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An integrated model and a decomposition-based approach for concurrent layout and material handling system design ☆

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Abstract

This paper presents an integer programming formulation that 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 concerns, including the capacity of the material flow network and of the handling transporters, as well as the tradeoff between fixed (construction and acquisition) and variable (operational) costs. For realistic industrial cases, the size of the problem prevents the solution using explicit or implicit enumeration methods. Instead, the global model is decomposed into standard optimization problems: quadratic assignment, fixed charge capacitated network design, and non-depot distance-constrained vehicle routing. An integrated solution method, guided by a simulated annealing scheme, solves the global shop design problem. The algorithm takes advantage of the proposed decomposition and converges to a final design which is feasible with respect to all problem constraints. The method is applied to redesign the facility of a large manufacturer of radar antennas. The resulting shop configuration exhibits substantially decreased material handling effort, and requires significantly smaller investment costs compared to the existing facility.

Keywords: Facility layout; Material handling systems; Manufacturing systems; Vehicle routing; Decomposition; Simulated annealing

1. Introduction

An important aspect of any production system is the design of its manufacturing shop, including the material handling system (MHS) 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, & White, 1992). Additional advantages of efficient shops include effective production management, improved on-time delivery performance, enhanced product quality, and decreased inventory holding costs (Tompkins et al., 1996). Shop design comprises two highly interconnected problems, i.e., layout and 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

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includes two highly inter-related sub-problems: (i) design of the material flow network that provides the resource interconnections (Herrmann, Ioannou, Minis, Nagi, & Proth, 1995); (ii) sizing of the transporter fleet, and allocation of the inter-group moves to these transporters (Herrmann, Ioannou, Minis, & Proth, 1999). Sub-problem (ii) will be referred to as *transporter routing* throughout this paper, to be analogous to the vehicle routing problem (Golden & Assad, 1988), with which it shares significant similarities.

Many sub-problems of shop design have been addressed in the literature with various degrees of success, as discussed in survey papers (Hassan, 1994; Heragu, 1992; Ioannou & Minis, 1998; Meller & Gau, 1996; Sinriech, 1995; Welgama & Gibson, 1995). However, limited research effort has been devoted to integrating them into a unified method, despite the potential benefits of such an integrated approach (Apple & McGinnis, 1992). The most noteworthy attempts towards shop design integration are reviewed below.

Montreuil (1991) formulated a complex mixed-integer program integrating the layout and material flow network design problems, without providing any solution method. The model complexity arose from constraints that account for the shape and size of resource groups, and from the large number of zero-one decision variables. To solve this problem, Montreuil, Venkatardi, and Ratliff (1993) proposed a two-stage procedure that first establishes adjacency relations between the resource groups via some design skeleton (e.g., a flow graph, planar adjacency graph or matching-based adjacency graph), and then defines the layout and the material flow network geometrically by solving a linear program. This sequential approach does not address the inherent couplings between the sub-problems, since the flow network is designed only for the layout derived by the design skeleton. Furthermore, the different objectives of the two design stages (adjacency relations in the first step, as opposed to material handling cost in the second one) may complicate global convergence of the procedure. Banerjee, Montreuil, Moodie, and Kashyap (1992) and Banerjee and Zhou (1993) presented a similar method that considers the fact that the overall material handling effort is affected by the topology of the flow network. The proposed approach automatically identifies segments of the network which are the best candidates for improvement, and systematically adjusts the design skeleton. The adjustments are implemented according to a hill climbing solution scheme that may converge to local optima.

Banerjee and Zhou (1995) constrained the formulation of Montreuil (1991) to a material flow network that consists of a single loop, i.e., a closed, unidirectional circuit along which transporters travel continuously. In this case, the mixed-integer program decomposes into: (i) a sequencing sub-problem that determines the order in which the resource groups are visited by a transporter as it traverses the loop, and (ii) a typical layout sub-problem. The authors proposed a genetic search-based algorithm to obtain integrated solutions to these two sub-problems. A similar problem, i.e., concurrent layout and single loop design, was solved by Wu and Egbelu (1995) through an iterative scheme that generates a near-optimal flow network given a feasible layout.

Montreuil's formulation was redefined (in terms of binary variables and department area constraints) by Meller, Narayanan, and Vance (1998). The authors, based on the acyclic subgraph structure underlying their model, proposed some general classes of valid inequalities, using which, they derived a branch and bound algorithm capable of moderately increasing the range of solvable problems. Also, Peters and Yang (1997) proposed an approach for integrated facility layout and material handling system design which addresses solely semiconductor fabrication facilities, while Chittratanawat and Noble (1999) developed an integrated model for solving (via a tabu search implementation) the facility layout, departmental pickup and drop-off locations and material handling equipment selection problems. However, none of the above methods considered in an integrated manner all issues pertaining to the concurrent layout and material handling system design.

Two interactive software tools for integrated shop design are noteworthy. McGinnis (1991) proposed a modular design methodology for AGV systems. The AGV Engineering workstation allows 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. These actions are performed in an interactive fashion and various system performance characteristics, such as traffic intensity at 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 redesign. Rembold and Tanchoco (1994) proposed a similar system to help the designer develop and analyze complex material flow systems. Finally, the first approach for concur-