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A Genetic Algorithm For Facility Layout Design In Flexible Manufacturing Systems

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A Genetic Algorithm For Facility Layout Design In Flexible Manufacturing Systems

Abstract

The flexible manufacturing system (FMS) facility layout problem (FLP) involves the positioning of cells within a given area so as to minimize the material flow costs between cells. The FLP design includes specifying the spatial coordinates of each cell, the orientation of each cell in either a horizontal or vertical position, and the position of each cell's pickup and dropoff points. The layout design problem is both tactically and strategically important since the layout plays a large role in determining the efficiency and flexibility of the system. The FMS layout problem differs from traditional layout problems in that there are additional constraints on a cell's shape and orientation and the location of the pickup and dropoff points must be determined. A mixed integer programming formulation for the FLP developed by Das (1993) is adapted and heuristically solved in this paper. Because of the NP-hard nature of the solution space, a genetic algorithm based decomposition strategy is proposed and computationally tested. A comparison of the computational results with the existing methods indicate that the heuristic is a viable alternative for efficiently and effectively generating layout designs for flexible manufacturing systems.

A Genetic Algorithm For Facility Layout Design In Flexible Manufacturing Systems

1. Introduction

Flexible manufacturing systems (FMSs) have emerged in recent years as a viable answer to meet the market demand for increased product variety, short product life cycles, and uncertain demand. From a strategic perspective, an efficient layout design is critical for the implementation of an FMS, since the layout is difficult to design, costly to modify, and significantly affects the efficiency of the entire system. It has been estimated that 20%-50% of the total operating expenses within manufacturing operations are attributed to material handling, and it has been reported that effective layout design will reduce these costs by at least 10%-30% (Tompkins and White, 1984). In addition to material handling costs, the facility layout also impacts the production costs and the work-in-process inventory levels.

The design problem in a flexible manufacturing system consists of three distinct stages: (i) selection and grouping of production and material handling equipment into cells, (ii) allocation of the machine cells to areas within the shop-floor (facility layout), and (iii) detailed layout of the machines within each cell (machine layout). The first problem in this design hierarchy, the cell grouping problem has been considered by numerous researchers in the past, and is not considered in this paper. This paper addresses the FMS facility layout problem (FLP) by assuming that the composition of each cell is known. The detailed machine layout within a cell can be determined using the same approach presented here by adjusting the level of detail to consider each cell as a separate layout problem.

The layout problem in an FMS differs from the traditional facility layout problem in that there are additional features that require explicit modeling. The cells in an FMS can be represented by rectangular blocks. The pickup/dropoff point positions of each cell are usually located on either one of the cell axes. (Das, 1993). In this paper, it is assumed that the pickup/dropoff positions are collocated and are restricted to be on either one of the cell axes. Hence an FLP design includes specifying the spatial coordinates of each cell, the orientation of each cell in either a horizontal or vertical position, and the positions of each cell's pickup and dropoff point. Figure 1 illustrates the conceptual configuration of a cell.

The general facilities layout problem considers the area of the cells, but not the shape, and has been modeled in the past in several ways, such as a quadratic assignment problem (QAP), a quadratic set covering problem (QSCP), a linear integer programming problem, and a graph theoretic problem (Kusiak and Heragu, 1987). In contrast, the general machine layout problem (MLP) also considers the cell geometry, and QAP and other integer programming formulations have been suggested for determining the

machine layout. The above methods are unable to adequately solve the FMS layout problem because they neglect the additional constraints on cell orientation and pickup and dropoff point positions (Das, 1993). It has been proven that the facility layout problems fall into the class of NP-complete problems (Kusiak and Heragu, 1987). Since the layout problem in an FMS is at least as hard as the general facility layout problem, it also belongs to the class of NP-complete problems. Thus, in general, there is no computationally efficient procedure found so far to optimally solve the FLP. Hence, the need exists to develop efficient heuristic algorithms to solve the FLP, which is both tactically and strategically critical for the successful implementation of the FMS.

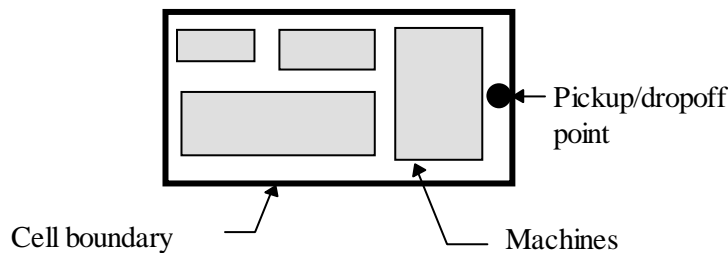


Figure 1. FLP cell illustration

Frameworks based on mixed integer programming (MIP) have been used recently to model facility layout problems. MIP formulations are able to capture all aspects of the FLP, but they are very difficult to solve using traditional branch and bound approaches. In this paper, a mixed integer programming formulation for the FLP developed by Das (1993) is adapted and heuristically solved using a genetic algorithm (GA) based decomposition strategy, which efficiently searches for good feasible solutions. The Das (1993) MIP formulation is used to provide a basis for comparing the performance of the proposed genetic search procedure in terms of both solution quality as well as computation time. The proposed solution procedure is demonstrated to be more computationally efficient and able to solve larger problems than the procedure proposed in Das (1993). As discussed later, the solution methodology proposed in this paper can also be directly extended to more general formulations for the FLP (e.g., separate pickup and deposits points for each cell) that the other solution procedures are unable to effectively solve.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature for the FMS layout problem. Section 3 presents the mixed integer programming formulation for the FLP. Section 4 describes the solution methodology based on the genetic search procedure. Section 5 provides computational results and comparisons with existing methods. Section 6 presents conclusions and future research extensions.

2. Literature Survey

The first FMS design step is to group the machines into cells. This step can be done in a variety of ways including group technology based algorithms such as those by Lee and Garcia-Diaz (1993) or Chan and Milner (1982).

Various techniques can be used to determine the layout of each cell depending on the characteristics of the particular problem. In general, the machine sizes are such that the pickup and dropoff points can be assumed to be located at the cell centroid. In fact, the solution procedure for the FLP can also apply to the machine layout design problem in an FMS cell, since the machine layout design problem is a micro-version of the FMS layout design problem. Heragu and Kusiak (1988 and 1990) contain more specific information about the machine layout problem.

This paper assumes that the machine arrangement inside a cell has been previously determined; thus, a cell geometry as well as the distance between the potential pickup and dropoff positions and the cell centroid are known. The FLP arranges the FMS cells on an open-field floor space in order to minimize the total material handling costs.

Traditional layout design problems have been extensively studied, but these procedures are unable to solve the FLP because of the insufficient design information on a cell's shape and pickup and dropoff point positions. For a detailed discussion of traditional layout approaches, readers are referred to Francis *et al.* (1992), Kusiak and Heragu (1987), and Meller and Gau (1996).

Some general machine layout design methods consider the cell shape constraints given a predetermined design configuration. The cell orientation is fixed to either horizontal or vertical and the pickup and dropoff points are assumed to be located at the cell centroid. Luggen (1991) identifies several commonly used FMS layout design configurations: spine, circular, ladder, and open-field layout. Figure 2 provides an illustration of these configurations. The open-field type layout, where there is no predetermined layout pattern, is difficult to solve and is the primary focus of this paper. For the other design configurations, readers are referred to Meller and Gau (1996), Hassan (1994), and Heragu and Kusiak (1988) for detailed discussions.

Heragu and Kusiak (1990) formulate a construction type open-field machine layout problem as an integer program. Solving this formulation is computationally inefficient, as reported by Heragu and Kusiak (1990), therefore, they develop an expert system approach to solve the machine layout problem. For a particular situation, the solution quality clearly depends on the appropriateness of the built-in decision rules.

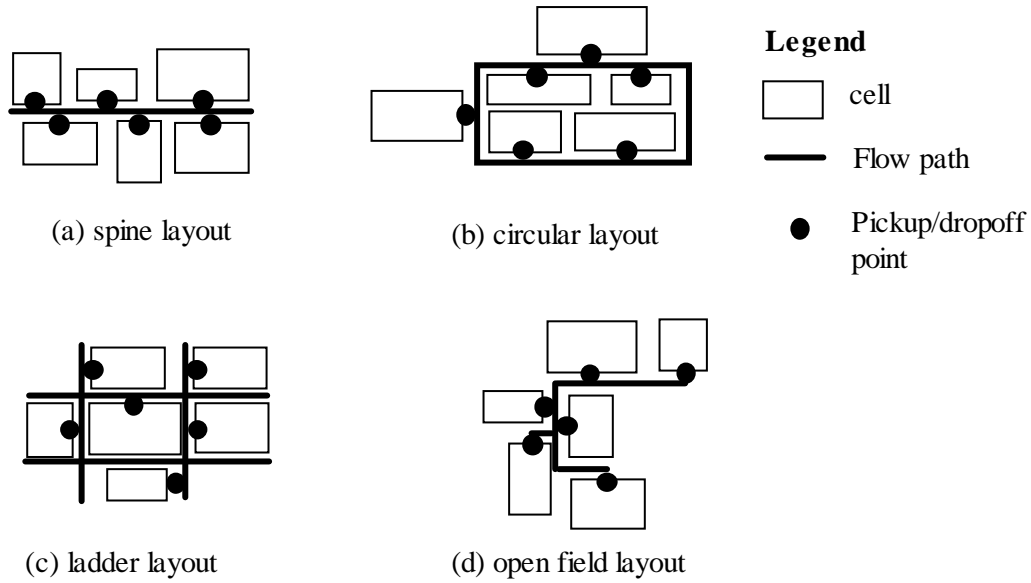


Figure 2. FLP configurations

When machine layout solution methods are applied to the FLP, they only provide a partial solution because of the lack of information on the pickup/dropoff point positions and cell orientation. Another problem for most of the existing machine layout procedures is that they require the location of sites to be known *a priori* (Jacob, 1987; Heragu and Kusiak, 1988). When a layout is constructed in an open-field configuration, these existing methods are unable to determine a suitable design.

Das (1993) proposed a four-step heuristic to solve the FLP. This heuristic develops an upper bound on the solution value, and then uses a loose approximation of the cell overlap constraints to solve a portion of the problem. These values are then fixed and passed to the next steps where the remainder of the problem is solved. This four-step heuristic is computationally inefficient as the problem size increases (Das, 1993). Section 5 provides computational results comparing the proposed genetic search heuristic for the FLP with the procedures of Das (1993).

3. FLP Mixed Integer Program Formulation

This paper focuses on developing an efficient heuristic to solve the FLP. This formulation assumes that each cell has a rectangular shape (or uses the smallest enclosing rectangle of a cell), the pickup and dropoff points are collocated and are restricted to be located on either one of the cell axes. The decision variables are the coordinates of the cell centroids within the floor space, the orientation of each cell, and the position of each cell's pickup/dropoff point position. Additional constraints are added to ensure that there is no

overlap between cells. The distance between cell pickup and deposit points is estimated with a rectilinear distance metric. The absolute value signs are removed by using additional variables and constraints.

3.1 FLP Formulation

This FLP formulation follows the one developed by Das (1993). Readers are referred to Das (1993) for further details about the formulation. First, a set of notation is defined for the MIP formulation. Let

N = the total number of cells in a layout

i, j : indices for cells; $i, j = 1, \dots, N$

u_{ij} = the directed flow density from cell i to cell j

ε_{ij} = the cost per unit distance for a unit of flow from cell i to cell j

M = a big number (i.e., a surrogate for infinity)

w_i = the width of cell i

v_i = the height of cell i ($w_i \geq v_i$)

O_i = offset of the pickup/dropoff point from the centroid of cell i

W = the width of the floor space

H = the height of the floor space

$Z_i = \begin{cases} 1, & \text{cell } i \text{ is in vertical position (the shorter side at the bottom)} \\ 0, & \text{cell } i \text{ is in horizontal position (the longer side at the bottom)} \end{cases}$

(x_i, y_i) = spatial coordinates of the centroid of cell i

(px_i, py_i) = spatial coordinate of the pickup/dropoff point of cell i

$\lambda_{1i} = 1$, pickup/dropoff point of cell i is on the right-hand side of the cell center; 0, otherwise

$\lambda_{2i} = 1$, pickup/dropoff point of cell i is below the cell center; 0, otherwise

$\lambda_{3i} = 1$, pickup/dropoff point of cell i is on the left-hand side of the cell center; 0, otherwise

$\lambda_{4i} = 1$, pickup/dropoff point of cell i is above the cell center; 0, otherwise

$\alpha_{ij} = 1$, if $x_i \geq x_j$ (i.e., the centroid of cell i is to the “right” of the centroid of cell j); 0, otherwise

$\beta_{ij} = 1$, if $y_i \geq y_j$ (i.e., the centroid cell i is “above” the centroid of cell j); 0, otherwise

θ_{ij} = binary variable indicating cell interference

$E_{ij}(F_{ij})$ = the positive (negative) component of $x_i - x_j$

$G_{ij}(H_{ij})$ = the positive (negative) component of $y_i - y_j$

$P_{ij}(Q_{ij})$ = the positive (negative) component of $px_i - px_j$

$R_{ij}(S_{ij})$ = the positive (negative) component of $py_i - py_j$

For modeling convenience, we define the following sets $\Lambda = \{(i, j) | i = 1, \dots, N; j = i+1, \dots, N\}$ and Π_1 (Π_2) = {the set of cells with pickup/dropoff point along the long (short) side}. Then, the mixed integer program formulation of the FLP is as follows.

$$\text{Minimize } \sum_{i=1}^N \sum_{j=i+1}^N \varepsilon_{ij} u_{ij} (P_{ij} + Q_{ij} + R_{ij} + S_{ij}) \quad (1)$$

subject to

$$x_i - x_j = E_{ij} - F_{ij} \quad (i, j) \in \Lambda \quad (2)$$

$$y_i - y_j = G_{ij} - H_{ij} \quad (i, j) \in \Lambda \quad (3)$$

$$E_{ij} \leq \alpha_{ij} M \quad (i, j) \in \Lambda \quad (4)$$

$$F_{ij} \leq (1 - \alpha_{ij}) M \quad (i, j) \in \Lambda \quad (5)$$

$$G_{ij} \leq \beta_{ij} M \quad (i, j) \in \Lambda \quad (6)$$

$$H_{ij} \leq (1 - \beta_{ij}) M \quad (i, j) \in \Lambda \quad (7)$$

$$E_{ij} + F_{ij} - \frac{1 - Z_i}{2} w_i - \frac{Z_i}{2} v_i - \frac{1 - Z_j}{2} w_j - \frac{Z_j}{2} v_j \geq -M\theta_{ij} \quad (i, j) \in \Lambda \quad (8)$$

$$G_{ij} + H_{ij} - \frac{1 - Z_i}{2} v_i - \frac{Z_i}{2} w_i - \frac{1 - Z_j}{2} v_j - \frac{Z_j}{2} w_j \geq -M(1 - \theta_{ij}) \quad (i, j) \in \Lambda \quad (9)$$

$$px_i = x_i + (O_i \lambda 1_i) - (O_i \lambda 3_i) \quad i = 1, \dots, N \quad (10)$$

$$py_i = y_i + (O_i \lambda 4_i) - (O_i \lambda 2_i) \quad i = 1, \dots, N \quad (11)$$

$$\lambda 1_i + \lambda 3_i = Z_i \quad i \in \Pi_1 \quad (12)$$

$$\lambda 2_i + \lambda 4_i = 1 - Z_i \quad i \in \Pi_1 \quad (13)$$

$$\lambda 1_i + \lambda 3_i = 1 - Z_i \quad i \in \Pi_2 \quad (14)$$

$$\lambda 2_i + \lambda 4_i = Z_i \quad i \in \Pi_2 \quad (15)$$

$$px_i - px_j = P_{ij} - Q_{ij} \quad (i, j) \in \Lambda \quad (16)$$

$$py_i - py_j = R_{ij} - S_{ij} \quad (i, j) \in \Lambda \quad (17)$$

$$\left. \begin{aligned} &Z_i, \alpha_{ij}, \beta_{ij}, \theta_{ij}, \lambda 1_i, \lambda 2_i \in \{0, 1\} \\ &0 \leq x_i, dx_i, px_i, E_{ij}, F_{ij}, P_{ij}, Q_{ij} \leq W \\ &0 \leq y_i, dy_i, py_i, G_{ij}, H_{ij}, R_{ij}, S_{ij} \leq H \end{aligned} \right\} \quad i = 1, \dots, N \text{ and } (i, j) \in \Lambda \quad (18)$$

Constraints (2) to (7) are used to eliminate the absolute value sign for the rectilinear distance between the centroid of cell i and the centroid of cell j . Constraints (8) and (9) are to ensure that there is no overlap between any pair of cells. The variables θ_{ij} force cells i and j to not overlap in either the vertical direction ($\theta_{ij} = 1$) or in the horizontal direction ($\theta_{ij} = 0$). Constraints (10) and (11) are the transformations of the

rectilinear distances between the pickup/dropoff point of cell i and its centroid. Constraints (12) to (15) relate a cell's pickup/dropoff point position to its cell centroid for the different configurations. Constraints (16) and (17) are used to remove the absolute value signs of the distance between the pickup/dropoff point of cell i and the pickup/dropoff point of cell j . Constraints (18) specify the bounds for each variable. Due to the interrelationships between pickup/dropoff points, λ_{3i} and λ_{4i} are not required to be integer restricted.

4. Solution Methodology

The formulation presented in Section 3 has $1.5(N^2 - N)$ binary variables for a layout problem of N cells and is very hard to solve for realistic problems using standard linear programming based branch and bound approaches. In this paper, a two step hierarchical decomposition approach is developed to intelligently search the solution space to obtain good solutions in a fast manner. The first step in the hierarchy is to determine the spatial sequence for cells in both x (horizontal) and y (vertical) directions. This step restricts the candidate region for a cell's location in an open-field floor space. A greedy genetic algorithm is developed to determine the spatial sequence for the cells, which defines the candidate regions. The second step in the hierarchy is to search this restricted space to obtain a good solution to the FMS layout problem. A slightly different genetic search procedure is developed to search the restricted solution space. Figure 3 illustrates this two-step GA based heuristic procedure for solving the FLP.

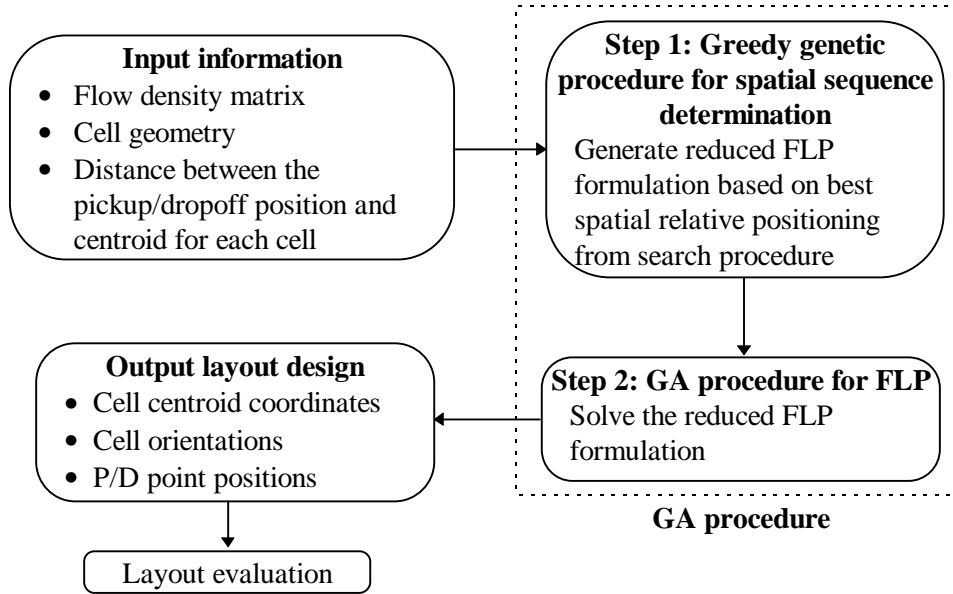


Figure 3. GA based two-step heuristic procedure

4.1 Overview of Genetic Algorithms

Genetic algorithms attempt to mimic the biological evolution process for discovering good solutions. They are based on a direct analogy to Darwinian natural selection and mutations in biological reproduction and belong to a category of heuristics known as *randomized heuristics* that employ randomized choice operators in their search strategy and do not depend on complete *a priori* knowledge of the features of the domain. These operators have been conceived through abstractions of natural genetic mechanisms such as crossover and mutation and have been cast into algorithmic forms (Arunkumar and Chockalingam, 1993). Repetitive executions of these heuristics need not yield the same solution.

A genetic algorithm maintains a collection or population of solutions throughout the search. It initializes the population with a pool of potential solutions to the problem and seeks to produce better solutions (individuals) by combining the better of the existing ones through the use of one or more genetic operators. Individuals are chosen at each iteration with a bias towards those with the best objective values. With various mapping techniques and an appropriate measure of fitness of individuals (*i.e.*, objective function value), a genetic algorithm can be tailored to evolve a solution for many types of problems, including optimization of a function or determination of the proper order of a sequence.

Theoretical analyses suggest that genetic algorithms can quickly locate high performance regions in extremely large and complex search spaces. In addition, the distributed and repeated sampling can lead to some natural insensitivity to noisy feedback. The genetic algorithm based heuristics are highly suited for application to large instances of problems that are hard to model and for which no satisfactory tailored algorithms are available. Readers are referred to Schaffer *et al.* (1992), Goldberg (1989), and Holland (1992) for more information about genetic algorithms.

For large MIP formulations, stochastic global optimization methods such as simulated annealing (SA) and genetic algorithms have recently shown great promise. The SA based approaches operate on one intermediate solution at a time, whereas GA utilizes the past information by simultaneously operating on a population of solutions. Genetic algorithms can combine the desirable features of two radically different previous solutions unlike the SA approach where only one previous solution is transmitted (Banerjee *et al.*, 1994). Researchers in the past have successfully applied genetic approaches for facilities layout design. In particular, Banerjee *et al.* (1992) and Banerjee and Zhou (1995) have successfully used a genetic approach to determine the facilities layout design for a single loop material flow path configuration.

4.2 Basic Genetic Algorithm Procedure

The search technique consists of generating an initial population of strings (symbolic representation of a set of solutions using binary bits) at random. Each solution is assigned a numerical evaluation of its fitness

by an objective function, which is a mathematical function that maps a particular solution onto a single positive number that is a measure of the solution's worth. During each iteration (generation), each individual string in the current population is evaluated using this measure of fitness. New strings (children) for the next generation are selected from the current population of strings (parents) by a process known as *selection*. A random selection process is used with a higher probability given for strings with higher fitness values. Such a selection scheme systematically eliminates low-fitness individuals from the population from one generation to the next. New generations can be produced either synchronously, so that the old generation is completely replaced, or asynchronously, so that the generations overlap. This paper uses the technique of *steady-state reproduction without duplicates* proposed by Whitley (1988) and Syswerda (1989). This technique creates a certain number of children to replace the parents in the population, but discards children that are duplicates of current individuals in the population.

Two genetic operators, *crossover* and *mutation*, are probabilistically applied to create a new population of individuals. In crossover, individual strings in the current population are randomly selected two at a time as parents, and the crossover operation exchanges cross sections of the parents to generate two new individuals. A cut point is randomly chosen within the breeding pair of parent strings. New individuals are formed by combining the initial components of the first parent string with the last components of the second parent string and vice versa. The number of crossovers done in a generation is controlled by the crossover rate (CR), which is defined as the ratio of the number of new individuals produced in each generation (by crossover) to the population size. *Mutation* involves flipping a 0 bit to 1 or vice versa. The number of bits to mutate and the specific bits to mutate are chosen in a random manner. The number of mutations performed in a generation is controlled by a mutation rate parameter (MR), which is defined as the ratio of the new individuals produced in each generation (by mutation) to the population size.

In the GA based solution procedure, the number of new individuals created at each iteration is $(CR + MR)P = \delta P$. The remaining individuals are obtained by deterministically copying the individuals with the top $(1-\delta)100\%$ fitness from the previous generation. Parent individuals are selected as candidates for *crossover* or *mutation* using the following *selection* process. An individual is selected at random and its objective function value is compared with the average objective function value of the generation. If it has a better objective function value than the generation average, it is accepted as a parent. If its objective function value is lower than the generation average, it is accepted as a parent with probability < 1 .

Genetic algorithms are domain independent because they require no explicit notion of a neighborhood. Hence, *crossover* and *mutation* may not always produce feasible solutions. Therefore, the feasibility of a newly created individual is ascertained before inserting it in the population to replace a parent string.

4.3 Genetic Algorithm Based Two Step Heuristic Procedure

The overall design of the specific genetic search procedure developed for solving the FLP is depicted in Figure 4. The details of the two steps in the heuristic procedure are presented in Section 4.3.1 and 4.3.2.

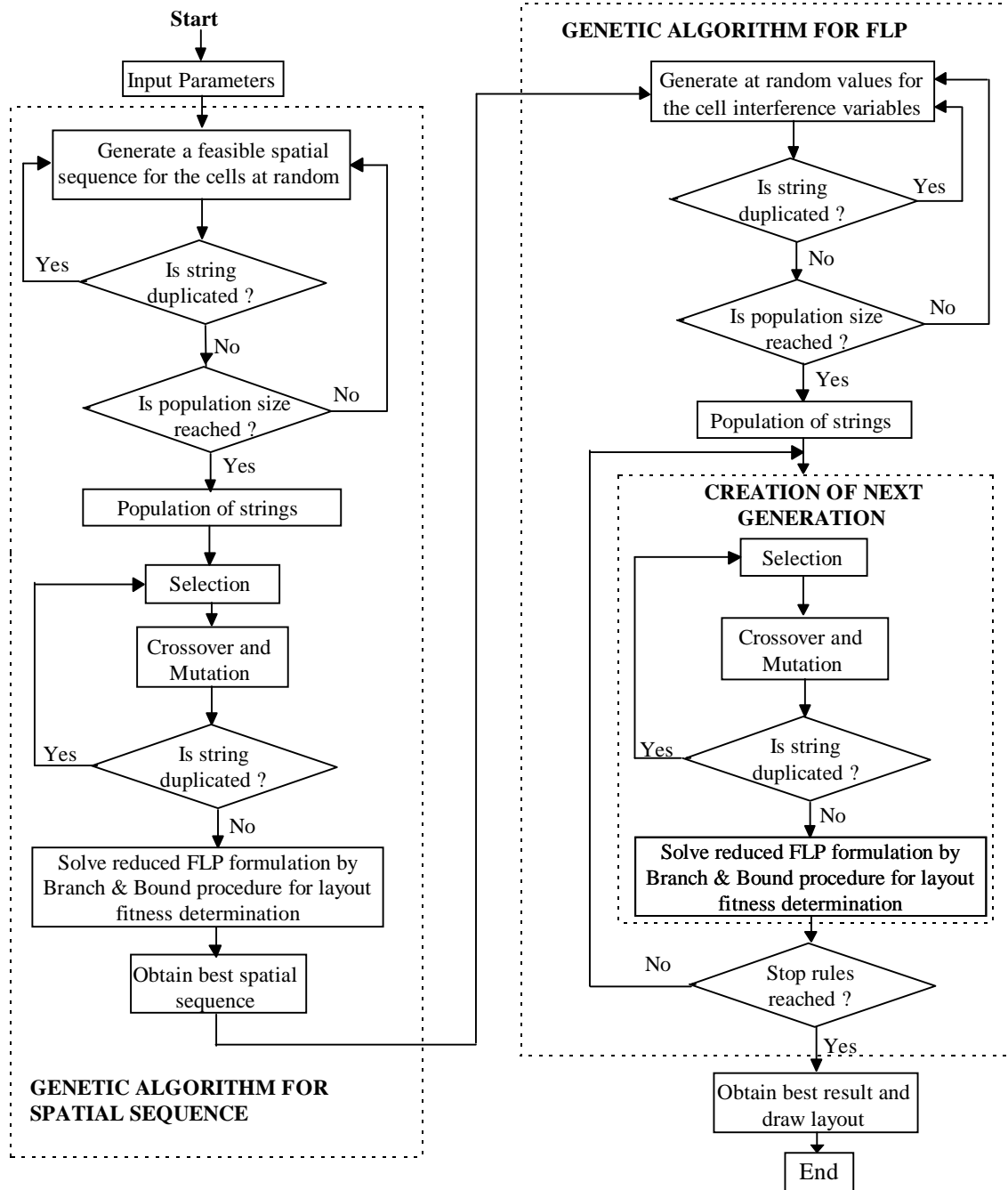


Figure 4. Genetic algorithm search procedure for FLP

4.3.1 Genetic Algorithm for Spatial Sequence Determination

The first step in the heuristic procedure for solving the FLP is to determine the relative spatial positioning among the cells. A greedy genetic algorithm has been developed to determine the spatial sequence for the cells in an open-field floor space. The algorithm performs a first search with no backtracking and hence the term “greedy” is used. The string for the genetic algorithm is in binary code and is of size $1.5(N^2 - N)$ for a layout problem of N cells. The first $0.5(N^2 - N)$ bits in the string represent the spatial sequence for the cells in the x (horizontal) direction corresponding to the variables α_{ij} in the formulation. The second $0.5(N^2 - N)$ bits in the string represent the spatial sequence for the cells in the y (vertical) direction corresponding to the variables β_{ij} in the formulation. The third $0.5(N^2 - N)$ bits in the string represent the cell interference information corresponding to the variables θ_{ij} in the formulation.

A feasible spatial sequence can be obtained by randomly generating unique values for x_i 's and y_i 's and ranking them according to these values. From these ordered x_i 's and y_i 's, the values for the α_{ij} and β_{ij} variables can be determined (recall that $\alpha_{ij}(\beta_{ij}) = 1$ if $x_i \geq x_j$ ($y_i \geq y_j$)). This process provides the values for the first $(N^2 - N)$ values of the string. For the cell interference variables θ_{ij} , a one in the string means that cell i and cell j will not overlap in the y (vertical) direction, and a zero in the string means that there will be no overlap in the x (horizontal) direction. The values for these variables are generated at random. A given string thus fixes the α_{ij} , β_{ij} , and θ_{ij} variables in the formulation. The resulting reduced formulation can be easily solved using a branch and bound procedure to determine the best layout given the restrictions specified by the string. The resulting material handling cost (objective value) for the cell layout specified by that particular string is considered as the measure of the string's fitness or competence.

The genetic algorithm procedure can be summarized as follows:

Initialize a population of feasible solutions

1. Generate at random a feasible spatial sequence for the cells (α_{ij} and β_{ij}) and values for the cell interference variables (θ_{ij}).
2. Repeat step 1 until P feasible solutions are obtained.

Evaluate each individual in the population

3. Based on the α_{ij} , β_{ij} , and θ_{ij} values determine the objective function value for each individual in the population using the branch and bound procedure. This step creates a specific layout that satisfies the relative position of cells specified by α_{ij} , β_{ij} , and θ_{ij} . The material handling cost of this layout is used as the objective function value for the individual.

Create new individuals using genetic operators

4. The genetic operators, *mutation* and *crossover*, are used to generate P new individuals. The parent individuals are selected as candidates for *mutation* and *crossover* based on the selection procedure described in Section 4.2. In *mutation*, a number, M , between 1 and $1.5(N^2 - N)$ is generated at random. From the selected parent individual, M bits are chosen at random and flipped (change a 0 bit to a 1 or vice versa). In *crossover*, two parent individuals are selected and a cut point is chosen at random. Two new individuals are formed by combining the initial components of the first parent string with the last components of the second parent string and vice versa. A layout is created based on the new string using the LP-based branch-and-bound procedure. The objective function value (material handling cost) is used to evaluate the fitness of the individual. Note that the individual string may not be feasible. That is, the mutation and crossover operations may create an inconsistent string (e.g. $\alpha_{ij} = 1$ and $\alpha_{jk} = 1$; but $\alpha_{ik} = 0$). Infeasible individuals are discarded and a new candidate string is formed.

Spatial Sequence Determination

5. The string with the highest fitness value among the generated P individuals (*i.e.*, lowest objective function value) gives the final solution for the first step in the hierarchy. The spatial sequence of the cells in this string (represented by the first $(N^2 - N)$ bits in the string) is considered as the best spatial sequence for the cells and this information is passed to the second step in the heuristic strategy to determine the solution to the FMS layout problem.

4.3.2 Genetic Algorithm for FMS Layout Problem

The spatial sequence information obtained from the first step is used to modify the FLP formulation presented in Section 3. Since the cell centers in the final layout must follow the spatial ranking determined in the first step, the integer variables α_{ij} and β_{ij} in the formulation can be fixed accordingly. The string for the genetic algorithm in this second phase is of size $0.5(N^2 - N)$ for a layout problem of N cells. The bits in the string represent the cell interference information corresponding to the variable α_{ij} in the formulation.

Once the spatial sequence of the cells is found in the first step and the α_{ij} and β_{ij} variables are fixed, the cell interference variables are determined based on the generated search strings from the second GA procedure. The resulting reduced formulation is solved using a standard linear programming based branch and bound methodology. This problem can be solved in a very efficient manner because the complicating cell spatial sequence and cell overlap constraints are no longer needed.

The genetic algorithm for the FLP can be described as follows:

Initialize a population of solutions

1. Generate at random the values for the cell interference θ_{ij} variables.
2. Repeat step 1, until P solutions are obtained.

Evaluate each individual in the population

3. Based on the spatial sequence (α_{ij} and β_{ij}) provided by the first phase in the heuristic strategy and the cell interference information θ_{ij} generated in step 1, determine the objective function value for each individual in the population using the branch and bound procedure. Again, the objective function value is the material handling cost of the layout that is determined to satisfy the α_{ij} , β_{ij} , and θ_{ij} values.

Create new individuals using genetic operators

4. The genetic operators, *mutation* and *crossover*, are used to generate δP new individuals ($\delta \leq 1$). This step is similar to step 4 of the procedure described in Section 4.3.1, with the only difference being that the string length is now $0.5(N^2 - N)$.
5. Determine the objective function value for each new individual as described in step 3.

Delete members of population to make room for inserting the new individuals

6. Retain the best $(1-\delta)100\%$ (in terms of objective function value) of the parent individuals and delete the rest to make room for the newly created individuals.
7. Insert the newly created solutions, and determine the average objective function value for the new generation.

Stopping rule

8. The search procedure (steps 1-7) is repeated until the average objective function value for the current generation differs from that of the previous generation by less than 1 percent, or the best solution in the population has not changed for 10 subsequent generations. Once this terminating condition has been reached, the facility layout that has the highest fitness (i.e., the lowest objective function value in terms of material handling cost) is selected as the best solution for the problem.

Though genetic algorithms are effective search techniques, they are known to be sensitive to control parameters, *e.g.*, population size, rates of crossover (*CR*) and mutation (*MR*), methods of selection, *etc.* (Schaffer *et al.*, 1992). Previous attempts at establishing an analytical measure for optimal choices of control parameters in genetic algorithms have not resulted in any closed form equations due to the complex nature of the interactions, the problem specific nature of the search procedure parameters, and computationally intensive validating procedures. In addition, all of the previous studies in parameter optimality considerations have focused on unconstrained optimization problems, whereas the FLP has

constraints. Based on all these factors, it was decided to conduct pilot studies beginning with parameter value ranges that have been previously reported to yield good results and then perturb them to determine good parameter values for the FLP problem under consideration (Banerjee *et al.*, 1994). The control parameter values and terminating condition used in the genetic algorithms were selected based on several preliminary runs with alternate control parameters and terminating conditions on different instances of the problem. These values were then used for the test problems reported in the computational results. The final parameter values used in the computational experiments for the genetic algorithm procedure are summarized in Table 1.

Table 1. Parameter values for the genetic procedure

<i>Description</i>	<i>Parameter</i>	<i>Values</i>
Population Size	P	50
Crossover rate	CR	0.8
Mutation rate	MR	0.1
Percentage of solutions replaced by new generation	δ	0.9
Probability of accepting an individual with fitness value less than average as a parent	γ	0.2

5. Computational Results

A study was performed to investigate the performance of the genetic algorithm based search heuristic in terms of both speed and solution quality. The results provided by the heuristic are compared with those provided by the four step heuristic of Das (1993) for the corresponding problem set used in that article.

Two problem sets are used for the computational experiments. The first problem set consists of five problems from Das (1993). The second problem set consists of three larger problems developed by the authors. In all problem sets, the cost per unit distance, ϵ_{ij} , is assumed to be 1.

The genetic algorithms are written in C and executed on an IBM RISC/6000 workstation. The algorithms make use of the callable libraries provided in the CPLEX (1994) optimization package. In the first problem set, the 4-cell and the 6-cell problems are solved optimally, which provides reference information regarding the solution quality of the proposed GA heuristic. Unfortunately for larger problems, *i.e.* layouts with more than 6 cells, optimal solutions could not be found. Furthermore, a good lower bound is not available for the FLP, since the linear programming relaxation of the FLP formulation has a value close to zero. When the integrality restrictions on the variables, θ_{ij} , are relaxed, the cell non-

overlap constraints are no longer enforced. Therefore, all cells are placed on top of each other, which results in a small objective function value.

Das (1993) reports results for the four-step heuristic solving the problems in set 1. These results are repeated in column 4 of Table 1, labeled “original four-step.” Since the computation times for the four-step heuristic were not reported in the paper, the authors implemented the four-step heuristic from Das (1993) to obtain some estimate of the computation times. Because these times turned out to be very long, a computational time limit of 72000 seconds was set for the second step, which has the longest computation time in the four-step heuristic. When this time limit was reached, the best known integer feasible solution was recorded and passed to the third step. The columns labeled “four-step” refer to our implementation of the four-step heuristic. It must be noted that Das’s original results are better in some cases, suggesting that very long run times were allowed or some specialized procedures were used to solve the four-step subproblems. The complete experimental results are summarized in Table 1, Table 2, and Figure 4.

Table 1. Material flow costs for problem set 1

No. cells	Optimal	Original Four-step	Four-step	GA Procedure	GA improvement
4	1393.6	1679.4	1631.6	1393.6*	17.08%
6	2612.7	2620.0	3163.4	2612.7*	21.08%
8	N/A	10777.1	10374.1	9174.8	13.07%
10	N/A	15878.3	20791.4	19777.3	5.13%
12	N/A	41267.5	49082.5	45353.5	8.22%

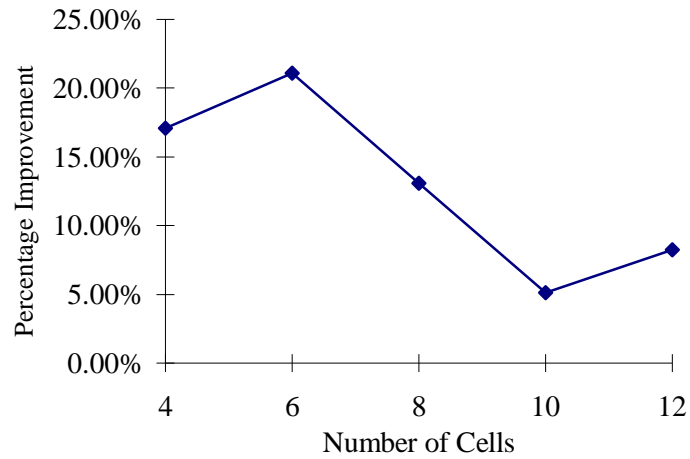
* Optimal solution obtained using the GA procedure

Table 2. Material flow costs for problem set 2

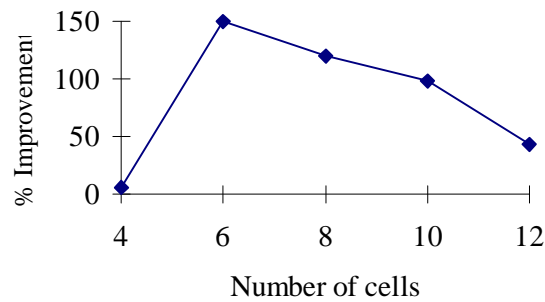
No. of cells	GA Procedure
14	51154.5
16	64371.4
18	78567.8

Table 3. Time comparisons for problem sets 1 and 2 (in seconds)

	No. of cells							
	4	6	8	10	12	14	16	18
Optimal	55	16980	N/A	N/A	N/A	N/A	N/A	N/A
Four-step	10	41286	36010	72220	72360	N/A	N/A	N/A
GA	66	273	297	725	1643	3128	4567	7200



(a) Solution quality



(b) Computation time

Figure 4. Proposed heuristic benefits relative to the four-step heuristic

A comparison of the results obtained using theDas (1993) “four-step” heuristic and the genetic algorithm based decomposition search strategy indicates that the genetic procedure performs better than the “four-step” heuristic in terms of both solution quality and computation time. For smaller problems (up to 6

cells), the genetic search procedure yields the optimal solution, and for larger problems, the solution provided by the genetic procedure is better than the ones provided by the “four-step” heuristic. Figure 4 indicates that the solution quality improves anywhere from 5 to 20%.

The proposed heuristic is also far superior in terms of computational efficiency. For a 10 cell problem, the solution time with the “four-step” heuristic is 72,220 seconds whereas the solution time with the genetic search procedure is 725 seconds. This shows that for reasonably large instances of the problem, the developed procedure can produce solutions of superior quality in run times that are orders of magnitude faster than the “four-step” heuristic. The run time performance of the heuristic is shown in Figure 4(b). In addition, it is possible to use the proposed heuristic to solve larger problems that are practically impossible to solve using the previously developed procedures.

It must be noted here that the above comparison is done based on a single run of the genetic procedure for each of the problems. Since the solution methodology uses a randomized search procedure, different runs may provide different solutions. For example, five runs of the 10 cell problem gave results ranging from 19024 to 20111. In practice, depending on the nature of the problem, several runs can be made, and the best solution among them chosen as the layout design. The computational efficiency of the procedure together with its high solution quality makes it a very attractive tool for layout designers, since alternative solutions for reasonable problem sizes can be repeatedly generated in a short time and the best solution adopted.

6. Conclusions and Future Research

A key issue in implementing an FMS is the facility layout design since the production function of an FMS is significantly affected by the layout of its manufacturing shop. The layout greatly impacts the production and material handling costs, the work-in-process inventory levels, and the overall efficiency of the manufacturing system. The FMS layout problem differs from traditional layout problems in that there are additional constraints on a cell's shape, orientation, and pickup/dropoff point positions, which further complicate the problem. In this paper, a heuristic strategy is developed for solving this problem.

Because of the NP-hard nature of the solution space, a genetic algorithm based decomposition heuristic strategy is employed to sample the decomposed search spaces. For smaller problems, this heuristic procedure yields optimal solutions, and for larger problems, the heuristic procedure outperforms the existing methods in terms of both speed and solution quality. The computational results with the existing methods indicate that the heuristic is an attractive alternative for efficiently and effectively generating layout designs for flexible manufacturing systems.

Conceptually, it is easy to extend the formulation for the FLP to include more general problem situations, e.g., separated pickup and deposit points that can be located anywhere along the boundary of the cell. The genetic algorithm procedure can be easily extended to this case since the string composition is not affected. In addition, the pickup and deposit locations could be modeled as decision variables in the problem. The proposed genetic algorithm could also be extended to this case. There are two possible methods: setting the decision variables explicitly in the genetic search procedure or setting those variables in the layout determination phase to check solution feasibility. Current research efforts are addressing this problem to determine the best approach with the aim of developing computationally efficient heuristics to solve the general FMS layout problem.

7. References

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