle routing problem (Golden and Assad 1988), with which it shares significant similarities. To implement the final facility design, dispatching and routing rules have to be selected for on-line transporter control. Both have a significant effect on the response of the manufacturing system and, consequently, affect the production throughput, equipment utilization, product cycle times and system flexibility (Jacobs-Blecha and Goetschalckx 1992).

The major problems of shop design have been addressed with various degrees of success in the literature. In the subsequent sections we will review significant research efforts and we will examine approaches that attempt to formulate and solve the two subproblems through integrated design methods. Specifically, Section 2 reviews a variety of solution approaches for the heavily studied layout problem. Section 3 summarizes recent research concerning the design of the material flow network, while Section 4 presents methods for evaluating the transporter fleet size and determining the sequence of operations performed by each active transporter. Section 5 surveys methods for the on-line material handling system control problem in terms of dispatching and routing rules. Section 6 presents recent work towards the integration of the shop design. The paper concludes in Section 7 by identifying opportunities for future research.

2 Facility layout

A rich body of literature addresses the placement of manufacturing entities (resources) within the area of the shop. In most cases a Quadratic Assignment Problem (QAP) formulation is employed. The objective is to minimize the total weighted distance between entities, in which weights reflect adjacency priorities or material flow volumes (Francis *et al.* 1992). Since the QAP is *NP*-complete (Sahni and Gonzalez 1976), research efforts have mainly concentrated on the development of heuristics to obtain near-optimal solutions. Kusiak and Heragu (1987) have classified the existing heuristics in: i) construction methods, ii) improvement methods, iii) hybrid methods, and iv) methods based on graph theory. The most representative heuristics of each type are examined below. At the end of the section, various simulated annealing approaches to the layout problem are presented.

In construction methods a layout is developed *ab initio*, i.e., entities are assigned to a site, one at a time, until a complete layout is obtained. CORELAP (Lee and Moore 1967) employs connectivities and preference relationships between entities, which may reflect material flow volumes, to compute a *total closeness rating* for each entity. It proceeds by assigning the entities to locations in decreasing order of this rating. ALDEP (Seehof and Evans 1967) utilizes a preference table to indicate the proximity desirability codes between entities, i.e., weighting factors that measure the desirability of entities to be near each other. These factors may represent the inter-resource material flow or other proximity functions. The layout construction proceeds in a manner similar to CORELAP; however, several different configurations are generated, starting from different initial entities, and the best one is proposed for final implementation. PLANET (Apple and Deisenroth 1972) also assigns entities iteratively to shop locations, based on the relationship (material flow or other proximity function) between each candidate and the entities already assigned. Other construction algorithms include MAT (Edwards *et al.* 1970), SHAPE (Hassan *et al.* 1986) and the FMS machine layout algorithms of Heragu and Kusiak (1988). All construction-based design methods have a common limitation; the solution obtained is usually a local minimum and is highly sensitive to the sequence of entity assignments. This is attributed to the fact that these procedures are *greedy* and, thus, myopic. In addition, the majority of these methods consider the entities to be equidimensional and do not use

rigorous geometric constraints, thus, resulting in layouts with area conflicts that can only be resolved *a posteriori*.

Improvement methods start from an initial solution to which systematic exchanges between entities are made until a satisfactory configuration is obtained. The most widely known among them is the steepest descent pairwise interchange procedure, CRAFT (Armour and Buffa 1963; Buffa *et al.* 1964). A similar method, which requires less computational effort than CRAFT, was developed by Nugent *et al.* (1968). Hillier (1963) and Hillier and Connors (1966) proposed an improvement method that is based on a *move desirability* table. This table indicates the changes in the value of the objective function if each entity is moved in each of four orthogonal directions (up, down, left and right), and the solution procedure selects the configuration change that results in the largest decrease of the objective function. This method has been revised by Picone and Wilhelm (1984). O'Brian and Abdel Barr (1980) complement a pairwise interchange procedure similar to CRAFT with an interactive stage, in which the user determines the final layout. Golany and Rosenblatt (1989) rank the shop locations in ascending order of the cumulative distance between each location and all other locations, and the resources in descending order of the material flow volumes between each resource and all other resources. During the initial assignment phase, locations and resources are matched according to the order they appear in the corresponding lists. Consequently, pairwise interchanges of entities are performed to improve the solution. Improvement-based design methods typically converge in local optimum layout solutions and are very sensitive to the initial layout provided. The reason is that only configuration changes that improve the objective function are accepted at each step of these algorithms. However, improvement methods tend to yield layouts of better quality than those obtained by construction procedures (Ioannou 1995). As is the case in construction methods, the majority of improvement methods consider entities to be equidimensional resulting in geometrical conflicts.

Hybrid methods combine the characteristics of construction and improvement methods. FLAC (Scriabin and Vergin 1985) and DISCON (Drezner 1980; 1987) are examples of hybrid methods. DISCON (Drezner 1980) creates a diagram in which each entity is represented by a disk. The disks are connected through springs with elasticity constants proportional

to the entity relationships. Overlapping is prevented by entity repulsion caused by spring compression. The system is modeled by a set of differential equations. A dispersion phase, in which the disks are placed apart is followed by a concentration phase which, after some transient motion, brings together entities with high spring constants. Drezner (1987) refined DISCON using eigenvalue theory. Although hybrid methods combine the advantages of construction and improvement methods, they share common drawbacks with them, including sensitivity to the initial assignment and convergence to local minima.

Graph theory-based methods use a weighted graph to represent the relationships between entities of a manufacturing facility (Foulds 1983; Goetschalckx 1992). Positive weights represent material flow volumes, while negative weights reflect environmental incompatibilities, such as those caused by noise and vibration. The goal is to place entities with a highly positive relationship next to each other, while entities with negative relationship are separated. When maximal relationships between adjacent entities are targeted, a maximum weight subgraph with edges only between adjacent entities is constructed (Carrie *et al.* 1978; Seppanen and Moore 1970). The latter can be converted to a feasible block layout only if it is planar, i.e., if it can be drawn in a two-dimensional plane without any of its edges crossing each other (Seppanen and Moore 1970). The adjacency graph and the block layout are dual graphs and, thus, contain the same information. The construction of the maximum weight subgraph can be modeled as a Maximum Weight Planar Subgraph problem, which has been proven to be *NP*-complete (Garey and Johnson 1979). Several heuristic techniques have been developed to solve this problem and are surveyed in Foulds (1983).

Goetschalckx (1992) presented a layout heuristic based on hexagonal, maximum weight, planar adjacency graphs, and Montreuil *et al.* (1987) developed a *b*-matching model for adjacency graphs. Substantial user interaction is required to use such models in facility layout problems, since the planar property is not ensured. Montreuil and Ratliff (1989) utilized cut trees to obtain a relationship graph which is transformed to a block layout by the designer. The quality of the layout is dependent on the user expertise and no optimality is guaranteed. Graph theory-based methods do not account for area constraints; furthermore, since the entities are represented by nodes of the associated graph, a second

design stage is required to transform the final graph to a feasible layout (Montreuil *et al.* 1993). Montreuil *et al.* (1993) formulated a linear programming problem to transform the output of a design skeleton into a net facility layout that accounts for entities and facility sizes and shapes. However, their approach is limited to rectangular entities.

The simulated annealing (SA) method, proposed by Kirkpatrick *et al.* (1983) for combinatorial optimization problems, succeeds to a great extent in overcoming both the sensitivity of the solution to the initial configuration and its convergence to local minima. This is accomplished by allowing uphill configurations by a certain probability, which decreases as the algorithm progresses. Wilhelm and Ward (1987) showed that SA is a promising approach for the QAP, though sensitive to a number of SA parameters. Heragu and Alfa (1992) proposed a hybrid SA method for the facility layout problem which uses the modified penalty algorithm of Heragu and Kusiak (1991) to generate an initial solution and improves this solution using SA. The modified penalty method (Heragu and Kusiak 1991) transforms the constrained layout problem into an unconstrained one by including the constraints in the objective function. The resulting problem is solved by the Powell algorithm. For some example problems, the hybrid SA produced the best known solutions. Kouvelis *et al.* (1992a) showed that SA can lead to significantly improved solutions by allowing only machines that share exceptionally large flows to be adjacent. Jajodia *et al.* (1992) and Proth and Souilah (1992) present two simulated annealing-based algorithms to obtain near-optimal manufacturing shop layouts. Their approaches adequately consider the actual dimensions of both the shop and the resources. Genetic algorithms, which exhibit similar behavior to SA methods, have also been proposed for the facility layout problem. The *slicing tree* method of Tam (1992) is an example of such algorithms. This method uses a symbolic layout representation that is based on strings of cut operators and resource indices, and applies reproduction, crossover, and mutation operators in the evolution schema that generates new layouts.

It is worth noting that optimal procedures for the QAP are available for small size layout applications (Bazaraa 1975; Hanan and Kurtzberg 1972). Barnes (1993) developed a procedure for computing tight bounds of the QAP, and Al-Khayyal and Larsen (1993) suggested a linear programming relaxation which they solved by a branch-and-bound algorithm to find an “approximate global optimal solution”. Foote *et al.* (1993) proposed a

branch-and-bound technique based on the cluster plot of Drezner (1987). The technique uses early search on particular branches for early fathoming. The branch-and-bound tree proceeds by spinning off from a corner of the facility, and entities with larger areas are tested first. However, only rectangular entities are considered, and no efficient lower bounds are proposed, resulting in high computational cost.

Additional research efforts on the areas of multi-level facilities, stochastic and dynamic layout, multi-objective layout optimization, and special layout configurations (e.g., single loop layout), can be found in a recent survey by Meller and Gau (1995).

3 Material flow path design

From the survey of the previous section, it is evident that a large body of literature has focused on the layout problem, and several powerful methods have been developed to place the shop resources in such a manner that inter-resource material handling is minimized. However, although the material handling effort also depends upon the topology of the network connecting the resources, limited attention has been paid to material handling network design.

The research in this area has focused on a few types of MHS, such as Automated Guided Vehicle Systems (AGVS) (Wilhelm and Evans 1987). For the case of unidirectional AGVS with fixed aisles, the problem of determining the path directions for a predefined material flow grid was first formulated by Gaskins and Tanchoco (1987) as a zero-one integer programming problem. This model has been extended by Kaspi and Tanchoco (1990) and Sinriech and Tanchoco (1991). Goetz and Egbelu (1990) developed a heuristic approach that reduces the number of constraints required to guarantee the unidirectionality of the paths. For the same type of MHS, Venkataramanan and Wilson (1991) presented a similar but more compact formulation based on strongly connected graphs. They also extended the model to account for unloaded flow information. All these models were solved by different branch-and-bound algorithms (Kaspi and Tanchoco 1990; Kim and Tanchoco 1991; Sinriech and Tanchoco 1991; Venkataramanan and Wilson 1991). Kouvelis *et al.* (1992b) proposed several heuristics to obtain near-optimal solutions for the above problem and analyzed

their computational complexity. They have also developed a solution technique based on simulated annealing. Their results showed that running the simulated annealing algorithm starting from the best heuristic solution, yielded the best guide path directions.

Seo and Egbelu (1995) have considered unloaded material flow in unidirectional AGV flow paths. They proposed a two stage approach that completes a partial flow network (i.e., a network that does not connect all input and output stations) in the most efficient way. Kim and Tanchoco (1994) addressed the same problem by appropriately augmenting the inter-station flow matrix before the design of the guide path. Sharp and Liu (1990) developed an analytical method for configuring fixed-path, closed-loop MH systems based on a mixed integer programming formulation. Egbelu and Tanchoco (1986) also studied the merits of bidirectional AGVS. Their simulation results showed that if bidirectional systems are used, the efficiency and productivity of the manufacturing shop is increased, compared to unidirectional AGVS, at the cost of control complexity and considerable guide path investment.

All studies mentioned above address a special fixed aisle system. In this case, the only design variable is the direction of each edge in the associated graph, the configuration of which has been fixed *a priori*. Kim and Tanchoco (1993) proposed a network design model which accounts for both transportation costs and fixed costs such as construction, space and control costs. Their solution approach consists of an enhanced branch-and-bound algorithm that employs a tighter bound and a more efficient search scheme compared to the one in (Kaspi and Tanchoco 1990).

Beyond AGVS with fixed aisles, a few research studies have considered general MHS flow path design problems. Proth and Souilah (1992) proposed a fast branch-and-bound algorithm to evaluate the shortest path between two departments/cells, which may serve as a flow path of the MHS. Their method, though applicable to every type of horizontal transportation system, does not account for some practical system constraints, such as material flow bounds within MHS aisles to prevent congestion. Montreuil and Ratliff (1989) suggested a cut tree algorithm to generate a minimum weight spanning tree, the edges of which represent flow path segments. Weights which reflect the minimum cut tree flows are assigned to each edge. Based on these weights, the flow path that corresponds to the

minimum material handling cost is determined. This is accomplished by adjusting the edge lengths in order to minimize the cumulative product of the flow through each edge and the edge length. The cut tree method is valid only when the flow path is selected *a priori* to be a spanning tree of the graph's input/output stations. Thus, it cannot address closed loops or multi-row configurations, which may be preferable in some manufacturing shops.

Chhajed *et al.* (1992) imposed a grid on the entire facility, the edges of which can be used as MHS aisles. The MHS flow path design consists of selecting the most appropriate edges of the grid and is formulated as a mixed integer problem. Applying Lagrangian relaxation of the mixed integer formulation they decomposed the problem into shortest path subproblems that may be solved in linear time. However, their formulation allows flow paths to pass through entity-occupied areas, which is clearly impractical. Finally, Maxwell and Wilson (1981) developed a network flow model for analyzing the traffic in dynamically loaded MHS with fixed paths. Their method is an analytical tool that can be used to evaluate the performance of candidate designs.

Herrmann *et al.* (1995a) have formulated the problem as a fixed charge capacitated network design model, which accounts for fixed costs associated with the activation of network arcs and variable costs that reflect the material handling effort. Arc capacities alleviate traffic congestion, while fixed costs result in more compact and favorable network designs. For the generic optimization problem, for which the linear programming relaxation does not provide tight approximations, the authors provided a new lower bound (Herrmann *et al.* 1994), which is based on iterative applications of the labeling method (Balakrishnan *et al.* 1989). They also proposed an effective heuristic that utilizes linear programming relaxations to identify the most (less) favorable candidate arcs for inclusion in (exclusion from) the flow network; the fixed cost of these arcs is decreased (increased) and the algorithm iterates until a near-optimal network is obtained. Numerical results indicated that the heuristic performs very well, and an industrial example demonstrated the applicability of the method in realistic design problems (Herrmann *et al.* 1995a).

4 Transporter routing

Within the context of manufacturing facility design, the transporter routing problem includes the evaluation of the number of carriers necessary to transfer material between the resource groups on the shop floor, estimation of the total distance (time) that the carriers travel unloaded, and assignment of the loaded and unloaded moves to individual transporters. The problem shares many common attributes with vehicle routing (Golden and Assad 1988), for which powerful solution approaches have been developed (Desrosiers *et al.* 1994); however, the distinct characteristics of the transporter routing problem in production environments call for specialized solution procedures. In the manufacturing systems research area, limited attention has been paid to the transporter routing problem, and most of the solution approaches rely on empirical rules or on computer simulation.

Egbelu (1987a) developed a set of formulas to calculate the minimum number of carriers in a manufacturing system. These formulas consider the loaded traveling times, the average transporter speed, and estimates of the unloaded traveling times provided by AGV users. The results of this work are mostly applicable to an initial economic justification of AGV systems. To address the same problem, Tanchoco *et al.* (1987) employed a queuing theory-based computer model (CAN-Q), and Wysk *et al.* (1987) used spread-sheet analysis. Their results compared favorably to a simulation-based method (AGVSim). All these approaches provide initial estimates for the number of carriers, which may be further refined by simulation. As such, they do not consider aspects of the problem that may be important during system operation, such as the distribution of moves (loaded and unloaded) among the vehicles. Newton (1985) used simulation directly to evaluate the number of necessary transporters in an AGV-based system which operates under given dispatching rules. This approach is specific to the shop operational rules.

For the problem of determining the AGV fleet size, Sinriech and Tanchoco (1992a) developed a multi-criteria optimization model that considers the trade-off between investment costs and system throughput. To support the design process, they proposed the use of decision tables relating the investment cost, the number of AGVs and their utilization, as well as the trade-off ratio between the corresponding conflicting costs. In this approach, the solution is guided by the designer and is not necessarily the optimal one.

The design of efficient horizontal unit-load material handling systems was studied by Maxwell and Muckstadt (1982). They considered the case in which the production rate of each manufacturing resource is constant and known. To determine the minimum number of AGVs, they solved a transportation problem that distributes the unloaded vehicle moves among pairs of resources in a way that minimizes the unloaded vehicle traveling time. Subsequently, they assumed that the designer can determine sequences of moves that originate and terminate at the same resource (*routes*) and assign them to AGVs. They supported this procedure by proposing a routing method that creates a delivery schedule with a near-constant inter-arrival time of material at each resource. In this work vehicle routes, which are critical in assigning moves to vehicles, are not determined analytically. This may limit the applicability of the approach in some large applications, in which route evaluation may be a complex, and often intractable, problem.

Bozer and Srinivasan (1992) presented a partitioning algorithm for the design of single vehicle loops. Given the location of input/output stations, the algorithm decomposes the manufacturing shop into groups of resources that form loops, each loop served by one vehicle. The method aims at distributing the workload evenly among the AGVs in the system. Single vehicle loops offer simplicity and allow analytical performance evaluation of the production system (e.g., throughput).

Herrmann *et al.* (1995b) developed an integer programming formulation of the transporter routing problem. Their model is similar to a non-depot, distance-constrained vehicle routing problem, and accounts for both fixed costs associated with the acquisition of handling transporters and variable costs associated with the transfer of parts/batches between resources. The authors proposed a heuristic method to identify routes and routes sets and provide near-optimal solutions. The heuristic starts from the assignment relaxation (Papadimitriou and Steiglitz 1982), which provides the optimal matchings between moves, and proceeds by applying a two stage bin-packing algorithm to group moves to transporters. The computational complexity of the heuristic is polynomial, and its worst case performance is bounded by ratios of problem parameters. However, both the model and the solution approach are based on the assumption that unit-load carriers are employed and no sharing of moves between different material flow types is allowed. This prohibits the application of

the method in the case of multi-load transporters, which are commonly used in practice.

5 Material handling system control

Assuming a fixed shop layout with predetermined material handling flow paths and fixed transporter fleet size, the MHS control problem addresses the assignment of the available transportation equipment to service requests by jobs waiting in the queues of department/cell output stations. Furthermore, transporter optimal routing from an output station to a destination input station is sought, when alternative paths exist. In this case the shortest path from the origin to the destination is typically followed, unless this path is congested. Most of the related work discussed below has addressed Automated Guided Vehicle (AGV) systems. However, it is equally applicable to all types of horizontal, carrier-based transportation systems such as rail carts, industrial trucks, forklifts etc. (Jacobs-Blecha and Goetschalckx 1992). Studies that use simulation to evaluate the performance of simple heuristic dispatching rules are presented first. Subsequently, control methods for special designs that are topologically simple, and, as a result, easily controllable are examined. Finally, research approaches that address the synthesis of control laws based on quantitative arguments are discussed.

Egbelu and Tanchoco (1984) used simulation to analyze two types of vehicle dispatching rules; workcenter initiated task assignment, and vehicle initiated task assignment. In the first case, as each job is completed by a workcenter and enters the workcenter's output buffer, an AGV service call is logged. The decision problem is to assign an AGV to handle the call. In the second case, idle vehicles initiate a request for work. The decision problem is to prioritize the workcenters requesting service, and to dispatch the vehicle to the workcenter with the highest priority. Egbelu and Tanchoco's simulations showed that workcenter initiated rules have little effect on shop throughput for busy shops. This work also reports a strong effect of the flow network design on the effectiveness of the dispatching rules, providing a significant indication that an integrated MHS flow path and control system design should be adopted.

Egbelu (1987b) used simulation to compare a *pull* strategy of vehicle dispatching with

the previous *push* strategies of Egbelu and Tanchoco (1984). When a vehicle becomes available, the *pull* strategy determines which station should be serviced next, based on current inventories at each station. Stations that are either starved or congested are given higher priorities. The *pull* strategy was found to be superior to the *push* strategy in batch manufacturing environments, in terms of job throughput. The simulation showed again the interrelation of MHS flow path and control system design. Newton (1985) proposed a combination of the first-come-first-serve rule with the simple dispatching strategy *vehicle-looks-for-work*. The heuristic is based on the observation that the average AGV travel distance can be reduced by having unloaded vehicles consistently pick-up jobs from locations closer to their last delivery point. The performance of this heuristic with respect to job throughput has also been evaluated through simulation.

The merit of topologically simple flow path designs for better AGV control has been examined by several authors. Bartholdi and Platzmann (1988) analyzed the operation of single-loop AGVSs using a control algorithm based on the first-encounter-first-serve (FEFS) rule. They showed that this rule performs significantly better than other *greedy* rules, and derived bounds on the level of serviceability. Bozer and Srinivasan (1991) proposed decomposing a standard network into several loops. In this so-called *tandem network* each loop is limited to one vehicle, operating under a *zone-blocking* control scheme (Malmberg 1990). Each vehicle follows the FEFS rule. The authors further developed Bartholdi and Platzmann's model (Bartholdi and Platzmann 1988) to predict the throughput capability of the single vehicle loop. Bozer and Srinivasan (1992) presented a partitioning algorithm for the design of single vehicle loops. Given the location of input/output stations, the algorithm decomposes the manufacturing shop into sets of resources that form loops. The method aims at distributing the workload evenly among the AGVs in the system. Sinriech and Tanchoco (1992b) simulated a single-loop AGVS and showed that the effect of unloaded vehicle moves is reduced in such a configuration. *Tandem networks* offer simplicity and allow analytical performance evaluation. However, their applicability to various types of manufacturing systems and their advantages over conventional networks requires further study.

Bohlander *et al.* (1990) proposed a hierarchical system for the AGV control problem.

They developed a software tool for dispatching rule generation, routing and traffic control. Their approach has been integrated with the Engineering Design Workstation developed at the Georgia Institute of Technology and described in (McGinnis 1990). The main control rule employed is the conventional *shortest-route-in-distance* which dispatches the vehicle to the nearest station requesting service. This rule is enhanced to avoid flow path segments that are congested. Furthermore, a predictive dispatching algorithm is proposed, based on estimates for future vehicle availability and requests for service. This work employs *a priori* assumptions on congestion and delays.

Hodgson *et al.* (1987) used a Markov Decision Process to model an AGVS and develop control rules. Three variables were employed to characterize the state of the system: i) the location of the vehicle, ii) the load being carried, and iii) the status of the queues at each input/output station. The authors developed near-optimal control strategies to maximize job throughput. Their study exhibited the complexity of modeling AGVS by Markov decision processes, which leads to a number of alternative states that increases exponentially with the size of the problem. Consequently, the approach is restricted to relatively small applications.

The vehicle dispatching problem in manufacturing systems bears significant similarity to the dial-a-ride problem in metropolitan transportation systems (Jacobs-Blecha and Goetschalckx 1992). The latter has been formulated by Psaraftis (1980) to minimize a combination of the time needed to service all requests, the time each customer awaits to be serviced and the time each customer spends on the vehicle. Constraints are imposed by vehicle capacity and service priorities. This work proposes a dynamic programming technique to solve the single-vehicle problem. Although the complexity of the proposed algorithm is exponential with the number of service requests, the computational effort is asymptotically lower than that of the dynamic programming algorithm for the traveling salesman problem. Jaw *et al.* (1986) extended Psaraftis' methodology to address the case of multiple vehicles. Jacobs-Blecha and Goetschalckx (1992) applied the algorithm of Psaraftis (1980) to horizontal transportation systems and proposed improvements in terms of efficiency and memory requirements. The above approaches assume that the sequence of job transfer requests is available *a priori*, which is not typically the case in a manufacturing environment. How-

ever, the problem formulation is compatible with just-in-time manufacturing practices, and the model, though deterministic, may offer significant insights into the effect of unloaded vehicle flow requirements during the facility design stage.

6 Literature contributions to integrated facility design

The need for an integrated approach to the design of manufacturing facilities has been recognized and discussed by several authors. Although the relevant subproblems (as defined in Figure 1) have been addressed in the literature, limited research has been devoted to integrating them into a unified design methodology.

Montreuil (1990) introduced a modeling framework for integrating the layout and material flow network designs. It generates *net layouts*, i.e., facility designs which include the location of the input/output resource stations, the MHS flow corridors and the physical aisle system. The author formulated a set of very complex mathematical programming problems, without proposing any solution methods. This is due to the complex constraints employed to account for the shape and size of departments/cells, as well as to the large number of zero-one decision variables.

Montreuil *et al.* (1993) identified two steps in the facility layout and flow path design process. First, adjacency relations between the manufacturing departments/cells are determined by using a design skeleton (Montreuil and Ratliff 1989). The latter may be a flow graph, a planar adjacency graph, a matching-based adjacency graph, a cut tree, or a set of locations of cell centroids. Subsequently, a linear programming model addresses the net layout problem. Banerjee *et al.* (1992) and Banerjee and Zhou (1993) extended the two-step approach of Montreuil *et al.* (1993) by automatically identifying qualitative layout anomalies, i.e., segments of the flow path which are the best candidates for solution improvements (Banerjee *et al.* 1992), and by repeatedly adjusting the design skeleton accordingly. They adopted a hill climbing solution strategy to perform such adjustments which may converge to local optima. Furthermore, the different objectives employed in each of the two design stages (adjacency relations in the first stage, as opposed to material handling cost in the second one) may, in some cases, prevent global convergence of the procedure.

Evans *et al.* (1990) proposed a procedure to simultaneously find the flow directions along a flow path network of fixed geometry, as well as to determine the locations of the input and output stations; the objective of this problem is to minimize the total vehicle travel distance during both loaded and unloaded trips. The authors proposed a recursive procedure that first solves the flow path optimization problem (Gaskins and Tanchoco 1987) based on a given input-output station location set, and then improves the layout (station locations) with the random search heuristic of Rabeneck *et al.* (1989).

A different integration issue has been introduced by Johnson and Brandeau (1991; 1992). The authors developed a design approach for AGV systems that accounts for control attributes, such as inventory at input and output stations. The design decision is to determine which workstations should be serviced by AGVs and how many vehicles are needed to meet a specified service level, while explicitly considering congestion effects caused by requests for service. The authors built upon the first-come-first-serve AGV control rule. Although this methodology requires a fixed layout and material flow network, it is the first attempt to integrate inventory considerations with AGV system design.

McGinnis (1990) presented a modular design methodology for an AGVS. An engineering workstation was developed to allow the designer to graphically generate an initial layout, including the MHS flow path, estimate the required number of vehicles, refine the layout, and evaluate unloaded vehicle dispatching rules as well as vehicle routing in an interactive fashion. Various system performance characteristics, such as traffic intensity in each flow path segment and total loaded and unloaded vehicle travel, are automatically evaluated. Furthermore, a discrete simulation tool is provided and some optimization modules are incorporated in the software. The AGV engineering workstation is a very helpful tool for the evaluation of candidate designs and the identification of attributes that require refinement and possibly re-design. If a good initial layout is provided to this system, and an experienced user guides the design process, the final solution will be of high quality.

Rembold and Tanchoco (1994) proposed a system similar to the engineering workstation of McGinnis (1990). Various design tools are modeled as objects and are integrated through a graphical user interface. The system intends to help the designer compose complex material flow systems. As with the AGV engineering workstation, the final solution depends

on the expertise of the designer and the sequence in which design modules are applied.

Dowlatshahi (1994) identified the need for a systematic and integrated facilities design. He proposed grouping the design factors into Design Factor Families and modules into Module Families, which will decouple the complex global problem into cohesive, bounded, and self-contained activities that can be addressed independently. The author proposed a clustering algorithm for grouping design factors and modules into families. However, since most of the design activities are interrelated, this algorithm may not yield independent families in many practical cases.

Ioannou and Minis (1995) proposed a binary program to model the global shop design problem in a comprehensive manner. The model addresses major decisions related to the layout, material flow network design, and transporter fleet size evaluation and routing. It also incorporates practical concerns such as arc and transporter capacities. The large number of variables and constraints required prevents the development of direct solution approaches. Instead, the model was decomposed to generic optimization subproblems (quadratic assignment, fixed charge capacitated network design, and transporter routing). These subproblems are systematically solved by an algorithm which generates, evaluates and accepts/rejects shop designs following a simulated annealing evolution scheme, until a near-optimal global shop design is obtained (Ioannou 1995).

7 Conclusions and opportunities for further research

This paper surveyed approaches for the subproblems related to manufacturing shop design. It reviewed existing heuristic and optimal methods for the layout of resource groups and the design of the material flow network. It also examined several simulation, rule-based, and mathematical programming techniques for determining good solutions to the transporter fleet size, routing, and control problems. Finally, the paper presented attempts towards the integration of the global design problem. Several issues of shop design remain open for future research, and constitute challenging problems.

Layout

The layout problem has been heavily researched in the past. Nevertheless, several

layout-related issues require additional study. From a theoretical perspective, the quadratic assignment problem that lies in the heart of the shop layout formulation requires further analysis; e.g., the structure of the polytope of the QAP constraints may be examined and possibly restricted via valid inequalities (Nemhouser and Wolsey 1988). From a practical perspective, the redesign of existing facilities (Delaney *et al.* 1995) is a very important problem, faced more frequently than clean-slate design. Finally, integration issues that arise from the concurrent design of the layout, the material flow network and the transporter routing problems, should be studied in-depth (Ioannou 1995).

Material flow network design

The multi-commodity, fixed charge capacitated network design model (Ioannou 1995), or its relaxations, e.g., the directionality model of Gaskins and Tanchoco (1987), that is employed to formulate the material flow network design problem, is a potential candidate for further research. In terms of theoretical developments, Magnanti and Mirchandani (1993) have introduced new facets and established polyhedral integrality properties for some special cases of the problem, while Wolsey (1989) has proved the existence of some valid inequalities. Thus, additional work could address the polyhedral structure of the general multi-commodity capacitated problem. In terms of practical issues, the integration of the flow path design problem with the shop layout and the transporter routing should be more thoroughly addressed (Ioannou 1995).

Transporter routing

The critical link between long term material handling system design and dynamic operation is the assignment of productive and non-productive moves to transporters. Thus, an effective transporter routing approach should minimize both the loaded and unloaded transporter travel between departments/cells. In doing so, the MHS workload is decreased, and the flow of material can be effectively controlled in real-time (Ioannou 1995). The principal difficulty in considering the transporter routing problem as an issue in the facility design process arises from the distinct nature of the MHS network design and the MHS operation problems. The former involves long-term decisions that are made off-line based on *static* information, such as production routings and average demands of finished products. The latter concerns *real-time* scheduling of the material handling transporters based

on the dynamic state of the production system; i.e., actual location and destination of the transporters, as well as queue lengths in input and output stations of departments/cells. The apparent discrepancy between real-time move sequences and move sequences estimated at the design stage could be perhaps alleviated by introducing time windows to reflect the time within which each loaded move is to be performed. For a related discussion in transportation systems (vehicle routing with time windows) see Desrochers *et al.* (1994).

Optimal solutions

Although the intractability of the shop design subproblems prohibits optimal solutions for large size problems, further investigation is needed to determine whether modern integer programming techniques may be employed to solve problems of reasonable size optimally. In particular, column generation-based solution methods could be pursued (Bahl 1983; Barnhart *et al.* 1994; Cattrysse *et al.* 1990; Crama and Oerlemans 1994; Desrosiers *et al.* 1994; Desrochers and Soumis 1989; Ribeiro *et al.* 1989).

Operational considerations

Another important decision that could be incorporated into the shop design model is the maximum level of inventory allowed in the input/output buffers of the resource groups. This level is directly related to the batch/lot sizes and the inventory policy of the manufacturing facility. Inventory considerations at the design level have been introduced by Johnson and Brandeau (1995) for an application of Automated Guided Vehicles.

Material handling system control

The sequence of moves performed by transporters is usually assumed independent of the on-line control policies during shop design. In reality, however, the material handling system responds to batch transfer requests according to the dynamic state of the system. Thus, the effect of material handling control on system design (and *vice-versa*) should be further examined. For example, it is useful to consider the effect of the transporter dispatching and routing rules on the unloaded transporter travel. This could provide a more accurate estimate of the unloaded transporter moves, and consequently, allow for a more effective shop design based on inter-resource group interactions that better reflect reality. Such a study could also determine relationships between standard shop configurations (layout and flow network, e.g., single loop, linear, etc.) and appropriate control rules (routing and

dispatching, e.g., first-come-first-serve, nearest-time, etc.).

Acknowledgements

This work was supported in part by the National Science Foundation under Grants # NSF D CDR 8803012 and NSF EEC 94-02384.

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