



## A review of the modern approaches to multi-criteria cell design

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The purpose of this paper is to provide a review and comparison of the approaches to multi-criteria decision-making (MCDM) in the design of manufacturing cells. A brief description of existing classifications is provided, together with an overview on the MCDM. Selected papers are reviewed and a structured scheme is outlined which allows comparison of inputs, criteria, solution approaches and outputs across selected models. Finally the models are discussed and directions for new avenues of work are identified.

### 1. Introduction

Cellular manufacturing (CM) is an important application of group technology (GT) in which sets (families) of parts are produced in manufacturing cells or a group of various machines, which are physically close together and can entirely process a family of parts. The identification of part families and machine groups in the design of cellular manufacturing systems is commonly referred to as cell design/formation. There have been many efforts towards the design of manufacturing cells based on the selection of part families and machine groups, considering only a single criterion such as minimising inter-cell movement of parts. There has been pressure on the manufacturing industries in the world market competition to improve their performances with regard to such measures as shorter delivery lead-times, wider range of products, shorter set-up times, and of course lower prices. These pressures provide a number of conflicting criteria on which performance is evaluated. Thus the design of the manufacturing area is critical to the efficient performance of the business.

From a system designer's point of view it is very desirable to achieve an optimal solution with respect to all the criteria considered individually by researchers, but this is impossible because of the conflicts between various criteria. For example, minimising inter-cell movement of parts by means of machine duplication/part subcontracting deteriorates the objectives of maximising machine utilisation and minimising total cost. In fact, based on Keen (1977), optimisation in the traditional mathematical sense is impossible if multiple criteria are involved. Problems such as trade-off analysis between machine duplication, part subcontracting, and inter-cellular material handling costs should be addressed and presented as a decision model to the decision-maker (Offodile *et al.* 1994).

The purpose of this paper is to review those papers, which consider the cell design problem as a multi criteria decision-making problem. The initial section of the paper

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provides a brief description of the previous reviews on cell design models. The major part of the paper outlines an overview on the multi criteria decision making, together with the classification scheme used in the current survey. The final section provides a comparative discussion on the approaches used to deal with various criteria in the selected papers, a discussion on the gaps in the research area and future trends of new works.

## 2. A review on the previous work

Many models and solution approaches have been developed to deal with the problem of manufacturing cell design/formation since 1970s. The most common criteria considered for the design of manufacturing cells and a selection of research from the current decade is given in table 1.

There have also been some comprehensive review papers with different aims and viewpoints. King and Nakornchai (1982) provide a comprehensive review of the various approaches to the cell formation problem by the time. They classify all the models into four subdivisions: similarity coefficient, set theoretic, evaluative, and other analytical methods. Mosier and Taube (1985) partition the literature under four subtitles: part identification, grouping, scheduling in the GT shop, and GT implementation. Wemmerlov and Hyer (1986) review more than 70 papers and categorise them into four groups. Their classification scheme divides all the methods into two major groups based on the main data for grouping as either part attributes or routings. The latter branch is further classified into three divisions, i.e. approaches that identify firstly the machine groups and then part families, approaches that identify firstly the part families and then machine groups, and the approaches that identify part families and machine groups simultaneously. Chu (1989) provides a comprehensive bibliography of cellular manufacturing and partitions the literature into design-oriented and production-oriented approaches. The latter group is further partitioned into array-based, hierarchical, non-hierarchical, mathematical, graph theoretic, and heuristic approaches. Offodile *et al.* (1994) employ a taxonomic framework and divide all the methods for identifying machine-part families into three taxonomic frameworks of: visual methods, parts coding analysis, and production flow analysis. The models in the latter class up to 1991 are compared based on their solution approach, decision variables, objectives and constraints.

Criterion	Selection references
minimising inter-cell movements	Klincewics and Rajan (1994), Joines <i>et al.</i> (1996), Sofianopoulou (1997), Cheng <i>et al.</i> (1996)
maximising parts and/or machines similarities (or minimising dissimilarities)	Kao and Moon (1991), Kaparathi and Suresh (1991), Chu (1993), Boctor (1991), Chen and Srivasata (1994), Askin <i>et al.</i> (1991), Lee and Carcia-Diaz (1993), Kusiak <i>et al.</i> (1993)
obtaining the block diagonal form of the part-machine incidence matrix	Kaparathi and Suresh (1992), Kaparathi <i>et al.</i> (1993), Suresh and Kaparathi (1994), Mukhopadhyay <i>et al.</i> (1994), Chen and Irani (1993)
minimising cell load unbalances	Venugopal and Narendran (1992 b)
minimising number of exceptional elements	Song and Hitomi (1992), Amirahmadi and Choobineh (1996)

Table 1. Some single criterion models for cell design in the 1990s.

None of the above mentioned reviews considers the number of criteria (single or multiple) as a measure for classification. The aim of this paper is to establish this measure as a major classifier on the cell design models and to present a review on the multi criteria models. It is not the intention of this paper to review single criterion models for cell design; readers are referred to King and Nakornchai (1982), Mosier and Taube (1985), Wemmerlov and Hyer (1986), Chu (1989), and Offodile *et al.* (1994).

### 3. An overview on the multi-criteria decision-making

Criteria are measures, rules and standards that guide decision-making. As selecting or formulating different attributes, objectives or goals conducts decision-making, all three categories can be referred to as criteria (Zeleny 1982). The multi-criteria decision-making (MCDM) problems based on the above definitions are categorised by Zeleny (1982) as: multi-attribute decision-making (MADM), multi-objective decision-making (MODM) and goal programming (GP). The manufacturing cell formation problem, taking multiple criteria into consideration, becomes compatible with the MODM and GP problems. For a more detailed comparison of MADM and MODM problems, readers are referred to Hwang and Yoon (1981).

#### 3.1. Multi-objective decision-making

In its most general form, the MODM problem can be stated mathematically as follows:

$$\begin{aligned} \max [f_1(x), \dots, f_k(x)] \quad \text{subject to} \\ g_i(x) \leq 0, \quad \text{for } i = 1, \dots, m, \quad x \in X \end{aligned} \quad (1)$$

where  $X$  is some subset of  $R^n$ ,  $f_1$  are objective functions and the  $g_i$  are constraints. This problem includes  $n$  decision variables,  $m$  constraints and  $k$  objectives. It is possible that some or all of the functions are nonlinear. The problem (1) is also known as the vector maximum problem or VMP. A solution to the problem (1) is defined as non-dominated if no other solution exists which could improve one or more objectives without detriment to some other objective. A necessary and sufficient condition for a solution to be efficient is described by Hartley (1983) as follows: a feasible  $x \in X$  is efficient if and only if there is no feasible to satisfy  $y \in X$  to satisfy  $f(y) \succ = f(x)$ , where  $f$  is the vector-valued function whose  $i$ 'th component at  $x$  is  $f_i(x)$  and  $=, \succ$  denote, respectively, weak and strict component-wise inequality whilst  $\succ =$  denotes ' $=$  but not  $=$ '. Two well-known approaches to solve the VMP are the constraint method and the weighting method. In the constraint method, one of the objectives is selected for optimisation and the other objectives are added to the set of constraints in the form of inequalities with a minimum acceptable level. In the constraint method, problem (1) is reformulated as follows:

$$\begin{aligned} \max f_j(x) \quad \text{subject to} \\ g_i(x) \leq 0, \quad \text{for } i = 1, \dots, m \\ f_l(x) \geq \varepsilon_l, \quad \text{for } l = 1, \dots, k; l \neq j, \quad x \in X \end{aligned} \quad (2)$$

where  $\varepsilon_l$  denotes the minimum acceptable level for the  $l$ th objective.

In the weighting method, a single objective function, i.e. the weighted sum of the individual objectives is defined, and in this manner, the multi-objective problem is changed to a single objective problem as follows:

$$\begin{aligned} \max \quad & \sum_{l=1}^k w_l \cdot f_l(x) \quad \text{subject to} \\ & g_i(x) \leq 0, \quad \text{for } i = 1, \dots, m, \quad x \in X \end{aligned} \quad (3)$$

The weights assigned to the objectives are usually normalised, i.e.

$$\sum_{l=1}^k w_l = 1.$$

A major drawback of the above methods is the dependency of the solution to the values of  $\varepsilon_l$  and  $w_i$  which are determined subjectively by the decision-maker *a priori*. For a comprehensive study of the approaches to the MODM problem, readers are referred to Hwang and Masud (1978) and Szidarovszky *et al.* (1986).

### 3.2. Goal programming

The notion of goal programming (GP) is the attempt to minimise the set of deviations from prespecified multiple goals, which are considered simultaneously but are weighted according to their relative importance. A general GP problem can be formulated as follows:

$$\begin{aligned} \min \quad & \sum_{i=1}^m p_i (d_i^+ + d_i^-) \quad \text{subject to} \\ & \sum_{j=1}^n c_{ij} \cdot x_j + d_i^+ - d_i^- = b_i \quad \text{for } i = 1, \dots, m \end{aligned} \quad (4)$$

where  $x_j$  are  $n$  decision variables,  $d_j^-$  and  $d_i^+$  denote, respectively, negative and positive deviations from the  $i$ th goal (or slack and surplus variables in case an equation represents an ordinary constraint),  $b_i$  are  $m$  goals or rigid constraining values, and  $c_{ij}$  are technological coefficients.  $p_i$  in the objective function stand for pre-emptive weights or priority weights determining the hierarchy of goals. Goals of higher priority levels are satisfied first, and only then are the lower priority goals considered.

The model (4) could be handled as a single objective minimisation problem by means of the traditional techniques of linear, non-linear, integer, or mixed integer programming where appropriate. For a detailed discussion on various approaches to solve the GP problem, readers are referred to Hillier and Lieberman (1986) and Zeleny (1982).

## 4. Review of papers

The design of manufacturing cells with respect to multiple criteria has been an attractive research topic since 1990. This section presents a review on the main features of the models developed in this field. The main criterion for the selection of papers for this study has been the consideration of at least two criteria simultaneously in the solution approach of the model. Therefore such research as Vannelli and Hall (1993) and Hadley (1996), which separate machine group/part family for-

mation in two stages that consider one independent objective at each stage, are not included.

Sankaran (1990), to consider multiple goals in the cell formation procedure, primarily solves a single objective model whose objective function is the sum of five distinct cost functions. The optimal solution of the single objective model is then broken down into two cost aspiration levels, i.e. operating cost and capital investment cost. These two optimal costs along with five other goals are then combined in an integer linear goal programming model. The set of the goals considered by the author includes: minimum similarity of parts based on their needed machines and tools (two goals), available machining capacity, minimum and maximum number of total parts movement (two goals), the optimal capital investment on machines, and the optimal operating cost.

Wei and Gaither (1990) develop a four objective cell formation model to minimise the bottleneck cost, maximise the average cell utilisation, minimise intra-cell load imbalances, and minimise inter-cell load imbalances. The bottleneck cost may be either the cost difference between making a bottleneck part inside and outside the cellular system, or the cost incurred by transporting the bottleneck part between cells. The authors develop a 0–1 programming model for small problems and a heuristic to solve both small and large problems. Both the optimal model and the heuristic seek to maximise a weighted additive utility function comprised of the above four objectives.

Shafer and Rogers (1991) apply goal programming in three unique situations: setting up an entirely new system and purchasing all new equipment, reorganising the system using only existing equipment, and reorganising the system using existing and some new equipment. The latter model, which is more compatible with the rest of the cell design models, is selected for detailed comparison in the next section. The criteria considered by the authors include: minimising set-up times (through parts sequencing), minimising intercellular movements, minimising the investment in new equipment, and maintaining an acceptable machine utilisation level. The proposed goal programming models combine the  $p$ -median (for identifying part families) and the travelling salesman problem (to determine the optimal sequence of parts). The authors then propose a heuristic to solve realistically sized problems.

Shafer *et al.* (1992) present a mathematical programming model for dealing with exceptional elements. They develop an initial solution using any of the cell formation procedures. Exceptional elements are then primarily eliminated by changing the design or process plans of the parts. Further elimination of the exceptional elements is carried out using part subcontracting or machine duplication through an optimisation model. The authors include three cost factors in the form of a single minimisation objective function, i.e. cost associated with intercellular transfer, machine duplication, and part subcontracting. In fact they use a weighting approach to unify three different objectives with equal weights.

Venugopal and Narendran (1992 a) propose a bi-criteria mathematical model for the machine-component grouping problem. The authors consider two minimisation objectives: minimise the volume of inter-cell moves, and minimise the total within cell load variation. Their solution approach is based on finding satisfactory or compromise solutions by means of genetic algorithms.

Dahel and Smith (1993) develop a 0–1 integer model for minimising inter-cell moves and a multi-objective model to form cells which are both flexible and have minimum interactions based on the results of the first model. They measure flexibility

of a cell (routing flexibility) based on the number of different parts which could be handled by the cell. A greater degree of routing flexibility can be achieved by assigning a greater variety of machines to a cell, that in turn increases workflow among the cells and thus deteriorates the objective of minimising inter-cell moves. The authors use the constraint method (Cohon 1978) to obtain non-dominated solutions for the multi objective model.

Logendran (1993) develops a model to minimise total inter-cell and intra-cell movement of parts and to maximise cell machine utilisation. These objectives are unified through the weighting approach in the form of a single objective. The original model is formulated as a quadratic binary programming model and then converted into a linear binary programming model.

Min and Shin (1993) attempt to form both machine cells and human cells simultaneously by means of a mixed integer goal programming model. The goals are concerned with the level of parts similarity, available machine processing times, machine capabilities/operator skill matching, and the difference between the wages of the cells operators and the rest of the operators. A heuristic is then developed for machine cell formation and operators allocation in two subsequent stages.

Sankaran and Kasilingam (1993) develop an integer programming model to determine cell membership in a GT-based flexible manufacturing system along with cell size and capacity selection. The developed objective function can be viewed as the sum of the processing costs, the spatial cost, the annual amortisation costs, and the inter-cell and intra-cell movement costs. In other words, the weighting approach is used to deal with multiple objectives. The authors then present a heuristic to solve the model.

Gupta *et al.* (1995) develop a minimisation model that takes into consideration the weighted sum of both inter-cell and intra-cell moves. The authors use a genetic algorithm for solving the model. There is attention on the minimum acceptable level of machine utilisation in the procedure of part assignment to the cells.

Liang and Taboun (1995) in an attempt to achieve a compromise solution between flow-line efficiency and job-shop flexibility develop a bi-criterion nonlinear integer programming model. The objectives of the model are to maximise system flexibility (measured based on the number of part types accommodated into the focused cells), and to maximise system efficiency (measured based on the degree of part similarities). The authors assume that no inter-cell movement is allowed and all exceptional parts should be sub-contracted. They use the weighting approach to unify the two objectives in the form of a single objective. A heuristic is then proposed which consists of two phases, i.e. generation of approximate efficient (or non-dominated) solutions, and calculation of the best solution based on the approximate efficient solution. The constraint method is used to generate approximate efficient solutions.

Suresh *et al.* (1995) employ a three-phase hierarchical approach to cell formation. In phase I of the solution approach, a neural network clustering technique is used to identify potential part families and their associated machine groups. A mixed integer goal programming formulation is then used in phase II to assign individual machines to a specified number of cells. The model of phase II attempts to satisfy the conflicting goals of: maximising the cell independence, minimising the purchase of new equipment and maximising the routing flexibility. Phase III aims to minimise inter-cell traffic further for families that may still have to be processed in more than one cell by means of a 0–1 programming model.

Akturk and Balkose (1996), by means of a coding scheme which includes both design and manufacturing attributes of parts, calculate the similarity and dissimilarity of parts and makes use of them in a six objective model. The objectives are concerned with minimising: the dissimilarity of parts based on the design and manufacturing attributes, the dissimilarities based on the operation sequences, the total machine investment cost, the sum of the workload variability in each cell, the workload variability of different cells, and the number of skipping which refers to the number of machines a part skips in its operation sequence. The authors suggest a multi-objective cluster analysis heuristic to deal with these objectives simultaneously. The analytic hierarchy process (AHP) is employed to determine priority of the objectives in order to unify them.

Boctor (1996) develops a number of mixed integer models, of which model P1 is selected as a multi-objective model for this study. The objective function of the model P1 is composed of two cost terms, i.e. machine duplication cost and inter-cell movement cost, which should be totally minimised. These two cost functions do not move in the same direction in such a way that decreases the second term, i.e. the cost of inter-cellular movements is achieved partly through machine duplication that in turn increases the first cost term. The author unified these two conflicting criteria in the form of a single objective function through a weighting approach with equal weights assigned to each criterion. Simulated annealing is then used to obtain good solutions for the optimisation model.

Gupta *et al.* (1996) present three models for the machine cell-part grouping problem. Their model 3 is a bi-criteria model that considers simultaneously the minimisation of total weighted inter-cell and intra-cell movements, and the minimisation of the cell load variations. The authors employ a genetic algorithm to provide the decision-maker with a set of satisfactory solutions.

Ho and Moodie (1996) assume flexible routing for parts and have developed a two-stage solution approach. Part families are formed in stage 1 based on the similarities in their operation sequences by means of a heuristic procedure. Machines in stage 2 are allocated to the part families through a mixed integer programming model. The objective function of this stage is composed of three cost functions: operation cost, machine duplication cost, and a penalty cost for those operations that need to be performed in cells other than the ones that they have been assigned. The latter term could be considered as another definition for the inter-cell movement cost. The authors employ, in stage 2, the weighting approach to unify the three cost criteria.

Rajamani *et al.* (1996) develop a mixed integer programming model with the assumption of flexible process plans for parts. The objective function of the model is to minimise the sum of investment, process and material handling costs as a weighted sum of the three different cost functions. To solve the relaxed linear model the authors make use of a column generation scheme and the branch and bound technique.

Lee and Chen (1997) employ a weighting approach to combine two criteria, i.e. minimising inter-cell movement of parts, and maximising workload balance among duplicated machines. Their solution methodology is a three-phase approach, which determines machine cells and part families and allows for machine duplication where necessary. At the beginning, an estimation procedure is developed to determine workload balances for duplicated machines. In the second phase, machine cells and part families are constructed by means of a heuristic algorithm. Finally, a

heuristic procedure is employed to improve the solution quality of the formation result.

Su and Hsu (1998) consider three objectives in their model. The objectives are: minimising the total cost of inter-cell transportation, intra-cell transportation and machine investment; minimising intra-cell machine (in cell) load unbalance; and minimising inter-cell machine (in plant) load unbalance. The authors then unify these objectives through weighting, and solve the model by means of parallel simulated annealing. The authors make use of the crossover and mutation functions of a genetic algorithm to function as the generation mechanism of simulated annealing in order to cope with its main drawback, i.e. high execution time.

## 5. Comparison of the models and research direction

The comparison of the multi-criteria cell design models is carried out based on their inputs, criteria, solution approach and outputs. It should be noted that the classification scheme used in this study is partially influenced by the work of Offodile *et al.* (1994).

### 5.1. Comparison based on the inputs

The input data is primarily classified based on the source of the data. It is divided into four categories: parts data, machines data, constraints, and general data. The data related to the parts and machines are further classified based on the type of data such as: quantitative data and cost data. Figure 1 shows the classification of these inputs.

The input data of the previously discussed models are illustrated and compared in table 2. In this table the rows represent various inputs considered in the multi-criteria models. The most common input data of the models are required machines (by parts), process times, production capacity of machines, maximum cell size, and parts demand. It could be said that a base cell design model must contain at least such a set of input data. Other relatively common input sets include the number of available machines, the predetermined number of cells, the fixed process flow of parts, the acquisition cost of machines, the inter-cell transportation cost, and the minimum cell size. Fixed process flow, as it could be traced in table 2, is becoming

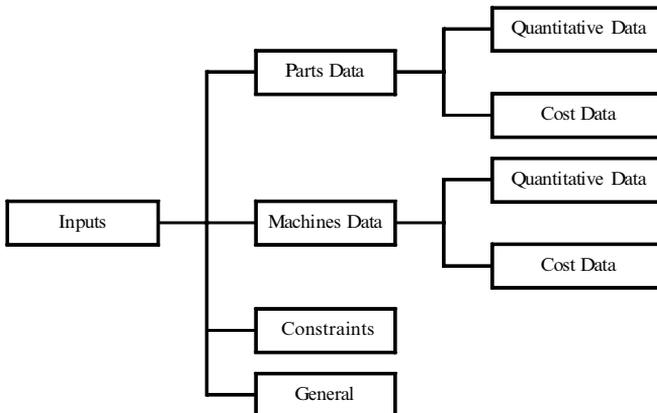


Figure 1. Classification of the inputs.

Inputs	Sankaran (1990)	Wei and Gathier (1990)	Shafter and Rogers (1991)	Shafter <i>et al.</i> (1992)	Venugopal and Narendran (1992)	Dahl and Smith (1993)	Lengdaran (1993)	Min and Shin (1993)	Sankaran and Kasilingam (1993)	Gupta <i>et al.</i> (1995)	Lang and Taboun (1995)	Suresh <i>et al.</i> (1993)	Akrok and Balkose (1996)	Boctor (1996)	Gupta <i>et al.</i> (1996)	Ho and Moodie (1996)	Rajamani <i>et al.</i> (1996)	Lee and Chen (1997)	Su and Hsu (1998)
<b>Parts data</b>																			
<b>Quantitative</b>																			
Demand	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Required machines	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Required tools	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Fixed process flow																			
Alternative process flows			*																
Alternative machines for perations	*		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Process times			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Set-up times			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Batch size			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Pallet capacity																			
Part coding																			
<b>Cost</b>																			
Direct prod. cost	*	*																	
Tool usage cost	*	*																	
Operator wage								*											
Subcontract cost.				*															
Intercell transport cost				*					*										
Intracell transport. cost	*								*										
Set-up cost									*										
Space cost									*										
<b>Machine data</b>																			
Number of each machine	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Production capacity	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Available tools																			
Space requirements																			
Acquisition cost	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Operation cost	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
<b>Constraints</b>																			
Fixed number of cells																			
Interval of cells number										*									
Max. utilisation										*									
Min. utilisation										*									
Max. cell size	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Min. cell size	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Max. cell output																			
Operator limitations																			
Funds available																			
Space available									*										
<b>General</b>																			
Operator skills																			
Arrangement of machines in cells																			
Arrangements of cells in plant																			*

Table 2. Comparison of the models based on their inputs

less important as a major input. That may be due to the increasing importance of flexibility that provides manufacturing system designers with more alternatives in process route of the parts. Such inputs as set-up times, the batch size, the direct production cost, the intra-cell transportation cost, and the minimum acceptable level of utilisation have been among the less common inputs. There have also been some inputs which are used in one single model only, e.g. the required tools for parts, the subcontracting cost, the space requirement of machines, and the operator limitations.

#### 5.1.1. *Future work direction: input data*

There is a need to consider some new sets of input data in the cell design process to incorporate some of the real aspects of the current industrial environment. Obviously the most common inputs as identified above need to be within all models. Flexibility of manufacturing is becoming a significant importance in modern manufacturing, so it would be essential to incorporate such an important factor in the set of input data by quantifying alternative process routes and flexible machining processes. It is also important to consider the operation cost of machines to maximise utilisation of the machines for higher efficiency. The stochastic nature of demand is another important feature of the manufacturing environment that should be considered in the design of the manufacturing facility.

Standardisation of the input/output data sets could be another direction for future work. The models should provide various levels of inputs, with core inputs going to a master set of outputs, followed by optional inputs which allow secondary outputs to be provided, and so on. To this end, further research should be done in order to facilitate the definition of the minimum set of input data to achieve a specific set of output. Some field studies in various industries might be useful in identifying these sorts of minimum input/output data sets.

#### 5.2. *Comparison based on the criteria*

The criteria used in the cell design have been classified by the authors under objectives and goals; objectives are classified by the authors, primarily based on their orientation, as cost-oriented, performance-oriented. Cost-oriented objectives are in the form of minimisation. Performance-oriented objectives are further divided into minimisation and maximisation. The goal programming models aim to minimise the deviation from the predetermined goals. The structure of this classification is shown in figure 2.

Table 3 gives a comparison of the models based on these criteria. There has been a vast diversity among the criteria considered by researchers. Minimising the machine duplication cost, minimising the inter-cell transportation cost, minimising the number of inter-cell movement of parts, and minimising the cell load unbalance of machines, have been the most popular criteria. In a lower level of importance, such criteria as minimising the intra-cell transportation cost and maximising flexibility are also included. There is also a set of unique criteria, especially in the form of goals, such as minimising deviation from the level of matching between operator skills and machine capabilities, minimising deviation from a predetermined level of machine investment cost, and minimising the amount of skipping. In addition to the diversity of criteria, the models with the same set of criteria were very scarce. In fact only Ho and Moodie (1996) and Rajamani *et al.* (1996) select the same set of criteria

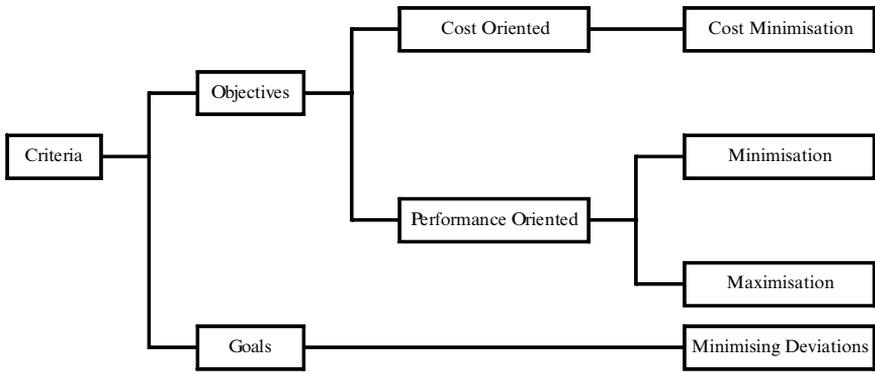


Figure 2. Classification of the criteria.

in their models. Thus it could be concluded that the majority of the multi-criteria cell design models are unique and cannot be compared with each other.

#### 5.2.1. *Future work direction: criteria.*

A vast area of research on cell design could be to develop models with a different combination of criteria that have not been previously considered simultaneously. For example, models which consider the total cost minimisation and the flexibility maximisation, along with a combination of other objectives, have not been reported. Another possible trend would be to develop more efficient solution approaches for models with the same set of criteria as an existing model.

A different trend should be research on handling different criteria in the procedure of cell design. The majority of the models use the weighting approach to unify the multiple objectives in the form of a single objective. A sophisticated objective function is an outcome of this approach, besides the fact that the weighting approach in many cases deals with optimising a senseless objective function. A future possible trend for the research in this field is to develop more efficient solution tools enabling system designers to achieve good solutions in a reasonable processing time. To investigate on the more efficient ways for finding non-dominated solutions is a good area of research for those models that consider multiple criteria simultaneously.

#### 5.3. *Comparison based on the solution approach*

The solution approaches are classified based on their solution techniques, into groups, which are presented in figure 3. Classification of the mathematical programming branch into constraint method, weighting method and goal programming is carried out based on models 2, 3 and 4 of section 3.1, respectively.

The solution approach of the models is compared in the top section of table 4. Mathematical programming has been the most common approach, where weighting method and goal programming have been applied most to the multi-criteria cell design. Goal programming applications were reported before 1995, and it seems that the approach lost its attraction in the second half of the 1990s. The constraint method has been employed in a single article. Due to the NP-complete nature of the problem, heuristics have been vastly employed to deal with real world problems. Genetic algorithms and simulated annealing have been the only reported search

Criteria	Wei and G�ather (1990)	Shaher and Rogers (1991)	Shaher et al. (1992)	Venugopal and Narendran (1992)	Dahel and Smith (1993)	Logendran (1993)	Min and Shin (1993)	Sankaran and Kasilingam (1993)	Gupta et al. (1995)	Lang and Taboun (1995)	Suresh et al. (1995)	Akurt and Balkose (1995)	Boctor (1996)	Gupta et al. (1996)	Ho and Modie (1996)	Rafamani et al. (1996)	Lee and Chen (1997)	Su and Hsu (1998)
Objectives																		
<i>min. cost of</i>																		
Machine duplication			*															*
operation cost			*															*
Part subcontracting		*	*															**
Intercell transportation		*	*															**
Intracell transportation																		
Space usage																		
Duplicated machines																		
Intercell movements				*		*												*
Intracell movements				*		*												*
In cell load unbalance																		
In plant load unbalance																		
Parts dissimilarity		*																
Skippings																		
Flexibility																		
Efficiency																		
Utilization																		
Cell independence		*																
<i>min. deviation from</i>																		
Parts similarity																		
Machine available processing time	*																	
Cell operator wages	*																	
Machine-operator skill matching																		
Minimum part movements	*																	
Maximum part movements	*																	
Machine investment cost	*																	
Operating cost	*																	
Set-up time																		
Utilisation		*																
Available funds		*																
Intercell moves		*																

Table 3. Comparison of the models based on their criteria

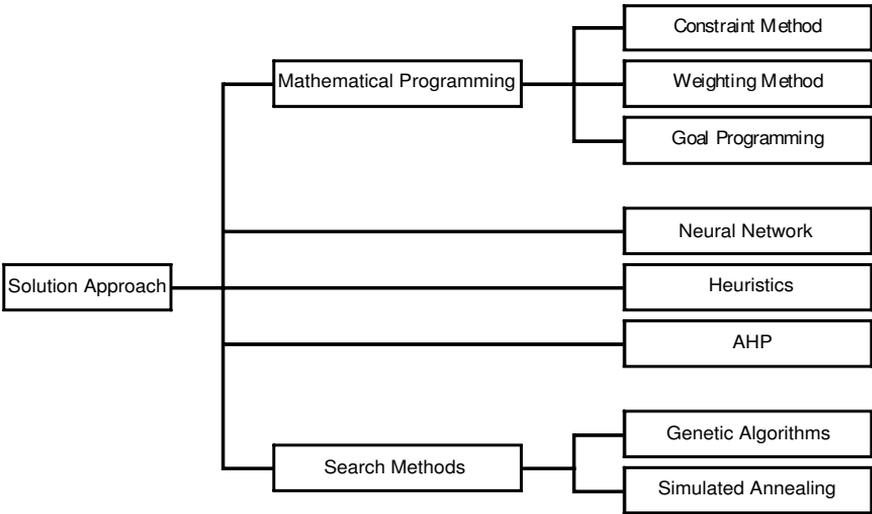


Figure 3. Classification of the solution approaches.

methods used to solve the models. Neural networks and the analytic hierarchy process (AHP) have been separately used as a part of the solution approach, along with other solution tools.

#### 5.3.1. *Future work direction: solution approaches.*

The most common solution approaches in the mathematical programming category have been the weighting method and goal programming. These approaches at most are able to find a single non-dominated solution. If the solution is not good enough to satisfy the system designer, the model should be resolved with different parameters. More researches is necessary in applying other multi-objective optimisation techniques in such a way that a rich subset of true non-dominated solutions is identified, from which system designers could select. Employing other solution approaches like the Tabu search or fuzzy clustering are some other potential research areas. Trying to make use of the optimisation capabilities of genetic algorithms and neural networks, which have inherent capability of parallel processing in the multi-objective cell design, are some possible research areas which have not been researched significantly.

#### 5.4. *Comparison based on the output*

Most of the models produce some information in addition to their major objectives. These additional outputs are classified based on their relation to the elements of grouping as part-related, machine-related, and general information. Figure 4 demonstrates the classification of the outputs.

The outputs of the models, in addition to those directly measured as criteria, are shown in the bottom section of table 4. Part families and machine groups are of course the main outputs of each cell design model. Duplicated machines, inter-cell movement, and machine utilisation have been among the common additional outputs. Duplicated machines had not been a major output in the first half of the decade, but since then have become a major output. There have also been some



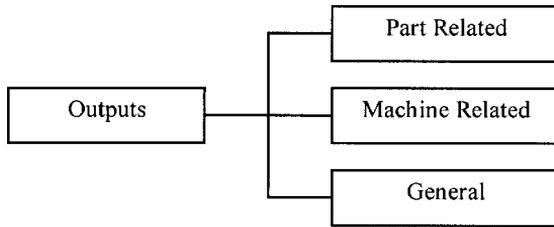


Figure 4. Classification of the outputs.

unique outputs such as different process plans, part sequencing and human groups which were considered for special cases and thus could not be regarded as a major output of a cell design model.

## 6. Conclusion

In this paper various approaches to the problem of multi-criteria cell design were investigated and reviewed. Previous reviews on cell design/formation were discussed and the need for this review was identified. A brief discussion on multi-criteria decision-making is given and multi-criteria cell design is categorised as either a multi-objective problem or a goal programming problem, along with an overview on these notions.

The reported papers on multi-criteria cell design were discussed and their modelling and solution approach were highlighted. Finally the models were compared, based on their inputs, criteria, solution approach and outputs. This comparison enables researchers to identify the research gaps in the literature.

Including some real aspects of the manufacturing environment (such as flexibility of manufacturing facilities as well as process routes, the stochastic nature of demand, and the standardisation of data sets) have been suggested for additional research work. Developing the new multi-objective cell design models with different sets of objectives is another possible research avenue. For example, models that consider cost minimisation and flexibility maximisation, along with maximising utilisation have not been reported. Such gaps in the modelling stage can easily be seen in table 3. Another possible trend could be work on the application of the other solution tools in the reported models. Minimising inter-cell part movement and maximising flexibility by means of multi-objective genetic algorithms, and minimising the sum of the cost of part subcontracting and inter-cell part movement by means of neural networks, are some examples of work to be investigated further in this field.

The majority of the works on multi-objective cell design unify the various objectives in the form of a single objective. The final result of such an approach is a compromise solution, whose non-dominance is not guaranteed. Pareto optimisation through simultaneous consideration of various objectives, and the ability to provide the decision-maker with a set of non-dominated solutions in a reasonable computation time, are other areas which need to be addressed.

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