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Cell formation and layout designs in a cellular manufacturing environment—a case study

M. BAZARGAN-LARI†*, H. KAEBERNICK‡ and A. HARRAF†

This paper presents the application of a recent integrated approach for the design of cellular manufacturing, addressing, concurrently, all three phases of the design—namely parts/machines grouping, intra-cell and inter-cell layout designs—to a white-goods manufacturing company. It provides a platform to investigate the impact of the cell formation method on intra-cell and inter-cell layout designs, and vice versa, by generating multiple efficient layout designs for different cell partitioning strategies. This approach enables the decision-maker to have wider choices with regard to the different numbers of cells and to assess various criteria such as travelling cost, duplication of machines and space requirement against each alternative.

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1. Introduction

Cellular Manufacturing (CM), an application of Group Technology (GT), utilizes the concept of divide and conquer and involves the grouping of machines, processes and people into cells responsible for manufacturing or assembly of similar parts or products (Heragu 1994).

Different and independent surveys conclude that significant improvements can be achieved as a result of implementing CM in areas such as lead times, set-up times, work in process, quality, machine utilization and employee job satisfaction (see, for example, Wemmerlov and Johnson 1997).

To determine the impact of CM on Australian manufacturers, a joint academia/industry survey was conducted. This survey included 209 companies, all with a minimum annual turnover of $25 million. The study revealed that 52% of the companies surveyed are already using or are in process of implementing CM, with a further 28% indicating their future plans to introduce CM to some part of their operations. Of the companies already using CM, more than 70% reported improvements in one or more aspects of lead times, lot sizes, labour productivity, set-up times, on-time delivery, labour flexibility and quality. The main attraction of CM to these companies was that it normally requires no additional capital investment or workers.

The design for cellular manufacturing involves three stages (Jajodia *et al.* 1992): (i) grouping of parts and production equipment into cells; (ii) allocation of the machine cells to areas within the shop floor (inter-cell or facility layout); and

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(iii) layout of the machines within each cell (intra-cell or machine layout). The realization of benefits expected from Cellular Manufacturing (CM) largely depends on how effectively the three phases of the design have been performed.

A common strategy adopted by many researchers in addressing these sub-problems is to address each phase separately and sequentially without evaluating the impact of each phase on the previous phase(s). This limitation results in generating solutions, which may be efficient to one particular phase, but it does not necessarily offer a good solution to the overall CM design (Hassan 1995). The existing layout algorithms for CM often fall short of addressing the practical issues normally present in a real-world problem. These limitations include lack of consideration for issues such as cells/machines dimensions, closeness relationships, aisles, location restriction-preferences and, most important of all, the possibility of generation multiple layout designs.

This paper presents the application of an integrated approach to the three phases of the design of cellular manufacturing to a white-goods manufacturing company in Australia. In this approach, the decision-maker is provided with multiple efficient alternative solutions according to different cell-partition strategies. It offers the flexibility to assess each alternative against tangible and intangible benefits and criteria.

This research work is the extension of the authors' work on the integration of inter and intra-cell layout designs (Bazargan-Lari and Kaebernick 1996a, 1997). In these publications it is shown how the two sub-problems pertaining to the layout design of CM are related, and the need for an integrated approach to address both the intra-cell and inter-cell layouts is demonstrated.

Sections 2 and 3 of this paper briefly present an overview of the mathematical model and the solution methodology proposed in the earlier publications. The solution methodology includes a hybrid of two optimization methodologies, namely *nonlinear goal programming* in the class of multiple-objective models and *simulated annealing* in the class of random search methods. Section 4 provides the mathematical background and the solution methodology to a modified cell formation method, and section 5 presents the application of the model to a manufacturing company in Australia. Finally, section 6 concludes this paper.

2. Mathematical model

Currently there are numerous optimization models in the literature for each of the three phases of the design for cellular manufacturing; namely, cellpartitioning, intra-cell layout and inter-cell layout. These models are developed separately without considering the impact of one phase on the other two. This approach (sub-optimization) results in a solution that may be good or even optimal for one phase but does not necessarily offer a good overall solution for all the three phases of the design.

In order to provide a comprehensive solution to all three phases of the design, this paper attempts to integrate the intra-cell and inter-cell layout design models developed by the authors (Bazargan-Lari and Kaebernick 1996a,b, 1997) with a modified exiting cell-partitioning model. This section provides a brief description of the mathematical model for the layout designs. The interested reader is referred to these publications for further details and explanations. In this model, since goal programming is used as part of the mathematical modelling (described later in section 3.1) the distinction between the objective function and the constraints is not as clear-cut as it is in the case with other mathematical programming models such as linear programming.

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In this paper we use the words 'efficient' and 'non-dominant' as synonyms. A point within a set is considered to be efficient (non-dominant) in that no other point is feasible at which the same or better performance could be achieved with respect to all criteria, with at least one criterion being strictly better (Steuer 1986).

2.1. *Machine layout model*

In this model the machines/work-centres are considered to be rectangular blocks with known dimensions. Three variables are associated with each block, namely the coordinates of the bottom left-hand corner (x,y), and the 'aspect ratio' o of the block. The variable aspect ratio is adopted to have control over the orientation of a block (discussed further in 2.1.5). Similar definitions are used by other researchers when considering the orientation of blocks/machines (see for example Tam and Li 1991 and Lacksonen 1994). This ratio is simply the height over the width of a block. Thus, if the aspect ratio is more than 1, it implies that the height is larger than the width of the block. In this case the block is considered to be vertical. If, however, the aspect ratio is less than 1 then the block is considered to be horizontal (see figure 1). The width and height of a block are defined as the sides parallel to the x-axis and the y-axis respectively, given by:

$$w_i(\text{width of block})_i = \left(\frac{a_i b_i}{o_i}\right)^{1/2}$$

$$h_i(\text{height of block})_i = (a_i b_i o_i)^{1/2},$$

where a_i,, b_i are the dimensions, and o_i is the aspect ratio of block i. The task of this model and solution methodology is to determine the coordinates (x,y) and aspect ratio (orientation) of each machine in the continuum plane by achieving and satisfying certain goals and constraints, explained as follows.

2.1.1. *Non-overlapping conditions*

The two blocks B_i and B_j are not overlapping if and only if they are at least x-projection or y-projection non-overlapping (Tam and Li 1991), i.e.

$$\max\begin{pmatrix}(x_i-(x_j+w_j))((x_i+w_i)-x_j),\\(y_i-(y_j+h_j))((y_i+h_i)-y_j)\end{pmatrix} \geq 0.$$

2.1.2. *Shop floor boundaries*

Each machine must be fully located inside the associated boundary. Taking the upper x and y boundaries of the shop floor as max_x and max_y we should have (see figure 2):

$$x_i + w_i \leq \max_y \qquad \forall i = 1,2,\ldots,n$$

$$y_i + h_i \leq \max_y \qquad \forall i = 1,2,\ldots,n$$

$$x_i, y_i \geq 0 \qquad \forall i = 1,2,\ldots,n$$

2.1.3. *Closeness relationships*.

The distance between two machines (blocks) is measured by the nearest pair of points, each on the perimeter of one block. For the two blocks i and j define $dx1_{ij}$,

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$dx2_{ij}$, $dy1_{ij}$, $dy2_{ij}$ as follows:

$$dx1_{ij} = (x_i - (x_j + w_j))$$
$$dx2_{ij} = ((x_i + w_i) - x_j)$$
$$dy1_{ij} = (y_i - (y_j + h_j))$$
$$dy2_{ij} = 99y_i + h_i) - y_j)).$$

Then the corresponding distances between these two blocks in the x and y directions are given by (see figure 1):

$$dx_{ij} = \begin{cases} 0 & \text{if } dx1_{ij} \times dx2_{ij} \leq 0 \text{ (the two blocks are } x\text{−projection overlapping)} \\ \min(|dx1_{ij}|, |dx2_{ij}|) & \text{otherwise.} \end{cases}$$

$$dy_{ij} = \begin{cases} 0 & \text{if } dy1_{ij} \times dy2_{ij} \leq 0 \text{ (the two blocks are } y\text{−projection overlapping)} \\ \min(|dy1_{ij}|, |dy2_{ij}|) & \text{otherwise.} \end{cases}$$

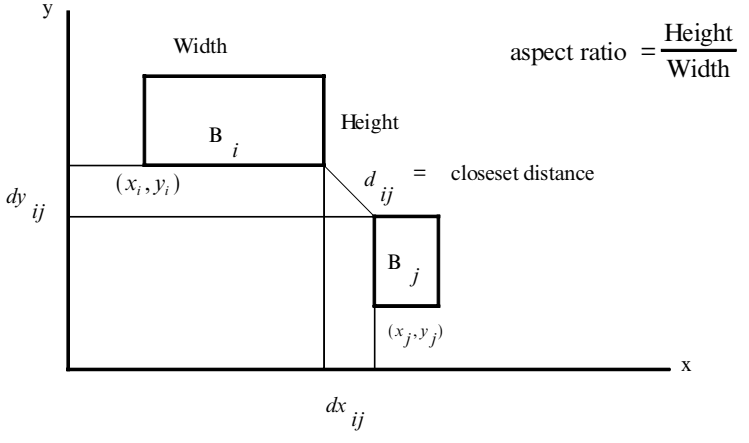

Figure 1. Definition of coordinates, aspect ratio, width, height and distances.

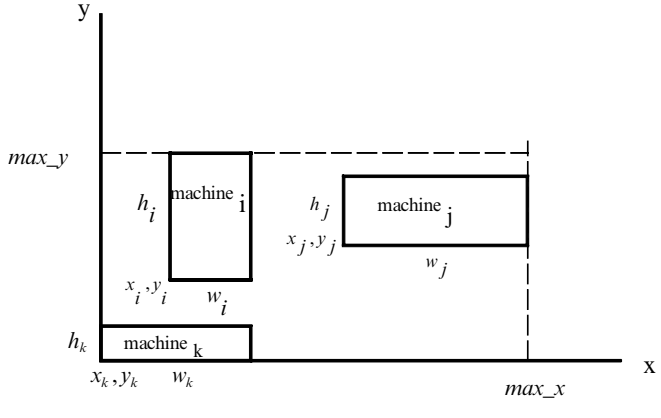

Figure 2. Definition of the cell-boundaries.

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The closest distance between the two blocks and is then given by (see figure 1):

$$d_{ij} = (dx_{ij}^2 + dy_{ij}^2)^{1/2}.$$

2.1.4. *Location restrictions/preferences*

Certain restrictions or preferences may exist for the physical location of a machine or work-centre. For example, the aisles represent such a restriction area where the machines should not be located. Let (α, β) be the coordinates of the bottom left-hand corner with γ_x and γ_y as the dimensions of such an area (see figure 3(*a*)). If we now desire that this area be restricted for the possible location of machine i then we should ensure that these two blocks do not overlap, i.e.

$$\max\begin{pmatrix}(x_i - (\alpha + \gamma_x))((x_i + w_i) - \alpha), \\ (y_i - (\beta + \gamma_y))((y_i + h_i) - \beta)\end{pmatrix} \geq 0.$$

Location restrictions can be used to address aisles and the irregular shape of sites (see figure 3(*a*)).

On the other hand, we may desire that a machine or a work-centre be located in a pre-specified location(s). Examples include cases, which a machine is already installed and its relocation would be economically unjustified. In this case, the machine should retain its location in the new layout configuration. To address this scenario we must ensure that the boundaries of the machine will be fully located within the specified area. The following set of constraints ensures the location of a machine within such an area (see figure 3(*b*)):

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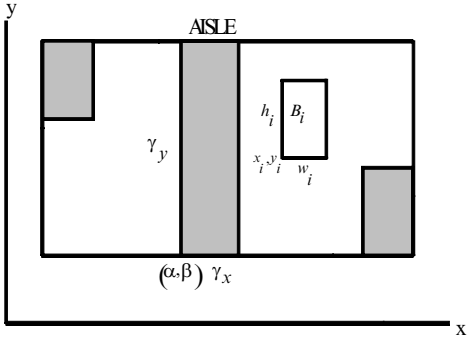
(*a*)



(*b*)

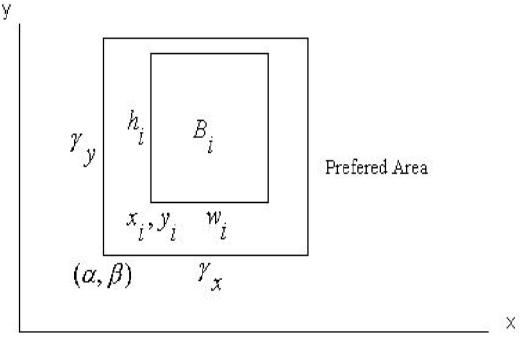


Figure 3. (*a*) Utilizing location restrictions to address aisles and irregular shape sites (shaded areas). (*b*) Utilizing location preferences for possible locations of machines/work-centres.

$$x_i \geq \alpha$$

$$y_i \geq \beta$$

$$x_i + \left(\frac{a_i b_i}{o_i}\right)^{1/2} \leq \alpha + \gamma$$

$$y_i + (a_i b_i o_i)^{1/2} \leq \beta + \gamma_y.$$

2.1.5. *Machine orientations*

In real-world layout problems the decision-maker often imposes certain constraints on the orientations of machines. Using the variable *aspect ratio*, it is possible to impose the desired restrictions on the orientations of the machines. These constraints include machine horizontal/vertical orientation or two or more machines having the same/opposite orientations.

If machine i is desired to be located horizontally then

$$o_i \leq 1.$$

Similarly, if machine i is desired to be located vertically then

$$o_i \geq 1$$

where o_i is the aspect ratio for machine i.

Furthermore, it may be desired that two or more machines have the same orientation in the final layout, i.e. they all be horizontal or vertical. To address this constraint we define:

$$r_i = \begin{cases} 0 & \text{if } o_i < 1 \\ 1 & \text{otherwise.} \end{cases}$$

$$r_j = \begin{cases} 0 & \text{if } o_j < 1 \\ 1 & \text{otherwise.} \end{cases}$$

Then to impose the same orientation on machines i and j we should have:

$$r_i = r_j$$

where $i, j \in \{\text{Machines desired desired to have the same orientations}\}$.

Similarly in order to impose opposite orientations on these two machines we should have:

$$r_i + r_j = 1$$

where $i, j \in \{\text{Machines desired to have opposite orientations}\}$.

2.1.6. *Travelling cost*

In this model, rectilinear distances between centroids of the blocks have been used to evaluate the travelling distances. In most machine layouts, material is transported to a cell by a carrier. It is therefore appropriate to consider frequencies of trips made by these carriers to account for the material flow between machines (Heragu and Kusiak 1988). Let f_{ij} denote the total frequencies of trips for all parts between machines i and j over a period of time. Then, the total rectilinear distances travelled by all parts, and between all machines, in the same period of time

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is given by:

$$\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} f_{ij}(|x_{ci}-x_{cj}|+|y_{ci}-y_{cj}|)$$

where n is the total number of machines and x_{ci}, x_{cj}, y_{ci}, y_{cj} are the x and y coordinates of the centroids of blocks i and j respectively, given by:

$$x_{ci} = x_i + \frac{1}{2}w_i$$

$$y_{ci} = y_i + \frac{1}{2}h_i$$

$$x_{cj} = x_j + \frac{1}{2}w_j$$

$$y_{cj} = y_j + \frac{1}{2}h_j$$

2.2. *Intra-cell layout model*

The intra-cell layout design is closely related to the machine layout model (Hassan 1995). The machine layout model presented in section 2.1 is now utilized to address intra-cell designs. The main difference between the intra-cell layout and the machine layout problem relies on the cell/shop floor boundaries. In machine layout problems the size (width and height) of the shop floor is normally assumed to be known *a priori* and the problem is to determine the location of the machines so that certain goals are achieved. In designing the intra-cell layout for CM, however, the objective is not only to identify the locations of the machines inside each cell, but also to determine the dimensions of the cells, which are not known, so their size is left to the layout designer to decide. Probably the only boundaries known in a manufacturing company planning to implement CM is the overall shop floor dimensions, which should accommodate all the cells.

The mathematical model is very similar to the machine layout problem. The variables described in section 2.1—namely (x_i,y_i) the coordinates of the bottom left-hand corner and the aspect ratio (o_i)—are used to determine the location of machine i with the known width and height (w_i,h_j), respectively. The objectives and constraints for this model are exactly the same as in section 2.1 except for the cell boundaries. In this model we aim at generating alternative efficient layouts for cells. Thus, the shape of the cell is left to be determined by the model as follows:

$$\max_x = \max\{(x_1+w_1),(x_2+w_2),\ldots,(x_n+w_n)\}$$

$$\max_y = \max\{(y_1+w_1),(y_2+w_2),\ldots,(y_n+w_n)\}$$

$$\textit{Area of the cell} = \max_x \times \max_y$$

$$x_i,y_i \geq 0 \qquad i = 1,2,\ldots,n$$

where $\max_x$ and $\max_y$ are the width and height of the cell, and is the number of machines inside the cell, respectively (see figure 2). The *area of the cell* is introduced to the problem formulation as part of the objective function which, we desire to minimize. The idea is to generate different cell boundaries (intra-cell layout design) for each cell. Each intra-cell layout design results in a different travelling cost. The

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solution methodology discussed in section 3 describes the procedure to generate and select these different solutions.

2.3. *Inter-cell layout model*

The inter-cell layout design concerns the location of the cells with respect to each other on the shop floor. The variables and constraints adopted for this model are similar to those presented for the intra-cell layout model. The procedure is to integrate all the possible combinations of intra-cell layout configurations to produce efficient multiple inter-cell layout designs. In this paper, without loss of generality we consider two criteria (objectives); namely cell/shop floor areas and travelling distances (cost). Therefore, an efficient (non-dominant) inter-cell solution has an area and travelling cost, for which no other solution can be found with a lower area and cost at the same time. The process of generating and selecting non-dominant solutions is explained in section 3.

3. Layout designs solution methodology

Nijkamp *et al.* (1990), proposed that the main reason for the increasing influence of multiple objectives/criteria models is to prevent the decision analysis from ending up with a single, 'forced' solution dictated by a researcher.

Solving the nonlinear mathematical programming model presented in the last section for problems with realistic constraints and numbers of machines (five machines or more) using conventional nonlinear single objective methods, often leads to unfeasible solutions. By unfeasible, it is meant a solution that violates constraint(s) that should absolutely be satisfied such as non-overlapping constraints. Similar difficulties were also reported by other researchers in solving the nonlinear optimization problems for layout in a continuum plane, such as the penalty methods in Heragu and Kusiak (1991), Van Camp *et al.* (1992) and the mixed integer programming in Lacksonen (1994).

Unfeasibility of the solutions occurs because of the assumption that all constraints are equally important and, the existing nonlinear algorithms try to satisfy all constraints simultaneously. However, in practice, not all of the constraints/objectives are of equal importance. For example, a feasible solution with a slightly higher travelling (cost) is preferred to an unfeasible but lower cost configuration.

Two optimization methodologies were found to be most useful in overcoming the above difficulties (Bazargan-Lari and Kaebernick 1997) in solving the machine/cell layout problems, namely *nonlinear goal programming* in the class of multiple-objective models and *simulated annealing* in the class of random search methods. Bazargan-Lari and Kaebernick (1996b) showed that this hybrid method produces better solutions than simulated annealing or goal programming independently. It was also shown that the hybrid method is capable of finding feasible solutions, where both simulated annealing and goal programming methods failed to do so, when separated.

These methods are capable of generating feasible, efficient and multiple layout designs for machines and cells based on two criteria: travelling distances and area of the cells.

The following presents a summary of the solution methodology adopted to solve the intra and inter-cell layout designs. The complete description for this hybrid methodology and the choice of parameters is presented in Bazargan-Lari and Kaebernick (1996a,b, 1997).

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Goal Programming (*GP*): GP is a useful tool to solve real world problems where multiple and often conflicting objectives are involved. The task is performed by trying to achieve as many goals as possible by minimizing the positive and negative deviations (over-achievements and under-achievements) of goals from some desired values according to a set of pre-emptive priority factors.

The Pattern Search method (Hooke and Jeeves 1961) in the class of the direct search method was adopted to solve the goal-programming model. This performs two types of moves, namely exploratory and pattern moves. The first type of moves is designed to explore the local behaviour of the objective function. This move is performed by a slight increment or decrement to the value of each variable in turn, while constantly checking the effect of such moves on the objective function. After each iteration, the exploratory move will determine the success or failure of that move. The pattern move on the other hand utilizes this information to determine the next probable direction, i.e. if the search has been successful a new base point is generated from the old base point in the direction of the successful exploration move. Otherwise, if the search is a failure, then the step size for exploration is reduced. These two moves are repeated until the step size becomes very small, i.e. below a predefined convergence value.

The pattern search method was found to be an appropriate solution methodology to solve the nonlinear goal-programming model because:

- unlike other nonlinear GP optimization methods (such as simplex based, gradient search and interactive approaches), the pattern search method does not require the functions to be convex and differentiable (note that we have absolute values in the total travelling distance objective function and therefore it may not be differentiable everywhere).
- The Pattern Search method, unlike other approaches, does not require a feasible initial solution to start the search. This is a useful capability of the model, since finding an initial feasible solution can be as difficult as solving the problem itself.

The pattern search method was originally developed for solving single objective, continuous variable, unconstrained optimization problems. It was adapted for solving nonlinear goal programming (NLGP) problems by Ignizio (1976) and further modified by Hwang and Masud (1979). In the modified approach of Hwang and Masud (1979), all real (absolute) constraints are transformed into goal constraints with the highest priority in the objective function. Then, the NLGP problem is partitioned into a series of single objective NLP (Nonlinear Programming) subproblems according to the different priorities of the NLGP problem. Each subsequent single objective NLP problem consists of: (1) the goal constraints associated with the single objective function under consideration and (2) a set of constraints that asserts the satisfaction of the previously achieved goals. The modified pattern search technique is used iteratively to solve the constrained single objective NLP problems.

Since the cell boundaries and non-overlapping constraints are absolute constraints and should be satisfied under any conditions, they are grouped as priority level 1. The satisfactions of the closeness relationships, location restrictions/preferences and orientation constraints depend on the decision-maker's preference. The decision-maker may impose strict satisfaction on all or some of these

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constraints, in which case they become rigid constraints and will be added to priority level; otherwise they become lower ranking priorities according to the decision-maker's preference. The travelling cost always has lower priority than the absolute constraints to ensure the feasibility of the solution.

Simulated annealing (*SA*): This technique has been extensively used to solve combinatorial problems. The main capability of SA is that, unlike other local search methods, the final solution does not get trapped in a local optimum and is not as sensitive to the initial solution. SA performs this task by simulating the annealing process (see Wilhelm and Ward 1987 for a further description). In SA, new solutions are continually generated from existing ones. The mechanism by which the values of temperatures are chosen is called the annealing schedule. The parameters associated with this mechanism are:

- Initial temperature. This is the melting point and normally should be large enough to ensure that more than 80% of the generated neighbours are candidates for acceptance (Kirkpatrick *et al.* 1983).
- Cooling ratio. The rate by which the temperature is decreased.
- Number of temperature steps. The number of times that annealing should be performed.
- Time at each temperature. This governs the policy to determine the achievement of equilibrium at each temperature.

The following equation, as was initially suggested by Kirkpatrick *et al.* (1983), was adopted to decrease the temperature:

$$t_i = (10)(0.9)^{i-1}, \qquad \text{for } i = 1,2,\ldots,k$$

where t_i is the temperature at the stage; 10 is the initial temperature; 0.9 is the cooling ratio; and k is the total number of temperature steps.

We adopted a similar approach to Wilhelm and Ward (1987) and Golden and Skiscim (1986) to check for the equilibrium at each temperature. They used the concept of epoch, *e*, an *a priori* specified number of successful pairwise interchanges at each temperature to determine whether the system is in equilibrium or not. Thus, for each temperature t_i in the annealing schedule, after *e* pairwise interchanges have been accepted, the mean of the total cost for that epoch is compared with the grand mean of the total costs for all preceding epochs at temperature t_i. If the mean total cost for the most recent epoch is sufficiently close (within ε) of the grand mean then the system is considered to be in equilibrium at that temperature. Therefore, the next annealing temperature is selected and the procedure is repeated for the new temperature. If, however, the system is not in equilibrium then the search at that temperature is repeated until enough new configurations are generated.

3.1. *Hybrid intra-cell layout method*

The following briefly describes the merging of the above two solution methodologies into a hybrid method. After obtaining a local minimum by pattern search, SA is used to exit the solution from an existing local optimum, in search of a better solution according to SA settings.

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Step 1. Input machine dimensions, closeness relationships, machine restrictions/preferences, orientation constraints, frequencies of trips between machines and their corresponding priorities according to the user's preference.

Step 2. Generate a layout S using the modified Pattern Search goal programming method.

Step 3. Generate a new layout (S′) based on one of the following actions (with equal ratios 1 : 1 : 1):

(i) a *move*, which involves the random displacement of a machine from its current location to another location. This task is performed by first randomly choosing a machine, then generating a new random location within the boundaries for that machine.

(ii) A *swap*, which involves the exchange of the locations for two randomly chosen machines.

(iii) An *orientation change* for a machine.

Step 4. If all of the priority levels pass the simulated annealing test, accept the new layout and set $S = S'$, go to step 5; otherwise go to step 6.

Step 5. If equilibrium is reached at the current temperature, go to step 6; otherwise go to step 3.

Step 6. If the stopping criterion is met, return S (final solution) and stop; otherwise reduce the temperature and go to step 2.

By equal ratios (step 3 above), it is meant that each of *move* or *swap* or *orientation change* has an equal chance of being selected. In order to select the action among these three, a random number between 0 and 1 is generated. If this random number is between 0 and 0.33 then *move* is selected. If it is between 0.34 and 0.67 then *swap* will take place; otherwise the action taken is *orientation change*. Different ratios were also tested, but the solutions generated did not vary significantly (Bazargan-Lari and Kaebernick 1996b).

Note that in the above procedure, the modified pattern search goal programming is performed only at the beginning of each temperature, not in the process of generating the new configurations.

A computer program was developed based on the above hybrid method.

3.2. *Generation of inter-cell layout designs*

In generating a machine and cell layout, three distinct sets of objectives/constraints have been considered. The first set concerns the feasibility of the solution, which should absolutely be satisfied. Any deviations from the target values in this set results in the solution being unfeasible. The second objective is to minimize the area of the cell (section 2); and, finally, the third one is to minimize the travelling cost. In this section we are particularly interested in trade-offs between the second and third set of objectives. The two extreme solutions are generated when we are not willing to make any trade-offs between the two set of objectives by placing one objective at a higher priority level than the other, according to goal programming properties.

The program is first run by assigning minimization of the area of the cell and the intra-cell travelling cost to priority levels 2 and 3 respectively. In this case minimizing the area has a higher priority over the travelling cost; therefore, the solution thus generated has the lowest area and highest intra-cell cost. This is because no trade-off is allowed between minimizing the area and travelling cost (point z_1^* in figure 4). Starting from this solution having the lowest area and the highest intra-cell cost, the

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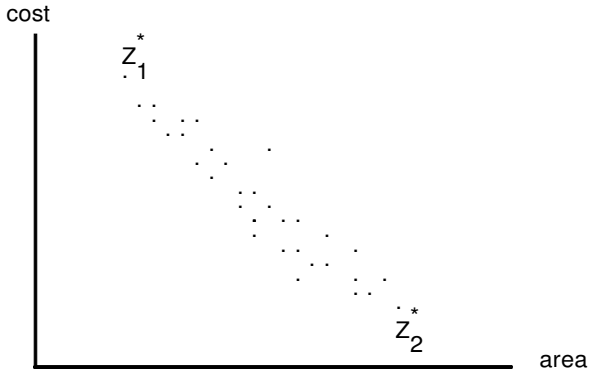

Figure 4. Generating non-dominant solutions.

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program is run again, reversing the priority levels of these two objectives. The solution thus generated has the largest area and the lowest travelling cost. During this transition of going from one extreme solution, having the smallest area and the largest cost, to the other with the smallest cost and largest area (point z_2^* in figure 4), a large number of solutions is generated. Among this large number of solutions many are efficient (non-dominated) points (as defined in section 2.3), which are saved by the program. This whole procedure is repeated again, reversing the priority levels from the start, and adding more efficient solutions to the list. This phase of the model is repeated for all cells, resulting in a number of efficient solutions for each cell.

Through this approach it is possible to generate various efficient points by assigning different priority levels to different constraints/goals.

The number of efficient solutions generated is normally large. Steuer (1986) suggests a filtering process to deal with such information overload. Filtering is a process of selecting subsets of points that are the most different from others, from a larger finite set of points.

The filtering relationship is an L_p-metric distance between pairs of vectors ν^t, ν^h given by:

$$\|\nu^t - \nu^h\|_p^{\pi} = \left[\sum_{i=1}^{q} (\pi_i |\nu_i^t - \nu_i^h|)^p\right]^{1/p}$$

where:

- q is the length of the vectors being filtered,
- π_i is the range equalization weight associated with the ith component of the vectors being filtered, and
- p is the metric parameter, $p \in (\{1,2,\ldots,\infty\})$.

Through the filtering process we can identify the points that are most significantly different from others. In the proposed model, the L_2 metric distance and the first point outside the neighbourhood, as introduced by Steuer (1986), were adopted. The filtering process is performed according to the following procedure.

A randomly efficient point among the set of non-dominated solutions is selected as the seed point and is added to the top of the list of the retained points. Each non-dominated point is then assessed with the seed point according to the test distance

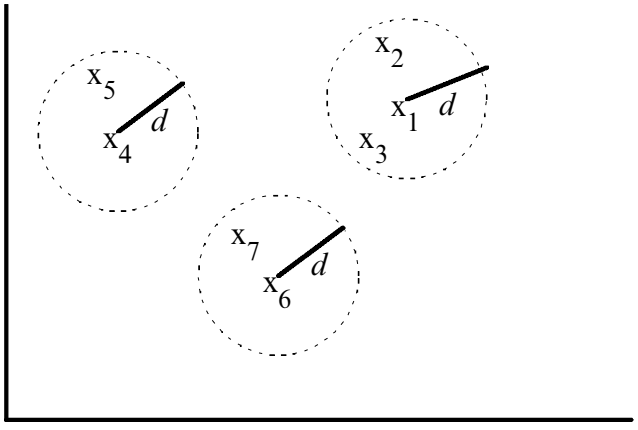

Figure 5. Method of first point outside the neighbour.

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relationship expressed above. Each point not satisfying the test is considered to be insignificantly different from the seed point and is excluded from further consideration. Any point, however, satisfying the test is added to the list of retained points. This process is continued, ensuring that each subsequent point is assessed against all the points retained in the filtering list until all the non-dominated points are evaluated. This process is shown in figure 5. In this figure we have seven efficient points which we would like to reduce to the three most different points. Starting with x_1 as the seed point, points x_2 and x_3 are excluded from further consideration since their L_2-norm distances from x_1 is less than d. Point x_4, however, is the first point to be significantly different from x_1 and is therefore retained by the filtering process. The subsequent points should be assessed against both x_1 and x_4. Point x_5 is excluded since its distance with x_4 is insignificant. Similarly, point x_6 is retained and x_7 is excluded from the list. Thus, the filtering process reduces the initial size of seven non-dominated points to x_1, x_4 and x_6. It is possible to vary the value for d so that the number of selected points is less or more than these three points.

Once efficient intra-cell layouts are generated for each cell, the filtering process extracts the most different designs. The program next seeks to generate alternative inter-cell layout designs by considering all possible combinations for intra-cell designs, again using the filtering process to select the distinct configurations.

4. Cell partitioning formulation

The main task of cell formation is to group the machines into cells to produce a number of part families (Chen *et al.* 1995). Currently there exist a large number of efficient cell-partitioning algorithms in the literature (Wemmerlov and Johnson 1997).

The task here is not to introduce a new cell-formation model, but to demonstrate how the existing models can be modified and adopted in order to be integrated with the intra and inter-cell layout designs presented in sections 2 and 3.

The model used and modified (without loss of generality), is the cell-partitioning approach developed by Heragu and Kakuturi (1997). This model utilizes part routing, annual demand and batch sizes to perform the cell formation. The major distinction between the algorithm presented by Heragu and Kakuturi (1997), and the

modified model in this paper is the approach taken to perform cell partitioning. The objective of the former algorithm is to determine the number of cells and their corresponding parts and the machines assigned to each cell so that the number of exceptional parts (the parts that require further processing outside their designated cell) is minimized. This approach results in only one cell-partitioning solution. In the modified model, however, we generate different solutions according to the possible number of cells permitted by the decision-maker. For each such cell-partitioning solution, different intra-cell and inter-cell layout designs are generated, based on the methodology described in section 4.1. This approach allows us to explore the impact of cell partitioning on layout designs and vice-versa.

The following notation and formulae are used to determine the flow between the two machines, i and j. The flow between two machines is determined as the sum of the trips for all parts that have two consecutive operations performed by these two machines. Let

- n total number of machines,
- m total number of parts,
- D_k demand for part k in a given period,
- B_k transfer batch size for part k,
- R_{ki} operation number for the operation done on part k using machine i,
- f_{ij} number of trips made by material handling equipment between machines i and j,
- C total number of cells,
- p,q represent two distinct cells ($1 \leq (p,q) \leq C$ and $p \neq q$),
- ic_{pq} inter-cell flow between cells p and q,
- IC total inter-cell flows between all cells.

Then

$$f_{ij} = \sum_{k=1}^{m} F_{ij}^{k}, \tag{1}$$

where

$$f_{ij}^{k} = \begin{cases} \dfrac{D_k}{B_k} & \text{if } |R_{ki} - R_{kj}| = 1 \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

In equations (1) and (2), F_{ij}^{k} is the number of trips made between the two machines i and j for part k. The condition $|R_{ki} - R_{kj}| = 1$, ensures that only the flow for which the operations on machines i and j are immediately consecutive is accounted for, f_{ij} is the sum of all these flows over all parts.

These formulations are now used to determine the inter-cell flow between two cells and, thereby, the total inter-cell flows between all cells. Define:

$$e_{ip} = \begin{cases} 1 & \text{if machine } i \text{ is in cell } p \\ 0 & \text{otherwise} \end{cases}$$

$$e_{jq} = \begin{cases} 1 & \text{if machine } j \text{ is in cell } q \\ 0 & \text{otherwise} \end{cases}$$

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then the inter-cell flow between the cells p and q and the total inter-cell flow between all pairs of cells, both in number of trips per period, are given by:

$$ic_{pq} = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} f_{ij} e_{ip} e_{jq} \tag{3}$$

$$IC = \sum_{p=1}^{C-1} \sum_{q=p+1}^{C} ic_{pq}. \tag{4}$$

The main task of the model is to identify the parts and machines assigned to each cell so that IC, the total inter-cell flows between all cells, is minimized for a given C. Again, note that the solution methodology proposed by Heragu and Kakuturi (1997); finds only one value for C so that the number of inter-cellular movements is minimized. In the proposed modified model, we identify the parts and machines assigned to each cell for every possible cell partitioning strategy. For example, we start with a cell partitioning strategy. We organize parts and machines into only two cells so that the total number of inter-cellular movements is minimized (the method of partitioning is described in section 4.1). We then generate intra-cell and inter-cell layout designs for these two cells. Next, repeating this process, we organize the parts and machines into a three-cell strategy. New layout designs are generated for this three-cell partitioning strategy. This whole procedure is repeated until all possible numbers of cells (normally an upper bound expressed by the decision-maker) are evaluated. At this stage, the decision-maker has complete information on the shape of the cells, the areas occupied and the impact of each cell-partitioning strategy on the material handling distances.

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4.1. *Cell-partitioning methodology*

Simulated Annealing is again adopted to determine the parts and machines assigned to each cell so that IC, the total inter-cell flow between all cells, is minimized for a given number of cells. The proposed Simulated Annealing algorithm uses the same annealing schedule as discussed in section 3 and adopts two actions to generate a neighbouring solution, namely a *move* or a *swap*.

- A *move* is performed by randomly selecting two cells from existing number of cells, then randomly choosing a machine inside one of these selected cells and moving it to the other (figure 6).
- A *swap* is to exchange two randomly selected machines inside two randomly chosen cells (figure 6).

Equal ratios (1 : 1) were assigned for selection of a *move* and a *swap*.

The steps undertaken to group the parts/machines and layout designs are as follows.

For (minimum number of cells $\leq C$ (number of cells) $\leq$ maximum number of cells) do;

Step 1. Input the maximum number of machines in each cell and determine the flow (f_{ij}) between any two machines using the formulae (1) and (2), initialize.

Step 2. Randomly assign machines to each cell in equal proportions, calculate the total inter-cell flows (IC) according to formulae (3) and (4).

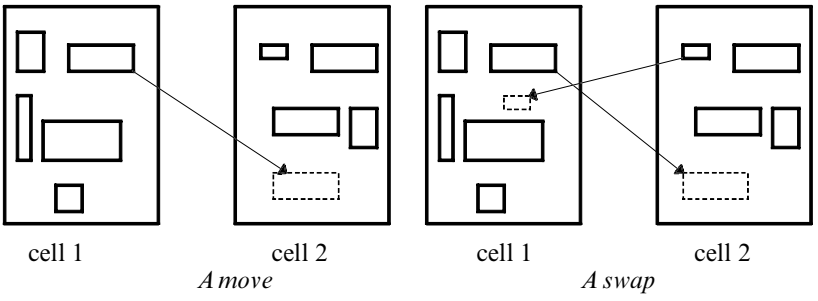

Figure 6. Generation of neighbourhood solutions using a *move*or a *swap*.

Step 3. Generate a neighbourhood configuration using the two actions *move* or *swap*, calculate the new flow (IC_{new}).

Step 4. If $IC > IC_{new}$ then accept the new solution and go to step 5; otherwise accept the new configuration subject to the simulated annealing method.

Step 5. If equilibrium is reached at the current temperature, then go to step 6; otherwise go to step 3.

Step 6. If all temperature steps have been evaluated, return the best configuration, develop the intra and inter-cell layout designs (section 3.2) and start the next cell formation; otherwise reduce the temperature, go to step 3.

Through this approach we can identify the bottleneck machines and exceptional parts that require inter-cellular movements. Once the machines are grouped into different cells based on the above algorithm for different cell partitioning strategies, the intra-cell and inter-cell layout designs are generated using the method described in section 3.

5. Case study

A medium sized Australian 'white-goods' manufacturing company, which produces electric household goods, implemented CM in 1995. Both the management and shop floor employees constantly felt the need for changing and improving the manufacturing system in the press-shop. Among the problems expressed were excessively long lead-times resulting in late deliveries or frequent backlogs, high volumes of work in process, confusion and difficulties over production planning, and ever-increasing material movements.

The management considered that CM could be an appropriate strategy for this company to overcome some of the difficulties described earlier. Furthermore, the management favoured this strategy, as the change did not require new capital investment. The cost of implementing CM included the cost of relocating the machines and equipment and, possibly, employee re-organization and education.

A total of 153 parts are produced in the press-shop. Table 1 presents the list of machineries and equipment used to produce these parts, the available number of presses, restrictions and the references used. The column 'restriction' in table 1, refers to the restrictions imposed by the company regarding the relocation of certain presses. These presses are very heavy and were installed on special foundations. Accordingly, any relocation of these machines incurred high costs and inconvenience. Furthermore, it was desirable that some departments retain their current locations, for instance, the raw material store, because of easy access to unloading docks.

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Department/Machine	Numbers available	Sizes ($m \times m$)	Restriction	Reference
Raw material store	1	23×14	Fixed	STOR
Guillotine area	1	14×10	Fixed	GULT
Degreasers	1	5×11		DGRS
110 ton feeder	1	10×5	Fixed	ORRI
Linisher	1	4×4	Fixed	LNSH
150 ton feeder	1	12×10	Fixed	AIDA
Brake press	1	8×4		BRAK
30 ton press	5	2.5×2.4		203A
200 ton press	5	3.5×2.4		200C
200 ton hydraulic press	2	4.2×2.8		200H
250 ton press	2	3.9×2.8	Fixed	250C
300 ton press	2	5.8×3.1	Fixed	300C
80 ton press	3	3.2×2.8		207A
200 ton wide	2	5.5×3.1		200W
110 ton press	1	2.8×1.9		PSCA
150 ton press	2	3.1×2.2		150C

Table 1. References used for departments and machines.

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These departments and machines are identified as 'Fixed' in the restriction column of table 1. The column 'reference' in table 1 represents the company's in-house names for departments and presses that we adopted for communication with the company and when labelling the layout designs.

Figure 7 shows the shop floor plan (a part of a larger shop floor) assigned specifically for location of cells and departments along with the corresponding dimensions.

Information regarding parts routings, annual demand, transfer quantities, machine sizes, aisles and clearance spaces were gathered. Considering the space and number of employees on the shop floor, the company could cope up to five cells.

Incorporating these constraints, the cell-formation algorithm provided four strategies, namely 2, 3, 4 and 5 cell-partitions. Table 2 presents only two inter-cell layout solutions (after the filtering process) for different cell-partitioning strategies. As was explained in section 3.2, it is possible to generate more solutions by varying the test distance d. In table 2, 'area' corresponds to the area of the smallest rectangle

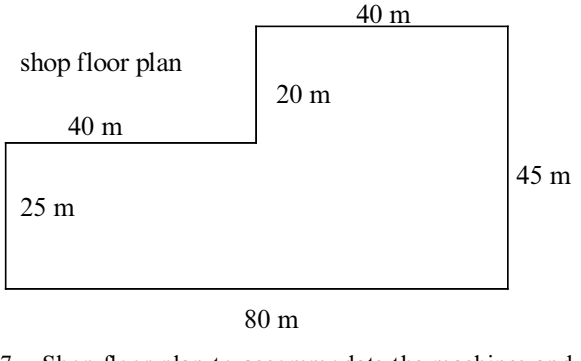

Figure 7. Shop floor plan to accommodate the machines and cells.

Strategy	Alternative	Area (m^2)	Travelling cost (km/year)
2-cell	a	1275	265.3
Partition	b	1192	283.8
3-cell	a	1188	293.3
Partition	b	1220	274.5
4-cell	a	1267	315.3
Partition	b	1279	305.5
5-cell	a	1184	332.3
Partition	b	1195	325.5

Table 2. Non-dominated inter-cell layout solution for different cell-partitioning strategies.

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enclosing the facilities in (m^2) and 'travelling cost' represents the travelling distances in km/year.

The complete information pertaining to the grouping, intra and inter-cell layout designs for these strategies was presented to management. Although the 2, 3 and 4 cell-partition provided autonomous cells with no inter-cellular movements, the 5-cell partition was selected by management. The 5-cell partitioning strategy generated inter-cellular movements for 12 parts. The company favoured this selection because:

- it assigned fewer parts per cell resulting in better supervision and planning,
- lower travelling cost,
- the company was able to duplicate the bottleneck machines from other parts of the plant thus avoiding inter-cellular movements.

Table 3 shows the parts and machine grouping for the 5-cell partitioning strategy favoured by management (with the corresponding number of machines duplicated in brackets).

As a test for our proposed layout methodology, the company independently developed a 5-cell layout based on traditional in-house expertise. Figures 8 and 9 present the inter-cell layout design generated by the company and one of the alternative solutions produced by the proposed method respectively. In these layout plans, RSVD denotes the reserved areas assigned to offices, washrooms, utilities, die-racks, etc. The solution generated by the proposed algorithm proved to be not only feasible by addressing all the constraints expressed by the company, but also provided a 30% lower travelling cost. This cost reduction attains larger magnitude when translated into other resources, such as time and money.

Cells	Number of parts	Machines assigned to the cells
Cell 1	80	203A (5), 207A(3)
Cell 2	18	200C (2), PSCA, 150C (2)
Cell 3	20	150C (1), 200W(1), 200H (1), 200C (3)
Cell 4	17	BRAK, 250C (1), 300C (1), 200H(2)
Cell 5	18	300C (1), 200W(1), 250C (1)

Table 3. Assignment of parts and machines to 5 cells.

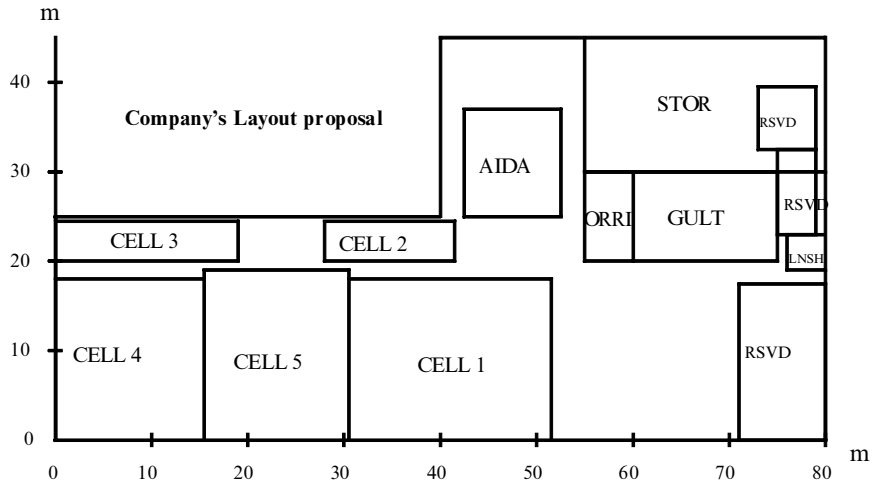

Figure 8. Layout configuration based on the company's proposal plan with a total travelling cost of 425.7 km/year.

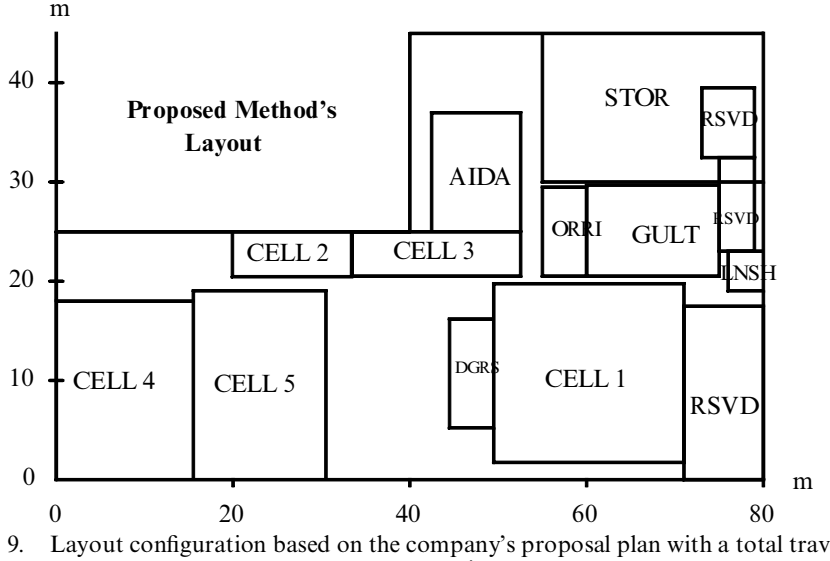

Figure 9. Layout configuration based on the company's proposal plan with a total travelling cost of 325.5 km/year.

It is of interest to mention that the intra-cell and inter-cell layout designs generated by the company were developed by an employee over several weeks based on his several years of working experience at the company, while the results obtained by the hybrid model were generated in less than 15 minutes. This statement is by no means intended to claim that the proposed method can fully and completely replace human expertise, but it should be looked at as an intelligent tool to assist the designer (employee) to generate better and more efficient layouts. The proposed method not only enables the designer simultaneously to target feasible and cost efficient solutions, but also perform 'what if' analysis.

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The selection of the 5-cell partition strategy by the company reconfirms the approach presented in this paper, in that a feedback system between the three phases of the design for CM is absolutely essential.

6. Conclusions

This paper presented how our integrated approach to layout design can be extended to address all three phases in the design of manufacturing cells. It was shown how the existing cell-formation algorithms can be modified and used to generate different cell-partition solutions. This proposed, integrated approach provides the decision maker with multiple efficient alternative solutions according to different cell-partition strategies. It offers the flexibility to assess each alternative against tangible and intangible benefits and criteria such as required area, travelling distances, machine duplications, company's long term objectives, etc. The capability of the proposed method was shown by applying it to an industrial CM design problem. The solutions generated proved to be not only feasible relative to the constraints expressed by the company but also provided a lower travelling cost. In addition, it was prepared at a fraction of traditional planning time and cost.

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