Technical Research Report

An Integrated Model for Manufacturing Shop Design

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T.R. 95-106

INSTITUTE FOR SYSTEMS RESEARCH

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

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Abstract

This paper presents an integer programming formulation for the manufacturing shop design problem, which integrates decisions concerning the layout of the resource groups on the shop floor with the design of the material handling system. The model reflects critical practical design concerns including the capacity of the flow network and of the transporters, and the tradeoff between fixed (construction and acquisition) and variable (operational) costs. For realistic industrial cases, the size of the problem prevents the solution through explicit or implicit enumeration schemes. The paper addresses this limitation by decomposing the global model into its natural components. The resulting submodels are shown to be standard problems of operations research. The decomposition approach provides ways to solve the integrated shop design problem in an effective manner.

Keywords: Facility Layout, Material Handling Systems, Manufacturing Systems, Vehicle Routing, Decomposition

1 Introduction

An important aspect of any production system is the design of its manufacturing shop, including the material handling system which integrates the production operations. A well designed shop results in efficient material handling and short transportation times between resources, leading to decreased production cycles and manufacturing costs (Francis, McGinnis and White 1992). Additional advantages of efficient shops include effective production management, improved on-time delivery performance, enhanced product quality, and decreased inventory holding costs (Ioannou 1995).

The goal of this work is to provide design methods for production systems that are inexpensive to construct and efficient to operate. Shop design comprises two highly interconnected problems, i.e., layout and material handling system (MHS) design. The former addresses the physical placement of the resource groups (e.g., functional departments or manufacturing cells) on the available area of the shop floor. The latter includes two highly inter-related subproblems: i) Design of the material flow network that provides the resource inter-connections (Herrmann *et al.* 1995a); ii) sizing of the transporter fleet, and allocation of the inter-group moves to these transporters (Herrmann *et al.* 1995b). Subproblem (ii) is referred to as *transporter routing* to be analogous to the vehicle routing problem (Golden and Assad 1988), with which it shares significant similarities.

Many subproblems of shop design have been addressed in the literature with various degrees of success, as discussed in some recent survey papers (Kusiak and Heragu 1987, Meller and Gau 1995, Ioannou and Minis 1995). However, limited research effort has been devoted to integrating them into a unified method, despite the potential benefits of such an integrated (Apple and McGinnis 1987). The most noteworthy attempts towards shop design integration are reviewed below.

Montreuil (1991) developed a modeling framework for integrating the layout and material flow network design problems, to generate *net layouts*, i.e., complete designs which include the location of the resource input/output (I/O) stations and the MHS flow corridors. The author formulated a set of very complex mathematical programming problems, but did not propose any solution methods. The model complexity arose from the constraints employed to account for the shape and size of departments/cells, and the large number of zero-one decision variables.

In a more recent work, Montreuil, Venkatardi and Ratliff (1993) identified two steps in the facility layout and flow path design process. First, a design skeleton establishes adjacency relations between the manufacturing departments/cells; flow graphs, planar adjacency graphs, matching-based adjacency graphs, cut trees, or sets of locations of cell centroids may serve as design skeletons. Subsequently, a linear program is solved to extract the net layout. Banerjee *et al.* (1992) and Banerjee and Zhou (1993) further developed the two-step method of Montreuil, Venkatardi and Ratliff (1993). Their approach automatically identifies qualitative layout anomalies, i.e., segments of the flow network which are the best candidates for solution improvements, and repeatedly adjusts the design skeleton. A hill climbing solution strategy is used to implement the configuration adjustments and, as a result, the solution obtained may be far from the optimum. Furthermore, global convergence cannot be guaranteed due to the inconsistency of the objectives employed in each of the two design stages.

McGinnis (1991) proposed a modular design methodology for an Automated Guided Vehicle (AGV) system. An engineering workstation was developed to allow the designer to graphically generate an initial layout and a material flow network, 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 calculated. Furthermore, a discrete event simulation tool and some optimization modules are incorporated in the software. The AGV engineering workstation is a very helpful tool for evaluating candidate designs and identifying attributes that require refinement and possibly, re-design. If a good initial layout is provided to this system and an experienced designer guides the procedure, the final shop design is expected to be of high quality. A system similar to the engineering workstation of McGinnis (1991) has been proposed by Rembold and Tanchoco (1994) to help the designer compose complex material flow systems. As with the AGV engineering workstation, the final design attributes are affected by the expertise of the designer and the sequence in which design modules are applied.

This paper formulates an optimization model that considers most major decisions involved in the design of a manufacturing shop; i.e., the placement of the resource groups (functional departments or manufacturing cells) on the shop floor, the topology of the material flow network, the transporter fleet size and routing, and the tradeoff between fixed and variable costs. We consider only horizontal, unit-load material handling transporters, which are commonly employed in practice. We also assume that the grouping/layout of individual machines into/within functional groups or cells has been performed in a preceding design stage (Ioannou and Minis 1995). The model accounts for practical system attributes such as the geometry of the shop floor, of the resource groups, and of the restricted areas, the capacity of the material handling system, the unloaded movement of transporters, and the operational efficiency of the final system. The complexity of the mathematical model, which is due to the large number of variables and constraints and to the non-linearity of some constraints, prohibits direct solution approaches. Instead, we decompose the global model to the natural components of the design model. The constituent mathematical subprograms are generic optimization models, which can be effectively solved.

The remainder of the paper is organized as follows: Section 2 establishes the need for integrating the shop design activities. Section 3 presents the geometrical model framework, the underlying assumptions, and the binary variables, and formulates a comprehensive integer program that incorporates most design decisions and critical practical concerns. Section 4 provides systematic procedures for the decomposition of the global problem into sub-models that are related to generic problems of operations research. Section 5 proposes a possible solution strategy, and Section 6 presents the conclusions of this work.

2 The need for integrated shop design

Shop design is a complex process influenced by both managerial and technical decisions which involve considerable tradeoffs. The merit of the final design depends on the *ease of operation* of the system; thus, the layout and MHS design should facilitate efficient dispatching and routing of transporters. To achieve such a result the following considerations are important:

- An effective shop design approach should minimize both the loaded and unloaded transporter travel between departments/cells. Unloaded moves, although unavoidable when transporters are dispatched from input to output stations, increase the workload of the MHS and, thus, decrease its responsiveness and flexibility. In minimizing the cumulative travel the MHS workload is decreased, and the flow of material can be more effectively controlled in real-time.

- The tradeoff between investment and operational costs should be examined at the design stage. The former include the cost of constructing the material handling network and acquiring the transportation equipment. Operational costs reflect the material handling effort during the lifetime of the production system. Considering this tradeoff will result in shop configurations that are economic to implement and efficient to operate.

- To evaluate a precise measure of the material handling effort, the actual inter-station distances (which are provided by the material flow network) are required. Thus, the layout and flow network design problems are interconnected and should be addressed concurrently to provide a shop design that will operate with minimal inter-station transportation times along the optimal set of fixed material flow paths.

- The transporter routing problem is inherently linked to both the design of the material flow network and the layout of the resource groups. The routing of transporters determines the unloaded moves necessary for continuous operation. However, unloaded transporter travel alters the intensity of inter-station interactions and introduce additional workload. This has a direct impact on both the relative placement of the resource groups, and the topology of the flow network.

3 The shop design model

The shop design objective proposed in this work seeks to balance the fixed investment versus the variable operational costs, targeting shop designs that are economic to construct and efficient to operate. This goal is expressed by a functional that comprises the total material handling effort during the design horizon, the fixed cost of building the material handling network, and the cost of purchasing the required transporters.

In addition to the fixed and variable costs, two major practical concerns are addressed: Traffic congestion in the flow network, and availability of transporters. To prevent traffic congestion, we place an upper bound on the material flow allowed through each segment of the network, beyond which the arc is considered to be congested. In order to accommodate flow beyond an arc's capacity, addition of more network segments may be necessary to provide alternative origin-destination paths for each transfer request. Transporter availability is critical in determining the transporter fleet size, and is expressed by a distance upper bound (assuming constant speed of transporters). The mathematical model that captures these issues is developed in the following subsections.

3.1 Representation of geometrical attributes

Consider an orthogonal grid imposed on the shop area as shown in Figure 1. The unit length of the grid is defined such that it is larger than the width of a typical aisle of the material handling system, and it is fine enough to adequately capture the geometry of the shop, the restricted areas, and the manufacturing resource groups.

The manufacturing resource groups to be placed on the shop floor form the set $\mathcal{R}$. Each resource group is decomposed into unit square building blocks, as shown in Figure 1. Although each building block is treated as a distinct entity, strong relationships are established between adjacent blocks of the same resource group in order to retain its size and shape in the final solution. For each block u we designate as $adj(u)$ the set of blocks that belong to the same resource group and are adjacent to (have a common edge with) u. The input and output stations for each resource group are represented by special blocks denoted by I and O in Figure 1. The set of all building blocks is denoted by $\mathcal{B}$, and the subsets of $\mathcal{B}$ that comprise input and output stations are denoted by $\mathcal{I}$ and $\mathcal{O}$, respectively. Note that I_a, O_a refer to the blocks modeling the input and output stations of resource group a.

Each intersection of the grid represents a node of the underlying graph G. Graph nodes are candidate positions for building blocks of resource groups and graph arcs are candidate

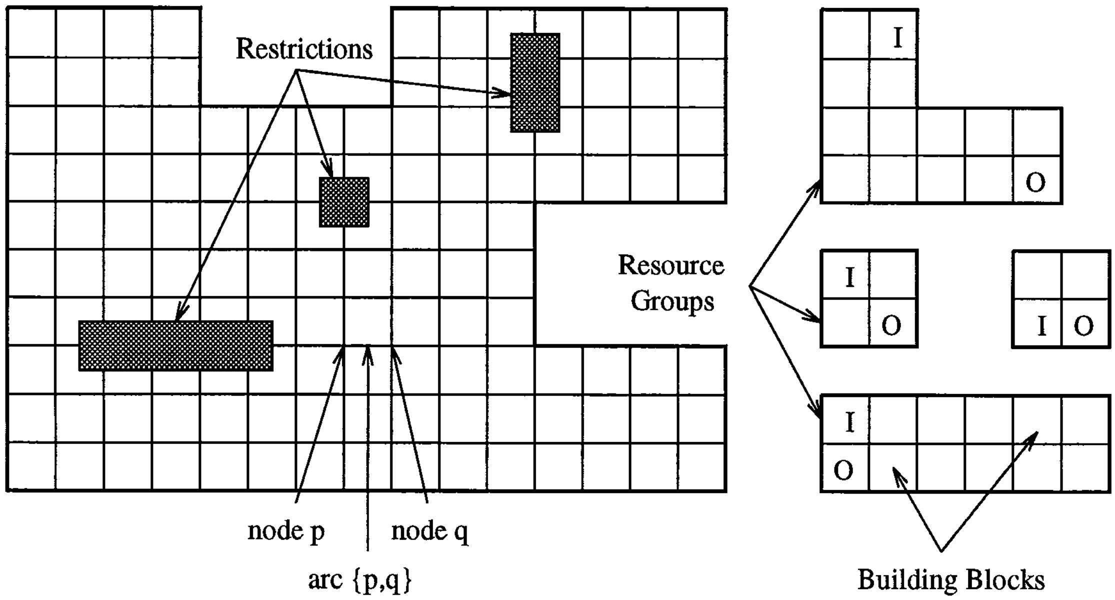

Figure 1: Representation of the shop and the resource groups

arcs of the material flow paths. The set of nodes that constitute graph G is denoted by N. The centroids of the building blocks of set $\mathcal{B}$ will be located on grid points, as shown in Figure 2. Note that the intersections of the shop grid which are inside restricted areas or areas occupied by manufacturing resource groups in a certain layout configuration (e.g., nodes p and q in Figure 2), are not considered as nodes available for material flow. The only exceptions are the nodes representing input and output stations of resource groups, through which material enters and leaves. Furthermore, the set of the graph's undirected arcs which connect nodes available for material flow is denoted by $\bar{A}$, and the set of directed arcs obtained by replacing each undirected edge with two arcs of opposite orientation, is denoted by A.

3.2 Assumptions and notation

The design model is based on the following assumptions:

i. The material flow paths are parallel to the building's walls and include only arcs of the grid imposed on the shop floor.

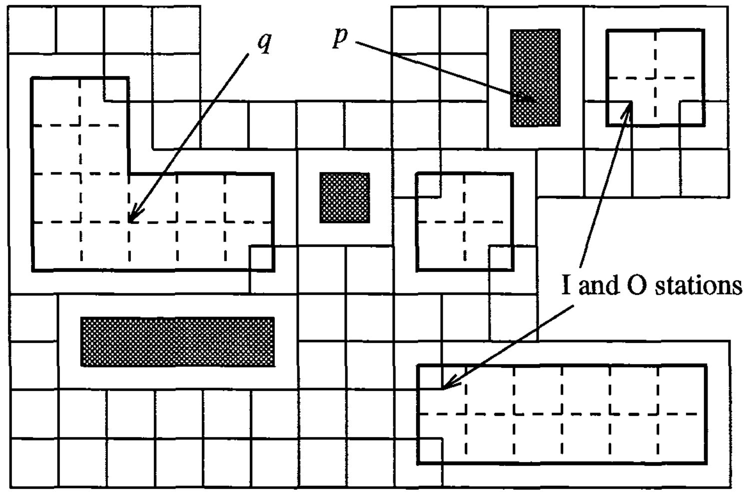

Figure 2: A feasible layout

ii. The inter-resource material flow rates, in terms of loads per time period, are constant and known. They are calculated from the production routings (sequences of operations) of the products to be manufactured and the forecasted product demand over the design horizon. In periodic production systems, i.e., systems with periodic demand and periodic flow patterns, the design horizon is equal to one period. In non-periodic systems, the design horizon is divided into equal time periods and the total demand is equally distributed over these periods. This uniform distribution of the demand, and thus of the requests for transporter service, is required to prevent unrealistic sequences of loaded moves for being assigned to transporters.

iii. Whenever a transporter visits the output station of a resource group, there always exists material to be transferred. This assumption is necessary since no real-time information is available at the system design stage.

iv. Only horizontal material handling transporters are considered (e.g. AGVs, manual or automated rail carts, industrial trucks, and forklifts) with unit load capacity. Thus, sharing of moves between different material flow types is not allowed, i.e., transporters cannot simultaneously serve more than one batch type. This results in one trip per flow request, which simplifies transporter scheduling.

There exist three types of transporter operations between a pair of manufacturing resource groups, as shown in Figure 3:

i. A *loaded move* i is the transporter operation from the output station of a manufacturing resource group to the input station of the destination group. The nodes of origin and destination of loaded move i are defined as $o(i)$ and $d(i)$, respectively. The set of loaded moves is denoted by L, and its cardinality ($|L|$) will be referred to as n throughout the text.

ii. An *unloaded move* is the transporter operation from the input station of a manufacturing resource group to the output station of another group, during which no load is carried. The set of all possible unloaded moves is denoted by U.

iii. A *complete move* is the concatenation of a loaded move and a subsequent unloaded move. The set of complete moves is denoted by C. Each element of C will be noted as (i, j), where i is the loaded move included in the complete move, and j the loaded move that follows i in the sequence of a transporter.

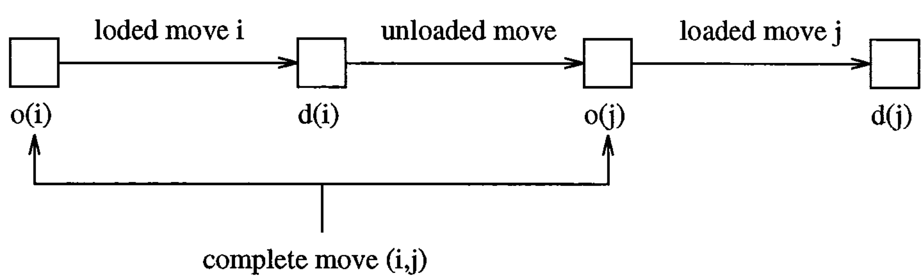

Figure 3: Definition of move types

Assuming that there exists a path between each input-output pair, it is easy to see that after the completion of a loaded move, a transporter can perform an unloaded move to the origin of any other loaded move in L. If the input/output stations of a resource coincide, this unloaded move may be of zero distance. As a result, either three or only two manufacturing resource groups may be included in a complete move. In the latter case, either $d(i) = o(j)$ or $o(i) = o(j)$ and $d(i) = d(j)$, where $i, j \in L$ are consecutive moves performed by the same transporter.

The material flow between each pair of resource groups $(a, b) \in \mathcal{R}^2$ is denoted by f_{ab}. The value of f_{ab} represents the volume of interactions between a and b, and is calculated from the part routings, the demands over the design time horizon, and the batch sizes. The levels of material flow form a square $|\mathcal{R}| \times |\mathcal{R}|$ matrix, known as the *material flow matrix.* In our formulation, we decompose each f_{ab} into unit load moves.

A cost β_{ij} is associated with each complete move $(i,j) \in C$. It reflects the time to perform the relevant loaded and unloaded transfer operations; β_{ii} is defined to be equal to ∞ since each loaded move has to be performed exactly once, and the sequence i, i is not feasible.

T is the fraction of the design time horizon T', during which transporters are available for travel. For each transporter k the capital investment is denoted by W_k; this cost is appropriately scaled to reflect the relative weights of the variable and fixed components of the objective function, and the length of period T. It is important to stress the need for appropriate scaling of the transporter capacity and acquisition costs, as well as the capacity and fixed cost of each arc of the network to allow for a coherent shop design model.

3.3 Definition of decision variables

Several sets of decision variables are introduced to model discrete choices concerning key attributes of the shop design activity. The first of them models the assignment of blocks of resource groups to nodes of G. A feasible assignment of the building blocks $u \in \mathcal{B}$ to grid nodes $p \in N$ provides a feasible shop layout, in which the resource groups retain their size and shape, and their input and output stations are not blocked. This assignment is modeled by:

$$e_{up} = \begin{cases} 1 & \text{if building block } u \in \mathcal{B} \text{ is located at node } p \in N \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

The values of these variables in the final solution provide the locations of the resource groups on the available area of the shop and, thus, the final shop layout. The above definition is closely related to the binary variables employed in quadratic assignment formulations (Wilhelm and Ward 1987).

The second set of decision variables determines whether an arc $\{p,q\} \in \bar{A}$ is active or not in the flow network:

$$y_{pq} = \begin{cases} 1 & \text{if arc } \{p,q\} \in \bar{A} \text{ is active in the flow network} \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

The values of arc-related decision variables in the final solution define the topology of the final material handling network, which depends on the arc fixed costs as well as on the arc capacities. The cost, F_{pq}, related to each arc $\{p,q\} \in \bar{A}$ depends on the construction, control, and maintenance costs of this segment of the network. In addition, an upper bound on the number of moves that an edge can accommodate within T is denoted by B_{pq}; this is the arc capacity.

The third set of decision variables models the choice of activating or not a transporter:

$$w_k = \begin{cases} 1 & \text{if transporter } k \in V \text{ is employed for some move in } L \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

The number of non-zero w_k variables in the final solution provides the final transporter fleet size. Note that a given set V of available transporters is assumed for modeling purposes.

The fourth set of decision variables relate the origin-destination path for each loaded and unloaded move to each transporter. The set comprises two subsets: For loaded moves,

$$\mathbf{x}^k_{ipq} = \begin{cases} 1 & \text{if loaded move } i \in L \text{ is performed by transporter } k \in V \text{ and} \\ & \text{the transporter path } o(i) \to d(i) \text{ includes arc } (p,q) \in A \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

For unloaded moves,

$$\mathbf{z}^k_{ijpq} = \begin{cases} 1 & \text{if unloaded move between } i,j \in L \text{ is performed by } k \in V \\ & \text{and the transporter path } d(i) \to o(j) \text{ includes arc } (p,q) \in A \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

The sum of all $\mathbf{x}^k_{ipq}$ and $\mathbf{z}^k_{ijpq}$ variables is the total material handling effort in the shop during the design horizon.

The last set of decision variables models the sequence of moves performed by each transporter:

$$h^k_{ij} = \begin{cases} 1 & \text{if transporter } k \in V \text{ performs complete move } (i,j) \in C \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

The values of these decision variables in the final solution translate into the sequence of loaded moves that each transporter should perform for minimal material handling. These sequences can serve as the basis for transporter real-time scheduling.

Finally, δ_{pq} is the Manhattan distance between grid points p and q, i.e., the sum of the absolute values of the differences between the horizontal and vertical coordinates of the two points p and q. This metric is known from the grid imposed on the shop floor.

3.4 Mathematical formulation

Based on the variable definitions and notation described above, the formulation of the global design problem is as follows:

<u>Problem GSD</u>

minimize

$$\sum_{k\in V}\sum_{i\in L}\sum_{(p,q)\in A} \mathbf{x}^k_{ipq} + \sum_{k\in V}\sum_{(i,j)\in C}\sum_{(p,q)\in A} \mathbf{z}^k_{ijpq} + \sum_{k\in V} W_k w_k + \sum_{\{p,q\}\in \bar{A}} F_{pq} y_{pq} \tag{7}$$

subject to :

$$\sum_{k\in V}\left[\sum_{(p,q)\in A} \mathbf{x}^k_{ipq} - \sum_{(q,r)\in A} \mathbf{x}^k_{iqr}\right] = e_{d(i)q} - e_{o(i)q} \quad \forall q\in N, \quad \forall i \in L \tag{8}$$

$$\sum_{k\in V}\left[\sum_{(p,q)\in A} \mathbf{z}^k_{ijpq} - \sum_{(q,r)\in A} \mathbf{z}^k_{ijqr}\right] = \sum_{k\in V} h^k_{ij}\cdot (e_{o(j)q} - e_{d(i)q}) \quad \forall q\in N, \ \forall (i,j)\in C \tag{9}$$

$$\sum_{k\in V}\left[\sum_{i\in L}(\mathbf{x}^k_{ipq} + \mathbf{x}^k_{iqp}) + \sum_{(i,j)\in C}(\mathbf{z}^k_{ijpq} + \mathbf{z}^k_{ijqp})\right] \le B_{pq} \qquad \forall \{p,q\}\in \bar{A} \tag{10}$$

$$\sum_{(i,j)\in C}\sum_{k\in V} h^k_{ij} = 1 \qquad \forall i\in L \tag{11}$$

$$\sum_{(i,j)\in C}\sum_{k\in V} h^k_{ij} = 1 \qquad \forall j\in L \tag{12}$$

$$\sum_{(i,j)\in C} h^k_{ij} - \sum_{(j,i)\in C} h^k_{ji} = 0 \qquad \forall i\in L, \quad k\in V \tag{13}$$

$$\sum_{(i,j)\in \mathcal{C}_{1,2}} h^k_{ij} \ge h^k_{i_1 j_1} + h^k_{i_2 j_2} - 1 \quad \forall (i_1,j_1),(i_2,j_2)\in C : j_1\ne i_2, \text{ and } i_1 \ne j_2$$
$$\forall \mathcal{C}_{1,2}, \quad \forall k\in V \tag{14}$$

$$h_{ij}^k \leq w_k \qquad \forall (i,j) \in C, \quad \forall k \in V \tag{15}$$

$$\sum_{(p,q)\in A} \left[\sum_{i\in L} \mathbf{x}_{ipq}^k + \sum_{(i,j)\in C} \mathbf{z}_{ijpq}^k \right] \leq T \qquad \forall k \in V \tag{16}$$

$$\mathbf{x}_{ipq}^k \leq \sum_{(i,j)\in C} h_{ij}^k \qquad \forall i \in L, \quad \forall k \in V \tag{17}$$

$$\mathbf{z}_{ijpq}^k \leq h_{ij}^k \qquad \forall (i,j) \in C, \quad \forall k \in V \tag{18}$$

$$\mathbf{x}_{ipq}^k \leq y_{pq} \qquad \forall i \in L, \quad \forall k \in V, \quad \forall \{p,q\} \in \bar{A} \tag{19}$$

$$\mathbf{z}_{ijpq}^k \leq y_{pq} \qquad \forall (i,j) \in C, \quad \forall k \in V, \quad \forall \{p,q\} \in \bar{A} \tag{20}$$

$$e_{uq} + y_{pq} \leq 1 \qquad \forall u \in \mathcal{B} \setminus \{\mathcal{I} \cup \mathcal{O}\}, \quad \forall \{p,q\} \in \bar{A} \tag{21}$$

$$e_{uq} + e_{vp} + y_{pq} \leq 2 \qquad \forall \{p,q\} \in \bar{A}$$
$$\forall a \in R, \ \forall u,v \in B : u = I_a, v = O_a \tag{22}$$

$$\sum_{u\in B} e_{uq} \leq 1 \qquad \forall q \in N \tag{23}$$

$$\sum_{q\in N} e_{uq} = 1 \qquad \forall u \in \mathcal{B} \tag{24}$$

$$\sum_{p\in N}\sum_{q\in N} e_{up} e_{vq} \delta_{pq} = 1 \qquad \forall u,v \in \mathcal{B} : u \in adj(v) \tag{25}$$

$$\mathbf{x}_{ipq}^k, \mathbf{z}_{ijpq}^k, e_{uq}, h_{ij}^k, w_k, y_{pq} \in \{0,1\} \quad \forall (i,j) \in C, \ \forall k \in V,$$
$$\forall \{p,q\} \in \bar{A}, \ \forall u \in \mathcal{B} \tag{26}$$

The objective of (7) includes both the fixed and variable costs. The first two terms provide the overall material handling effort during the design horizon. Specifically, the first term provides the total distance traveled by all transporters when performing loaded moves, and the second term provides the same metric for unloaded moves. The third term of the objective function reflects the cost of building the flow network; for each activated arc, the corresponding fixed cost is added to the objective function. The last term reflects the transporter acquisition cost; for each transporter that performs at least one loaded move, the corresponding purchase cost is added to the cost function.

Constraints (8) guarantee, for each loaded move, the continuity of the corresponding path on the physical network. These constraints can be thought of as flow conservation equations, with the origins of loaded moves (output station blocks) representing flow sources and the destinations (input station blocks) representing flow sinks. The first and second terms of the left-hand side of equation (8) represent the total flow of loaded move i into and out of node q of the grid, respectively. For the right hand side of (8), there exist three alternatives: i) If the output station from which loaded move i originates, $o(i)$, is assigned to node q, then $e_{o(i)q}$ is equal to 1; consequently, node q is a source of flow, and the right hand side is equal to -1. ii) If the input station to which loaded move i terminates, $d(i)$, is assigned to node q, then $e_{d(i)q}$ is equal to 1; consequently, node q is a sink of flow, and the right hand side is equal to 1. iii) If the input or output stations related to loaded move i have not been assigned to node q, then $e_{o(i)q} = e_{d(i)q} = 0$ and the right hand side of (8) is equal to 0; thus the flow through q is conserved.

Constraint (9) models, in a similar manner, the continuity of unloaded moves. In this case input and output stations are sources and sinks of flow, respectively. In addition, since the unloaded moves depend on the sequence of loaded moves performed by each transporter, the right hand side of (9) incorporates the relevant decision variables h_{ij}^k.

Constraint (10) limits the flow through an arc to the upper bound B_{pq} in order to prevent traffic congestion. The left-hand side of (10) represents the total number of times that transporters travel along arc $\{p, q\}$, during both loaded and unloaded moves. Imposing the capacity bound of (10) on each arc may introduce additional path segments (arcs) to the network in order to accommodate the flow beyond an arc's capacity.

Constraints (11)-(12) ensure that each loaded move in L is performed once, by exactly one transporter. Since transporters perform closed sequences of moves, both constraints are required in order to guarantee a feasible assignment of complete moves to transporters.

Constraints (13) force transporters to follow continuous paths in terms of loaded moves; i.e., if transporter k performs complete move $(i, j) \in C$, then it should perform exactly one move of the type $(j, j') \in C$, where j' is any move in L. These constraints can also be thought of as flow conservation equations: Consider each transporter as a distinct flow of unit intensity. The moves assigned to this transporter represent the nodes of an auxiliary graph. Flow conservation is imposed on each node of this graph to guarantee continuous movement of the transporter. Since transporters perform closed sequences of moves, no flow sources or sinks are present, and the right hand side of (13) is equal to 0 for each node of the graph, i.e., for each move in L.

The exponential set of constraints (14) enforces the, so called, subtour elimination; i.e., these constraints guarantee the existence of a single tour for each transporter $k \in V$. Note that a tour is a sequence of moves in the form $(i_1, i_2, ..., i_1)$. In (14), $C_{1,2}$ refers to any directed cut (Nemhouser and Wolsey 1988) of the graph of complete moves that separates (i_1, j_1) and (i_2, j_2). This type of constraints is encountered in the formulation of the well known traveling salesman problem (Golden and Assad 1988), in which the salesman has to visit a set of cities in sequence, before returning to his base.

Constraints (15) guarantee that no move is performed by inactive transporters. If transporter k is not acquired, $w_k = 0$; in this case, (15) forces all h_{ij}^k to be zero, and consequently, no move is assigned to this transporter. These constraints are inactive if $w_k = 1$.

Constraints (16) limit the overall distance traveled by each transporter. The left hand side is equal to the total number of times each arc is visited by transporter k while performing a loaded or unloaded move. The right-hand side of (16) is the time period T, appropriately scaled to reflect distances. Note that the time costs β_{ij} are not necessary in the formulation because of the unit length of each arc that results in constant traveling times of the transporter on each arc.

The set of inequalities (17)-(22) are forcing constraints. Constraints (17) state that if a loaded move is not performed by a transporter, no arc of the network should accommodate this move-transporter combination. On the other hand, if loaded move i is performed by transporter k, the right-hand side of (17) is equal to 1. In this case, there exists a loaded move j that follows i in the sequence of moves of transporter k. Constraints (18) enforce similar conditions for the unloaded move between any i and j.

Constraints (19) and (20) prohibit loaded and unloaded transporter moves to pass through arcs that do not belong to the flow network ($y_{pq} = 0$). These constraints are inactive for arcs forming material flow paths ($y_{pq} = 1$).

Constraints (21) ensure that when a block -which does not model an input or output station- is assigned to a grid node, the arcs that originate from or terminate to this node do not belong to the material flow network. Constraints (22) enforce this condition for the arcs between those resource groups in which input and output stations are adjacent.

The usual assignment constraints are expressed by (23)-(24): at most one resource block should be assigned to every grid node, and each block should be assigned to exactly one grid node. Constraints (25) force adjacent blocks of each resource to occupy adjacent grid points of the network; this is accomplished by forcing the Manhattan distance between the locations occupied by adjacent blocks to be equal to the grid unit length. Note that in order to preserve the shape of the resource groups, at least two adjacency relationships should be established for each block. Consequently, for modeling purposes, resource groups should comprise at least two rows of blocks. Finally expression (26) ensures that the decision variables assume binary values.

3.5 Enumeration of variables and constraints

To quantify the complexity of model **GSD**, it is useful to evaluate the numbers of decision variables and constraints as functions of problem parameters. Such parameters include the number of nodes and arcs of graph G, the cardinality $|V|$ of the set of possible transporters, the number of loaded moves per time period, $|L|$, and the number of building blocks that model the resource groups, $|\mathcal{B}|$. The number of variables of **GSD** is derived by considering the variable definitions, their indices, and the sets they refer to. Furthermore, the number of problem constraints is evaluated by examining the sets over which each constraint is expressed. Analytical expressions for each set of decision variables and each set of constraints of **GSD** are provided by Ioannou (1995). Based on these expressions, the total number of binary variables and constraints is given by Equations (27) and (28), respectively:

$$\mathcal{N}_{total} = |V| \cdot |A| \cdot |L|^2 + |B| \cdot |N| + \frac{|A|}{2} + |V| \cdot (1 + |L| \cdot |L - 1|) \tag{27}$$

$$\begin{aligned}\mathcal{M}_{total} \simeq \; & |N| \cdot (1 + |L|^2) + |V| \cdot |L| \cdot (2 \cdot |L| - 1) + |V| \cdot (1 + |L|) + 2 \cdot |L| + |N| \\ & + \tfrac{|A|}{2} \cdot (1 + |B \setminus \{I \cup O\}| + |I| + |V| \cdot |L|^2) + |B| \cdot (1 + |B|) + exp(|L|)\end{aligned} \tag{28}$$

In (28) $exp(|L|)$ is an exponential function of $|L|$. Furthermore, (28) does not hold at equality for every instance of **GSD** because of the number of block interrelations. Ioannou (1995) calculated the values of $\mathcal{N}_{total}$ and $\mathcal{M}_{total}$ for a small example in which two resource groups with four blocks ($|B| = 4$) are to be placed on a shop represented by six grid points ($|N| = 6$); the resources share three loaded moves per time period ($|L| = 3$). For this minimal problem, the number of binary decision variables was found to be $\mathcal{N}_{total} = 387$, and the total number of constraints was $\mathcal{M}_{total} = 341$. Thus, although general, the **GSD** model is very complex for even the smallest possible design problem which can be easily solved by hand. It is emphasized that the number of variables and constraints increases geometrically with the increase of the relevant parameters. Since manufacturing shops usually comprise several resource groups and transporters, direct solution of the corresponding **GSD** formulations by explicit or implicit enumeration methods is not possible.

4 Model decomposition

A well known approach for large-scale optimization problems is the decomposition of the global model to subproblems that are consistent and easier to address (Nemhouser and Wolsey 1988). Since **GSD** incorporates all key subproblems of shop design, a favorable decomposition should lead to these natural components, i.e., shop layout, material flow network design, and transporter routing. Recall from the formulation of Section 3 that constraints (23)-(25) reflect the usual quadratic assignment problem (QAP) related to shop layout. The standard objective of QAP expresses the material handling effort and is given by the first two terms of (7). The flow interactions between the resource groups are included in the objective function of **GSD** through the flow variables $\mathbf{x}_{ipq}^k$ and $\mathbf{z}_{ijpq}^k$. Also, constraints (11)-(16) are integral to the formulation of the transporter routing subproblem, the objective of which is to balance material handling effort and transporter acquisition costs by routing transporters over the fixed flow network of a certain shop layout (Herrmann *et al.* 1995b). Thus, the first three terms of (7) constitute the objective function of the transporter routing problem. Finally, constraints (8)-(10) and (19)-(20) are part of the flow network design subproblem (Herrmann *et al.* 1995). The objective of this subproblem comprises the material flow given by the first two terms of the objective function of **GSD**, as well as the construction cost of the network given by the last term of (7).

4.1 The material flow network design problem

The following systematic procedure derives the design model for the material flow network from the global formulation of **GSD**.

Step 1: Fixing variables

The material flow network design subproblem assumes a fixed shop layout. Thus, the assignment of resource blocks to grid nodes is given, and the associated global variables $e_{\zeta i}$ of **GSD**, $\forall \zeta \in \mathcal{B}$ and $\forall i \in N$, are fixed to either zero or one. Furthermore, in order to consider the shop traffic caused by unloaded transporter moves, the number of transporters and the sequences of loaded moves assigned to each transporter are assumed known. Thus, the **GSD** variables, w_κ, $\forall \kappa \in V$, related to the activation of the transporters, and $h^\kappa_{\lambda\mu}$, $\forall \kappa \in V$, and $\forall (\lambda, \mu) \in C$, related to the assignment of complete moves to transporters, are fixed to either zero or one.

Step 2: Eliminating constraints

A direct result of fixing the above variables to feasible binary values is that constraints (23)-(25), which ensure the feasibility of the layout, and constraints (11)-(15), which determine the sequence of loaded moves performed by each transporter, are redundant. In addition, constraint (16) which guarantees that the transporter availability is not exceeded, is no longer applicable since moves are already assigned to transporters, $\forall \kappa \in V$, and $\forall (\lambda, \mu) \in C$.

The reduced problem still includes a very large number of flow-related variables, and some grouping of moves to commodities is required. Inspired by classical formulations of the network design model, we transform the binary flow variables ($\mathbf{x}^\kappa_{\lambda ij}$ and $\mathbf{z}^\kappa_{\lambda\mu ij}$) to continuous ones, by aggregating the moves associated with each output-input station pair to one commodity $k \in K$ (K being the set of all commodities), with origin $O(k)$ and destination $D(k)$. For the first k_1 commodities of loaded moves ($0 < k \leq k_1 < |K|$), where k_1 is the number of non-zero entries of the material flow matrix, let x^k_{ij} denote the fraction of the flow of commodity k that travels along the directed arc (i, j):

$$x^k_{ij} = \frac{1}{f_k} \cdot \sum_{\kappa \in V} \sum_{\lambda \in L_k} \mathbf{x}^\kappa_{\lambda ij} \qquad 0 < k \leq k_1 \tag{29}$$

where $L_k = \{\lambda \in L : o(\lambda) = O(k), d(\lambda) = D(k)\}$, and $f_k = |L_k|$ is the flow for commodity $k \in K$ within the design horizon T. Similarly, for unloaded moves:

$$x_{ij}^k = \frac{1}{f_k} \cdot \sum_{\kappa \in V} \sum_{(\lambda,\mu) \in C_k} \mathbf{z}_{\lambda\mu ij}^{\kappa} \qquad k_1 < k \leq |K| \tag{30}$$

where $C_k = \{(\lambda, \mu) \in C : d(\lambda) = O(k), o(\mu) = D(k)\}$, and $f_k = |C_k|$. Note that C_k is known based on the sequences of loaded moves performed by the transporters.

It is important to mention that the mapping from x_{ij}^k to $\mathbf{x}_{\lambda ij}^{\kappa}$ is not one-to-one. Given the fractional flows x_{ij}^k, the exact move numbers λ of $\mathbf{x}_{\lambda ij}^{\kappa}$ cannot be determined directly.

Step 4: Aggregating constraints

The above aggregation of flow-related variables transforms constraints (8)-(9) of the global model to the following:

$$\sum_{(j,i) \in A} x_{ji}^k - \sum_{(i,l) \in A} x_{il}^k = \begin{cases} -1 & \text{if } i = O(k) \\ 1 & \text{if } i = D(k) \quad \forall i \in N, k \in K \\ 0 & \text{otherwise} \end{cases} \tag{31}$$

Note that since variables $e_{\zeta i}$ are fixed, the right hand side of (31) can be directly set equal to 1, 0, or -1. In addition, constraint (10) of **GSD** is transformed to:

$$\sum_{k \in K} f_k(x_{ij}^k + x_{ji}^k) \leq B_{ij} \qquad \forall \{i,j\} \in \bar{A} \tag{32}$$

Finally, constraints (19)-(20) are also aggregated to the single constraint:

$$x_{ij}^k, x_{ji}^k \leq y_{ij} \qquad \forall \{i,j\} \in \bar{A}, k \in K \tag{33}$$

The reduced model contains only two types of variables. The first type comprises variables y_{ij}, which model discrete design choices, while the second type comprises variables x_{ij}^k, which represent the fraction of the flow of commodity k that travels on the directed arc (i, j).

Step 5: Mixed-integer programming model

If (x, y) is the vector of design and flow variables, with $x = (x_{ij}^k)$ and $y = (y_{ij})$, the network design problem can be formulated as follows.

Problem CFP (Fixed Charge Capacitated Network Design Problem)

$$\text{minimize} \qquad Z_{\mathbf{CFP}} = \sum_{k \in K} \sum_{(i,j) \in A} f_k x_{ij}^k + \sum_{\{i,j\} \in \bar{A}} F_{ij} y_{ij} \tag{34}$$

subject to :

$$\sum_{(j,i) \in A} x_{ji}^k - \sum_{(i,l) \in A} x_{il}^k = \begin{cases} -1 & \text{if } i = O(k) \\ 1 & \text{if } i = D(k) \quad \forall i \in N, k \in K \\ 0 & \text{otherwise} \end{cases} \tag{35}$$

$$\sum_{k \in K} f_k (x_{ij}^k + x_{ji}^k) \leq B_{ij} \qquad \forall \{i,j\} \in \bar{A} \tag{36}$$

$$x_{ij}^k, x_{ji}^k \leq y_{ij} \qquad \forall \{i,j\} \in \bar{A}, k \in K \tag{37}$$

$$x_{ij}^k \geq 0 \qquad \forall (i,j) \in A, k \in K \tag{38}$$

$$y_{ij} \in \{0,1\} \qquad \forall \{i,j\} \in \bar{A} \tag{39}$$

4.2 The transporter routing problem

A systematic procedure similar to the one for the flow network design, derives the transporter routing problem from the global formulation of **GSD**.

Step 1: Fixing variables

The transporter routing problem assumes a fixed shop layout; thus, the assignment of blocks to grid nodes is known, and the global variables $e_{\zeta\rho}$ of **GSD** are fixed to either zero or one, $\forall \zeta \in \mathcal{B}$ and $\forall \rho \in N$. In addition, since this subproblem assumes a fixed topology of the material flow network, the set of active arcs is known, and consequently, the global variables $y_{\lambda\mu}$ of **GSD** are also fixed to either zero or one, $\forall \{\lambda, \mu\} \in \bar{A}$.

Simplification of some variables is also in order based on the assumption that the paths between the origin and destination of any loaded move $i \in L$ and the unloaded component of any complete move $(i,j) \in C$ are fixed. Expression (40) provides the variable cost of loaded move $i \in L$:

$$\sum_{k \in V} \sum_{(\lambda,\mu) \in A} \mathbf{x}_{i\lambda\mu}^k \tag{40}$$

This cost is known, since $\sum_{k \in V} \mathbf{x}^k_{i\lambda\mu}$ is fixed, $\forall(\lambda, \mu) \in A$. Furthermore, the variable cost of the unloaded move between loaded moves $i, j \in L$ is given by:

$$\sum_{k \in V} \sum_{(\lambda,\mu) \in A} (\mathbf{z}^k_{ij\lambda\mu} \cdot h^k_{ij}) \tag{41}$$

where the variable h^k_{ij} of **GSD** determines if loaded moves $i, j \in L$ are matched. From expressions (40)-(41) we can determine the cost coefficients β_{ij} which provide the distance of a complete move when the transporter speed is constant and the times related to loading and unloading are not considered:

$$\beta_{ij} = \sum_{(\lambda,\mu) \in A} \sum_{k \in V} (\mathbf{x}^k_{i\lambda\mu} + \mathbf{z}^k_{ij\lambda\mu}) \tag{42}$$

Equation (42) holds for those loaded moves that are matched, i.e., for $i, j \in L$ such that $\sum_{k \in V} h^k_{ij} = 1$. The definition of the β-coefficients is extended to all possible loaded move pairs $(i, j) \in C$ as follows. For each pair of a loaded move and a *possible* unloaded move, the arcs (λ, μ) of the corresponding paths are known; thus, β_{ij} is defined by:

$$\beta_{ij} = \text{cost of the path } o(i) \rightarrow d(i) + \text{cost of the path } d(i) \rightarrow o(j) \quad \forall i, j \in L \tag{43}$$

For loaded move i, the only decision to be made is the selection of the transporter that performs this move (superscript k). The decisions involved with the possible unloaded move between i, j are: i) whether this unloaded move is performed, and ii) the selection of the transporter (superscript k). All these decisions are modeled by the variables h^k_{ij}; i.e., the values of h^k_{ij} provide all pairs of loaded moves that are performed in sequence (and the unloaded move that connects them), as well as the transporters that perform these moves. Since the paths used to perform these moves are also known, the values of the global variables $\mathbf{x}^k_{i\lambda\mu}$ and $\mathbf{z}^k_{ij\lambda\mu}$ are fixed. Consequently, the latter variables can be eliminated in the transporter routing problem.

Step 2: Eliminating/transforming constraints

A direct result of fixing the $e_{\zeta\rho}$ and $y_{\lambda\mu}$ global variables to feasible binary values is that constraints (23)-(25) and (21)-(22) of **GSD**, respectively, are no longer required. Furthermore, based on equation (42), constraint (16) of **GSD** can be appropriately transformed as follows.

$$\sum_{(\lambda,\mu)\in A}\left[\sum_{i\in L}\mathbf{x}^k_{i\lambda\mu}+\sum_{(i,j)\in C}\mathbf{z}^k_{ij\lambda\mu}\right]\le T \;\Leftrightarrow\; \sum_{i\in L}\sum_{(\lambda,\mu)\in A}\mathbf{x}^k_{i\lambda\mu}+\sum_{(i,j)\in C}\sum_{(\lambda,\mu)\in A}\mathbf{z}^k_{ij\lambda\mu}h^k_{ij}\le T$$
$$\Leftrightarrow \sum_{(i,j)\in C}\beta_{ij}h^k_{ij}\le T \qquad \forall k\in V \quad (44)$$

where $\sum_{(\lambda,\mu)\in A}\mathbf{z}^k_{ij\lambda\mu}h^k_{ij} = \sum_{(\lambda,\mu)\in A}\mathbf{z}^k_{ij\lambda\mu}$, because of constraint (17) of **GSD**. The third inequality in (44) holds since $\sum_{(\lambda,\mu)\in A}\mathbf{x}^k_{i\lambda\mu}$ is the variable cost of loaded move $i\in L$ and $\sum_{(\lambda,\mu)\in A}\mathbf{z}^k_{ij\lambda\mu}h^k_{ij}$ is the variable cost of complete move $(i,j)\in C$. The sum of these two costs also expresses the cost coefficient β_{ij} in (43).

The elimination of the $\mathbf{x}^k_{i\lambda\mu}$ and $\mathbf{z}^k_{ij\lambda\mu}$ variables renders constraints (8)-(9) and (17)-(20) of **GSD** redundant. Finally, the arc capacity constraints (10) of **GSD** are not considered in the transporter routing subproblem.

Step 3: Reducing the objective function

The transporter routing problem targets the minimization of the fixed acquisition and the variable operational costs of the material handling system. The former is given by the third term of (7), $\sum_{k\in V}W_kw_k$, while the latter is expressed as:

$$\sum_{k\in V}\sum_{i\in L}\sum_{(\lambda,\mu)\in A}\mathbf{x}^k_{i\lambda\mu}+\sum_{k\in V}\sum_{(i,j)\in C}\sum_{(\lambda,\mu)\in A}\mathbf{z}^k_{ij\lambda\mu}=$$
$$\sum_{k\in V}\sum_{i\in L}\sum_{(\lambda,\mu)\in A}\mathbf{x}^k_{i\lambda\mu}+\sum_{k\in V}\sum_{(i,j)\in C}\sum_{(\lambda,\mu)\in A}\mathbf{z}^k_{ij\lambda\mu}h^k_{ij}=\sum_{(i,j)\in C}\sum_{k\in V}\beta_{ij}h^k_{ij} \quad (45)$$

The last equality holds since the β_{ij} cost coefficients for each complete move $(i,j)\in C$ are the sum of the variable costs of a loaded and unloaded move, as in (44).

After completing Steps 1-3 above, only two types of variables are necessary to formulate the problem the transporter routing problem: w_k, which denotes which transporter $k\in V$ performs at least one loaded move in L and, h^k_{ij}, which is associated with each complete move $(i,j)\in C$ and denotes the sequence of moves performed by each transporter. The routing cost, β_{ij}, attributed to each complete move $(i,j)\in C$ is derived from equation (43).

Step 4: Integer programming model

Following the previous assumptions and simplifications, the global shop design problem **GSD** is reduced to the following:

Problem TRP (Transporter Routing Problem)

$$\text{minimize} \qquad Z_{\mathbf{TRP}} = \sum_{k \in V} W_k w_k + \sum_{(i,j) \in C} \sum_{k \in V} \beta_{ij} h_{ij}^k \tag{46}$$

subject to :

$$\sum_{(i,j) \in C} \sum_{k \in V} h_{ij}^k = 1 \qquad \forall i \in L \tag{47}$$

$$\sum_{(i,j) \in C} \sum_{k \in V} h_{ij}^k = 1 \qquad \forall j \in L \tag{48}$$

$$\sum_{(i,j) \in C} h_{ij}^k - \sum_{(j,i) \in C} h_{ji}^k = 0 \qquad \forall i \in L, \quad k \in V \tag{49}$$

$$\sum_{(i,j) \in \mathcal{C}_{1,2}} h_{ij}^k \geq h_{i_1 j_1}^k + h_{i_2 j_2}^k - 1 \quad \forall (i_1, j_1), (i_2, j_2) \in C : j_1 \neq i_2, \text{ and } i_1 \neq j_2$$
$$\forall \mathcal{C}_{1,2}, \quad \forall k \in V \tag{50}$$

$$\sum_{(i,j) \in C} \beta_{ij} h_{ij}^k \leq T \qquad \forall k \in V \tag{51}$$

$$h_{ij}^k \leq w_k \qquad \forall (i,j) \in C, \quad k \in V \tag{52}$$

$$h_{ij}^k, w_k \in \{0, 1\} \qquad \forall (i,j) \in C, \quad k \in V \tag{53}$$

5 Overview of an integrated design approach

The two MHS design subproblems (**CFP** and **TRP**) of Section 4 and the shop layout subproblem are generic optimization models. In particular, **CFP** is a multi-commodity, fixed charge, capacitated network design problem (Herrmann *et al.* 1994), which is *NP*-complete, and arises in many applications of communication and transportation networks. We have developed effective solution approaches for **CFP** that are suitable for manufacturing systems (Herrmann *et al.* 1995a). These heuristics have exhibited consistent performance for a variety of problem parameters, when tested against tight lower bounds (Herrmann *et al.* 1994).

The transporter routing problem (**TRP**) bears significant similarities with the non-depot, distance constrained vehicle routing problem with a twofold objective: minimization of the number of vehicles and of the total distance traveled (Golden and Assad 1988). We have proposed effective solution methods for this type of vehicle routing which are based on the assignment relaxation of the problem (Herrmann *et al.* 1995b). The methods utilize the special structure of the underlying graph, in which multiple arcs correspond to the same origin and destination. The performance of these algorithms has been established through theoretical evaluation of computational complexity, worst-case analysis, and extensive computational tests (Herrmann *et al.* 1995b, Ioannou 1995).

Finally, as mentioned before, the layout problem is an implicit quadratic assignment problem, for which the quadratic objective is linearized through the flow variables $\mathbf{x}_{ipq}^{k}$ and $\mathbf{z}_{ijpq}^{k}$.

We have developed (Ioannou 1995) an integrated shop design method that solves **GSD**. The method uses a global search scheme based on the simulated annealing algorithm to evaluate different shop designs and select the most appropriate one. It also incorporates a systematic generator of feasible layouts, which evolve to favorable configurations following a typical annealing process. The simulated annealing procedure solves the layout QAP. The overall cost of the layout generated in each iteration of the procedure is evaluated through a composite algorithm that solves **GSD** when the quadratic assignment variables e_{up} are fixed (i.e., the layout is known). This composite algorithm integrates the solution approaches for **CFP** and **TRP** presented in Herrmann *et al.* (1995a,b). The algorithm guarantees the feasibility of the resulting shop configuration and leads to near-optimal material handling system designs for the given layout. The simulated annealing-based search scheme converges to a complete, near-optimal shop design, that includes the actual location of the resource groups on the shop floor, the input/output station interconnection network, and the number of transporters required to serve the material flow. The quality of the final solution, as with any simulated annealing application, depends on the parameters of the search. Our implementation however, has produced exceptionally good results for numerous small to medium-size examples as well as for a large industrial application (Ioannou 1995).

6 Conclusions

This paper presented an integer programming formulation of the integrated shop design problem. The model incorporates major design decisions, such as the location of the resource groups on the shop floor, the activation of network arcs and transporters, the routing of each loaded and unloaded move over the flow network, and the sequence of moves performed by each transporter. The model also captures most critical practical concerns in the form of constraints (traffic congestion and transporter availability), or as integral parts of the objective function (tradeoff between fixed and variable costs). By evaluating the numbers of variables and constraints of the design model, it was found that explicit or implicit enumeration schemes are impractical for realistic applications. To address this issue, the global model **GSD** was decomposed to its natural components which were shown to be generic problems in operations research. They include the multi-commodity fixed charge capacitated network design, the non-depot distance constrained vehicle routing, and the quadratic assignment problems. We have developed solution approaches for these subproblems and used them in a synthetic global design method that solves **GSD** in a satisfactory manner.

Acknowledgements

This work was supported in part by the National Science Foundation under Grant # NSF EEC 94-02384. We would like to thank Professor Michael O. Ball for his help in expressing the subtour elimination constraints.

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