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# Multi-objective machine-component grouping in cellular manufacturing: a genetic algorithm

CHIH-MING HSU and CHAO-TON SU

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**Keywords** group technology, cellular manufacturing system, machine-cell formation, machine-component grouping, genetic algorithm

**Abstract.** The cellular manufacturing system (CMS) is an important group technology (GT) application. The first step of CMS design is cell formation, generally known as machine-cell formation (MCF) or machine-component grouping (MCG). A genetic algorithm (GA) is a robust adaptive optimization method based on principles of natural evolution and is appropriate for the MCG problem, which is an NP complete complex problem. In this study, we propose a GA-based procedure to solve the MCG problem. More specifically, this study aims to minimize (1) total cost, which includes intercell and intracell part transportation costs and machines investment cots; (2) intracell machine loading imbalance; and (3) intercell machine loading imbalance under many realistic considerations. An illustrative example and comparisons demonstrate the effectiveness of this procedure. The proposed procedure is extremely adaptive, flexible, efficient and can be used to solve real MCG problems in factories by providing robust manufacturing cell formation in a short execution time.

## 1. Introduction

Group technology (GT) is a manufacturing philosophy which identifies and exploits the similarity of parts and processes in design and manufacturing. One specific application of GT is cellular manufacturing (CM). CM strives to attain the benefits of a product-oriented layout for medium variety, medium volume production environments by processing a family of parts in a group of machines. Cellular manufacturing system (CMS) design involves three preliminary stages: cell formation, machine layout in the cells and cell arrangement. Cell formation is the first and most difficult step in CMS design, and includes identifying parts with similar processing requirements (part family) and the set of machines that can process the corresponding family of parts (machine group). This is known as machine-cell formation (MCF) or machine-component grouping (MCG).

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The conventional approaches used to address the MCG problem are coding and classification (C&C) and production flow analysis (PFA). Extensive time and cost are the major disadvantages associated with developing a complex computer system for C&C (Perrego *et al.* 1995). The binary machine–part incidence matrix used in PFA only contains information regarding technological variables. Some important information, e.g. operation sequence, operation time, production quantity and backtracking of the part and the machine capacity is lost, thereby limiting the modelling accuracy of a realistic environment. Moreover, Ballakur and Steudel (1987) showed that under fairly restrictive conditions, the MCG problem is NP complete. Hence, optimizing a large-scale MCG problem is relatively difficult when using an optimization approach such as the integer programming model. Therefore, attaining a more feasible approach to resolve the MCG problem is highly desirable. Genetic algorithms (GA) are one such alternative.

In this study, we propose a GA-based procedure to solve the MCG problem. More specifically, this study aims to minimize (1) total cost, which includes intercell and intracell part transportation costs and machines investment costs; (2) intracell machine loading imbalance; and (3) intercell machine loading imbalance. An ideal cell formation can be found while many realistic considerations are involved, e.g., machine capacities, duplications and investment costs, intercell and intracell part transportation costs, setup times, operation sequences and operation times of parts.

## 2. An overview of earlier work

In 1963, Burbidge formally defined the MCG problem. C&C and PFA are two conventional techniques for solving MCG problems. C&C analysis is only appropriate for parts which are easily recognized. PFA utilizes routeing information or operation sequences to form part families. PFA methods can be divided into four types: (1) matrix formulation (McAuley 1972, King 1980, Seifoddini and Wolf 1986, Luong 1993, Chow and Hawaleshka 1993, Ribeiro and Pradin 1993, Perrego *et al.* 1995, Balakrishnan 1996); (2) graph theory (Rajagopalan and Batra 1975, Vannelli and Kumar 1986, Vohra *et al.* 1990, Askin and Chiu 1990, Askin *et al.* 1991, Rath *et al.* 1995); (3) mathematical formulation (Purcheck 1974, Kusiak 1987, Ben-Arieh and Chang 1994, Dahel 1995); and (4) other methods such as expert systems (Kusiak 1988), neural networks (Kaparthi and Suresh 1992, Chu 1993, Suresh and Kaparthi 1994, Burke and Kamal 1995), fuzzy set theory (Chu and Hayya 1991), and simulated annealing (Venugopal and Narendran 1992a, Chen *et al.* 1995).

GA is a robust adaptive optimization method based on principles of natural evolution. The GA search method does not tend to be trapped in a local optimum because it does not search along the contours of the function being optimized. The most striking feature of GA is perhaps that it makes hardly any assumptions about the problem space which it is searching (Whitley *et al.* 1990). Moreover, developing and representing a global search method are relatively easy; such a method is capable of a much faster search than might be expected. Hence, a GA search method is quite appropriate for the MCG problem which has a complex solution space and is not easily optimized. Venugopal and Narendran (1992b) presented a GA-based algorithm to design manufacturing cells with two objectives: intercell part flow and within-cell load balance. They considered limitations of machine capacities, production amounts and processing times of parts. However, the two populations subject to two different criteria may not simultaneously achieve satisfactory solutions. Gupta *et al.* (1995) developed a genetic approach for the MCG problem with the objectives of minimizing total intercell and intracell moves. Their study is extended by Gupta *et al.* (1996) who considered one more objective which minimizes within cell load variation. Both researches consider many realistic factors, e.g. machine capacities, operation times, operation sequences and the simple design of cell layouts. However, some important issues, e.g. backtrackings and setup times of parts, machine investment costs, machine duplications and the intercell machine loading balance, were not addressed. Moreover, they assumed that all parts have the same transportation costs (which is not true in almost all situations), thereby limiting the practical nature of their approaches.

## 3. The model of a cell formulation problem

Designing a cellular manufacturing system may require consideration of different criteria, e.g. maximizing machine utilization and scheduling flexibility, balancing machine loading, minimizing total cost and intercell part flow. These objectives generally conflict with each other. Therefore, simultaneously optimizing several different objectives is a relatively difficult task. In this study, minimizing the total cost and machine loading imbalances are of primary concern. The former prioritizes minimizing total cost which involves machine investments and intercell and intracell part transportation costs. Also the posterior objective concentrates on balancing both intracell and intercell machine loadings.

Hence, our studied cell formation problem can be formulated as follows:

Minimize
(1) total cost (machine investment costs and part transportation costs)
(2) intracell machine loading imbalance
(3) intercell machine loading imbalance
subject to
(1) each machine is assigned exactly to one manufacturing cell;
(2) each operation of each part is operated exactly on one machine;
(3) constraints of machine capacities;
(4) limitations of total number of machines in each cell.

In this model, three objectives with different scales and units are to be simultaneously optimized. To combine the above three objectives into one function, the following notations are given:

$TH_{m,i}$ machine type $m$ hours demanded by part type $i$

$C_m$ capacity of machine type $m$

$N_{\min,m}$ minimum required number of machines type $m$

$$= MININT\left(\sum_{i\in \text{Parts}} TH_{m,i}/C_m\right)$$

where $MININT(a)$ rounds up $a$ to the nearest integer

$I_m$ investment cost of machine type $m$

$MIC_{\min}$ minimum machine investment cost

$$= \sum_{m\in \text{machine types}} N_{\min,m} \times I_m$$

$O_i$ total number of operations of part type $i$

$IRTC_i$ intercell transportation cost of part type $i$

$IATC_i$ intracell transportation cost of part type $i$

$TC_{\max}$ maximum cost of part transportations

$$= \sum_{i\in \text{Parts}} IRTC_i \times (O_i - 1)$$

$TC_{\min}$ minimum cost of part transportations

$$= \sum_{i\in \text{Parts}} IATC_i \times (O_i - 1)$$

$PC_{\max}$ maximum cost $= TC_{\max} + MIC_{\min}$

$PC_{\min}$ minimum cost $= TC_{\min} + MIC_{\min}$

$H_{i,j}$ machine $j$ hours demanded of part type $i$

$CAP_j$ capacity of machine $j = C_m$ where machine $j$ belongs to machine type $m$

$U_j$ machine $j$ utilization

$$= \sum_{i\in \text{Parts}} H_{j,i}/CAP_j$$

$N_k$ total number of machines in cell $k$

$CU_k$ cell $k$ utilization

$$= \sum_{j\in \text{Cell}\ k} U_j/N_k$$

$LU_k$ machine loading imbalance of cell $k$

$$= \sum_{j\in \text{Cell}\ k} (|U_j - CU_k|)/N_k$$

$NC$ total number of cells

$IALU$ intracell cell machine loading imbalance

$$= \sum_{k\in \text{Cells}} LU_k/NC$$

$IRLU$ intercell machine loading imbalance

$$= \text{MAX}\{|CU_1 - CU_2|, |CU_1 - CU_3|, |CU_1 - CU_4|, \ldots, |CU_{k-1} - CU_k|\}$$

$DN_m$ total number of machine type $m$ in the final result of grouping machines

$DUP_m$ total number of duplications of machine type $m$ is the final result of grouping machines $= DN_m - N_{\min,m}$

$MIC_{\text{dup}}$ total investment cost of machine duplications

$$= \sum_{m\in \text{Machine types}} I_m \times DUP_m$$

$MIC_{\text{total}}$ total machine investment cost $= MIC_{\min} + MIC_{\text{dup}}$

$T_{i,l}$ 1, if the $l$th and $(l+1)$th operations of part type $i$ are operated in different cells
0, otherwise.

$TC_{\text{total}}$ total part transportation cost

$$= \sum_{i\in \text{Parts}} \sum_{l=1} (T_{i,l} \times IRTC_i + (1 - T_{i,l}) \times IATC_i)$$

The machine duplications make efforts to reduce the total cost. Hence, the sum of the total investment cost of machine duplications and the total cost of part transportations satisfies the following equation:

$$TC_{\min} \le MIC_{\text{dup}} + TC_{\text{total}} \le TC_{\max}$$

The total cost is the sum of total machine investment cost and part transportation cost, i.e.

$$PC_{\text{total}} = \text{Total cost} = MIC_{\text{total}} + TC_{\text{total}}$$

which must vary between $PC_{\min}$ and $PC_{\max}$. Hence, total cost can be normalized by

$$F_1 = (PC_{\text{total}} - PC_{\min})/(PC_{\max} - PC_{\min}) \qquad (1)$$

which varies between 0 and 1.

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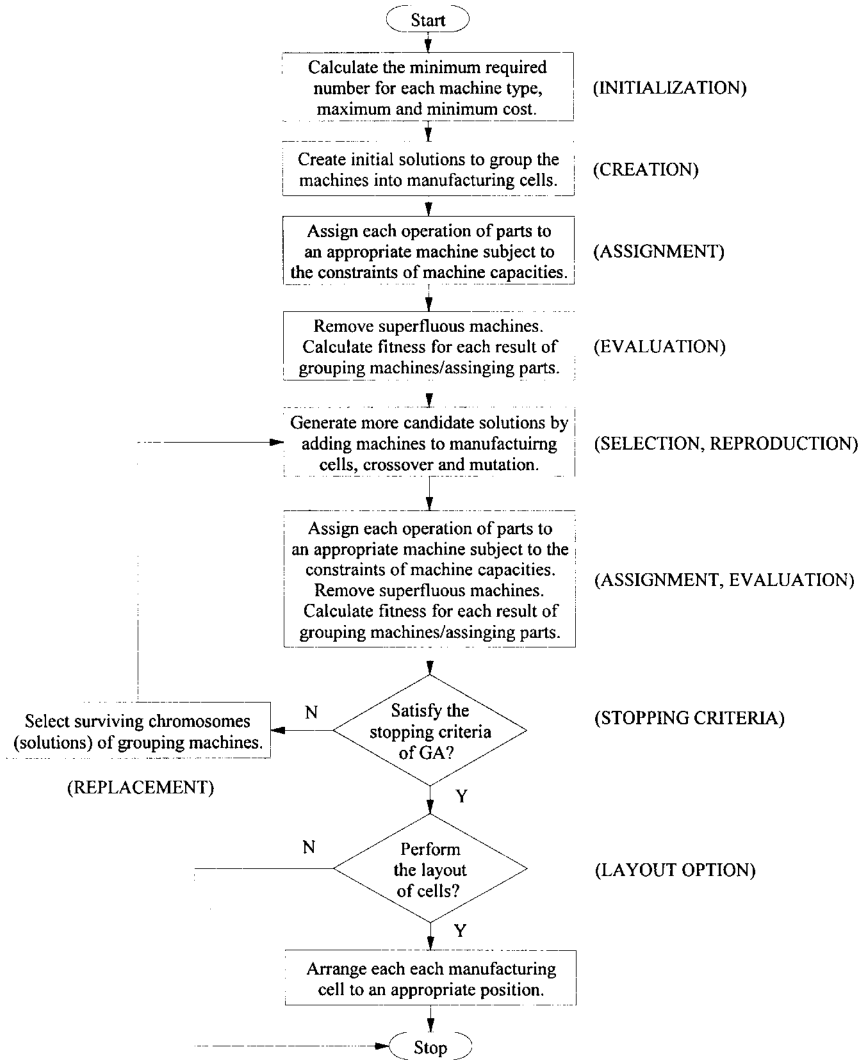


Figure 1. Flow diagram of the proposed GA-based procedure.

The intracell machine loading imbalance ($IALU$) is an index which denotes the status of machine loading within cells. A smaller index implies smoother flow of parts inside each cell, which subsequently leads to minimization of WIP within each cell. According to its definition, $IALU$ varies between 0 and 1/2 and can be transformed by

$$F_2 = 2 \times IALU \tag{2}$$

which varies between 0 and 1.

Similarly, intercell machine loading imbalance ($IRLU$) is an index which represents the deviation of average machine loading between cells. According to the definition, $IRLU$ varies between 0 and 1 and does not need to be normalized. Hence the last objective function $F_3$ is directly defined as

$$F_3 = IRLU \tag{3}$$

Therefore, the three objective functions in our model can be combined to be

$$F = w_1 \times F_1 + w_2 \times F_2 + w_3 \times F_3 \tag{4}$$

where $w_1$, $w_2$ and $w_3$ are user-defined weights which allow users to flexibly determine the importance of each criterion. This model is a mathematical problem with NP completeness. In the next section, we develop a highly effective heuristic procedure based on GA to solve this complex problem.

## 4. The proposed GA-based procedure for cell formation problems

In GA, the first critical task is to genetically represent a solution. Here, the possible solution for grouping

Table 1. Parts information.

| Part | Intercell part transportation cost | Intracell part transportation cost | Operation sequence | Operation time | Setup time |
|---|---|---|---|---|---|
| 1 | 100 | 10 | 8, 15, 1, 8, 9, 14 | 1, 4, 2, 4, 5, 3 | 0·2, 0·3, 0·1, 0·2, 0·3, 0·3 |
| 2 | 110 | 11 | 2, 13, 7, 17, 9 | 2, 2, 3, 2, 3 | 0·3, 0·1, 0·3, 0·2, 0·3 |
| 3 | 90 | 9 | 10, 14, 3, 16, 5 | 1, 1, 1, 2, 1 | 0·2, 0·2, 0·2, 0·2, 0·1 |
| 4 | 80 | 8 | 17, 4, 18, 12 | 2, 2, 4, 2 | 0·3, 0·2, 0·3, 0·2 |
| 5 | 120 | 12 | 17, 6, 11 | 5, 2, 2 | 0·4, 0·2, 0·3 |
| 6 | 100 | 10 | 6, 17, 14, 17 | 5, 2, 2, 2 | 0·3, 0·2, 0·3, 0·1 |
| 7 | 80 | 8 | 14, 5, 16 | 1, 2, 3 | 0·2, 0·1, 0·2 |
| 8 | 90 | 9 | 16, 14, 5, 10, 14 | 3, 1, 3, 2, 2 | 0·2, 0·1, 0·1, 0·1, 0·2 |
| 9 | 80 | 8 | 1, 14, 17, 15, 11, 14 | 1, 1, 2, 3, 1, 2 | 0·1, 0·3, 0·1, 0·2, 0·2, 0·2 |
| 10 | 80 | 8 | 9, 8, 1, 11, 8 | 1, 2, 3, 2, 2 | 0·1, 0·1, 0·2, 0·2, 0·1 |
| 11 | 80 | 8 | 11, 8, 15, 9, 11 | 1, 1, 3, 3, 3 | 0·2, 0·1, 0·2, 0·3, 0·2 |
| 12 | 80 | 8 | 15, 8, 11, 1, 13, 9 | 1, 3, 3, 3, 2, 3 | 0·1, 0·3, 0·5, 0·4, 0·1, 0·1 |
| 13 | 80 | 8 | 17, 13, 7, 13, 2 | 3, 2, 3, 3, 1 | 0·1, 0·2, 0·1, 0·2, 0·1 |
| 14 | 80 | 8 | 14, 10, 3, 10, 5, 16 | 1, 2, 3, 3, 4, 4 | 0·3, 0·2, 0·2, 0·1, 0·2, 0·2 |
| 15 | 90 | 9 | 3, 10, 16, 14 | 1, 2, 3, 2 | 0·1, 0·3, 0·3, 0·2 |
| 16 | 80 | 8 | 18, 12, 4, 18, 17 | 1, 4, 2, 1, 2 | 0·1, 0·2, 0·2, 0·1, 0·2 |
| 17 | 110 | 11 | 12, 4, 17, 18, 17 | 2, 2, 1, 5, 1 | 0·1, 0·3, 0·1, 0·3, 0·2 |
| 18 | 100 | 10 | 17, 6, 11, 6 | 4, 2, 2, 3 | 0·3, 0·2, 0·3, 0·1 |
| 19 | 90 | 9 | 17, 18, 12, 4 | 2, 3, 2, 1 | 0·2, 0·3, 0·2, 0·1 |
| 20 | 120 | 12 | 3, 16, 3, 10 | 1, 2, 2, 2 | 0·2, 0·2, 0·2, 0·2 |
| 21 | 80 | 8 | 11, 14, 17, 6, 14 | 3, 1, 1, 3, 2 | 0·4, 0·2, 0·1, 0·2, 0·2 |
| 22 | 90 | 9 | 13, 2, 9, 17, 2, 5 | 2, 2, 5, 2, 4, 4 | 0·2, 0·2, 0·3, 0·2, 0·1, 0·3 |
| 23 | 100 | 10 | 11, 15, 8, 1, 8, 9 | 1, 1, 3, 4, 1, 2 | 0·2, 0·1, 0·1, 0·3, 0·1, 0·3 |
| 24 | 90 | 9 | 1, 15, 14, 11, 9, 15 | 2, 1, 2, 2, 2, 2 | 0·3, 0·1, 0·3, 0·4, 0·1, 0·1 |
| 25 | 80 | 8 | 5, 13, 5, 7, 9 | 5, 3, 4, 2, 4 | 0·3, 0·3, 0·1, 0·3, 0·2 |
| 26 | 70 | 7 | 13, 2, 5, 7, 9, 13 | 1, 3, 3, 2, 4, 1 | 0·1, 0·2, 0·3, 0·1, 0·5, 0·1 |
| 27 | 80 | 8 | 5, 17, 3, 10, 16, 3 | 2, 1, 4, 2, 4, 1 | 0·2, 0·1, 0·2, 0·1, 0·3, 0·1 |
| 28 | 110 | 11 | 12, 4, 17, 4 | 3, 2, 1, 3 | 0·2, 0·2, 0·1, 0·2 |
| 29 | 120 | 12 | 4, 17, 4, 12 | 2, 1, 5, 1 | 0·2, 0·2, 0·1, 0·1 |
| 30 | 80 | 8 | 14, 11, 17, 6, 7 | 3, 1, 1, 2, 2 | 0·3, 0·1, 0·1, 0·1, 0·3 |
| 31 | 80 | 8 | 17, 14, 6, 10, 11 | 4, 2, 3, 3, 1 | 0·3, 0·3, 0·3, 0·1, 0·1 |
| 32 | 80 | 8 | 10, 14, 5, 14, 3, 16 | 1, 2, 2, 2, 3, 1 | 0·1, 0·1, 0·3, 0·1, 0·3, 0·1 |
| 33 | 100 | 10 | 7, 9, 17, 13, 2, 13 | 1, 2, 1, 1, 3, 2 | 0·2, 0·2, 0·4, 0·2, 0·2, 0·1 |
| 34 | 110 | 11 | 8, 9, 15, 1, 14 | 3, 1, 4, 1, 3 | 0·3, 0·1, 0·4, 0·1, 0·4 |
| 35 | 90 | 9 | 2, 7, 13, 5, 7, 17 | 1, 2, 3, 2, 2, 1 | 0·1, 0·2, 0·4, 0·3, 0·1, 0·3 |

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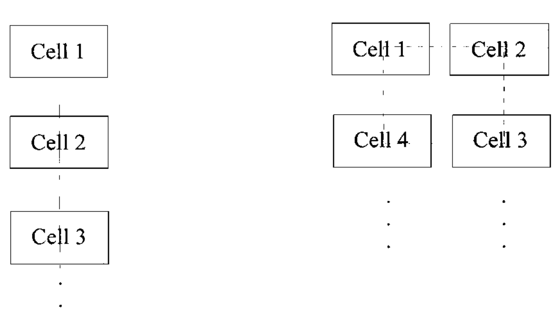
Table 2. Machines information.

| Machine type | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Capacity available | 22 | 20 | 26 | 25 | 22 | 25 | 21 | 24 | 22 | 27 | 22 | 22 | 26 | 22 | 25 | 28 | 25 | 22 |
| Investment cost | 600 | 700 | 550 | 800 | 700 | 750 | 800 | 650 | 700 | 900 | 800 | 700 | 750 | 600 | 700 | 700 | 550 | 800 |

machines into cells is represented by a chromosome. Each gene in the chromosome represents the manufacturing cell where the gene's corresponding machine is grouped. For instance, chromosome (1,1,2,3) can represent that the four machines are grouped in cells 1, 1, 2 and 3, respectively. Another issue of GA is the fitness function which is defined as the degree of a solution (chromosome) that reaches pre-specified targets, i.e. simultaneously minimizing total cost, and intracell and intercell machine loading imbalances. Figure 1 illustrates a flow diagram of the proposed GA-based procedure. A more detailed description is given in Appendix A.

| | | Cell 1 | | | | Cell 2 | | | | | | Cell 3 | | | | | Cell 4 | | | | Cell 5 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | P\M | 6 | 11-1 | 14-2 | 17-3 | 2 | 5-1 | 7 | 9-2 | 13 | 17-1 | 3 | 5-2 | 10 | 14-1 | 16 | 4 | 12 | 17-2 | 18 | 1 | 8 | 9-1 | 11-2 | 14-3 | 15 |
| Cell 1 | 5 | 2 | 3 | | 1 | | | | | | | | | | | | | | | | | | | | | |
| | 6 | 1 | | 3 | 2,4 | | | | | | | | | | | | | | | | | | | | | |
| | 18 | 2,4 | 3 | | 1 | | | | | | | | | | | | | | | | | | | | | |
| | 21 | 4 | 1 | 2,5 | 3 | | | | | | | | | | | | | | | | | | | | | |
| | 30 | 4 | 2 | 1 | 3 | | | 5 | | | | | | | | | | | | | | | | | | |
| | 31 | 3 | | 2 | 1 | | | | | | | | | 4 | | | | | | | | | | 5 | | |
| Cell 2 | 2 | | | | | 1 | | 3 | 5 | 2 | 4 | | | | | | | | | | | | | | | |
| | 13 | | | | | 5 | | 3 | | 2,4 | 1 | | | | | | | | | | | | | | | |
| | 22 | | | | | 2,5 | 6 | | 3 | 1 | 4 | | | | | | | | | | | | | | | |
| | 25 | | | | | | 1,3 | 4 | 5 | 2 | | | | | | | | | | | | | | | | |
| | 26 | | | | | 2 | 3 | 4 | 5 | 1,6 | | | | | | | | | | | | | | | | |
| | 33 | | | | | 5 | | 1 | | 4,6 | 3 | | | | | | | | | | | | 2 | | | |
| | 35 | | | | | 1 | 4 | 2,5 | | 3 | 6 | | | | | | | | | | | | | | | |
| Cell 3 | 3 | | | | | | | | | | | 3 | 5 | 1 | 2 | 4 | | | | | | | | | | |
| | 7 | | | | | | | | | | | | 2 | | 1 | 3 | | | | | | | | | | |
| | 8 | | | | | | | | | | | | 3 | 4 | 2,5 | 1 | | | | | | | | | | |
| | 14 | | | | | | | | | | | 3 | 5 | 2,4 | 1 | 6 | | | | | | | | | | |
| | 15 | | | | | | | | | | | 1 | | 2 | 4 | 3 | | | | | | | | | | |
| | 20 | | | | | | | | | | | 1,3 | | 4 | | 2 | | | | | | | | | | |
| | 27 | | | | | | 1 | | | | 2 | 3,6 | | 4 | | 5 | | | | | | | | | | |
| | 32 | | | | | | | | | | | 5 | 3 | 1 | 2,4 | 6 | | | | | | | | | | |
| Cell 4 | 4 | | | | | | | | | | | | | | | | 2 | 4 | 1 | 3 | | | | | | |
| | 16 | | | | | | | | | | | | | | | | 3 | 2 | 5 | 1,4 | | | | | | |
| | 17 | | | | | | | | | | | | | | | | 2 | 1 | 3,5 | 4 | | | | | | |
| | 19 | | | | | | | | | | | | | | | | 4 | 3 | 1 | 2 | | | | | | |
| | 28 | | | | | | | | | | | | | | | | 2,4 | 1 | 3 | | | | | | | |
| | 29 | | | | | | | | | | | | | | | | 1,3 | 4 | 2 | | | | | | | |
| Cell 5 | 1 | | | | | | | | | | | | | | | | | | | | 3 | 1,4 | 5 | | 6 | 2 |
| | 9 | | | | 3 | | | | | | | | | | | | | | | | 1 | | | 5 | 2,6 | 4 |
| | 10 | | | | | | | | | | | | | | | | | | | | 3 | 2,5 | 1 | 4 | | |
| | 11 | | | | | | | | | | | | | | | | | | | | | 2 | 4 | 1,5 | | 3 |
| | 12 | | | | | | | | 6 | 5 | | | | | | | | | | | 4 | 2 | | 3 | | 1 |
| | 23 | | | | | | | | | | | | | | | | | | | | 4 | 3,5 | 6 | 1 | | 2 |
| | 24 | | | | | | | | | | | | | | | | | | | | 1 | | 5 | 4 | 3 | 2,6 |
| | 34 | | | | | | | | | | | | | | | | | | | | 4 | 1 | 2 | | 5 | 3 |

Figure 2. Machine–part incidence matrix (including operation sequence of parts).




(1) Linear single-row cellular layout (2) Linear double-row cellular layout

Figure 3. Basic cell layouts of two different types.

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Table 3. Results of minimizing total cost (Problems 1–3).

| Literature problem | Total number of cells | Layout type | Total moves | Workstations in cell $i$ | | | |
|---|---|---|---|---|---|---|---|
| | | | | Cell 1 | Cell 2 | Cell 3 | Cell 4 |
| 1 | 2 | 1 | 3·80 | 1, 2, 3, 4 | 5 | | |
| | | 2 | 3·80 | 1, 2, 3, 4 | 5 | | |
| | 3 | 1 | 5·00* | 5 | 1, 2, 3 | 4 | |
| | | 2 | 5·00* | 5 | 1, 2, 3 | 4 | |
| | 4 | 1 | 6·90@ | 5 | 1, 3 | 2 | 4 |
| | | 2 | 6·78* | 1 | 4 | 2 | 3·5 |
| 2 | 2 | 1 | 6·30 | 1, 5 | 2, 3, 4, 6, 7 | | |
| | | 2 | 6·30 | 1, 5 | 2, 3, 4, 6, 7 | | |
| | 3 | 1 | 7·50* | 1, 5 | 2, 4, 6, 7 | 3 | |
| | | 2 | 7·50* | 1, 5 | 2, 4, 6, 7 | 3 | |
| | 4 | 1 | 9·40* | 5 | 1 | 2, 4, 6, 7 | 3 |
| | | 2 | 8·88* | 4 | 2, 6, 7 | 1, 5 | 3 |
| 3 | 2 | 1 | 3·50 | 1, 3, 4, 5 | 2 | | |
| | | 2 | 3·50 | 1, 3, 4, 5 | 2 | | |
| | 3 | 1 | 4·30* | 1, 3 | 4, 5 | 2 | |
| | | 2 | 4·30* | 1, 3 | 4, 5 | 2 | |
| | 4 | 1 | 6·50* | 2 | 5 | 4 | 1, 3 |
| | | 2 | 5·68* | 4 | 2 | 1, 3 | 5 |

*The proposed GA-based procedure is better than Logendran's (1991).
@The proposed GA-based procedure is better than Logendran's (1991) and Gupta *et al.*'s (1996).

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## 5. Numerical illustration

In this section, we present a numerical example to demonstrate the effectiveness of the proposed GA-based procedure for cell formation problems. Tables 1 and 2 summarize the cell formation problem. Table 1 lists the preliminary information of the problem including intercell and intracell part transportation costs, operation sequences, operation and setup times in a production cycle. Table 2 denotes the machine types, capacities available and investment costs in a production cycle. We assume that the basic cell layout does not exist and the intercell and intracell part transportation costs already consider the effect of the part transportation distances. Hence, step 10 of our proposed procedure is not performed. The total number of cells is five and the total number of machines in each cell varies from four to eight. The combination of weights in the fitness function is set to be $w_1 = 1$, $w_2 = 1$ and $w_3 = 1$. The ideal result of grouping machines/assigning parts can be achieved by going sequentially with the proposed procedure which was coded in C language and implemented on a Pentium PC. Figure 2 shows the final machine–part incidence matrix including operation sequences of parts (e.g. part 1 is operated on machines 8, 15, 1, 9–1 and 14–3 sequentially). Notably, machine types 14 and 17 duplicate one more machine 14–3 and 17–3, respectively, and the total cost is 19197.

## 6. Comparisons with previous work

To display the superior strengths of the proposed procedure, four MCG problems from previous literature are solved by our GA-based procedure. The first problem originates from Ballakur and Steudel (1987). The second one comes from the problem (Logendran 1991) modified from Tabucanon and Ojha (1987). The third problem comes from Logendran's modified version (Logendran 1991) of the problem first considered by King and Nakornchai (1982) and then by Waghodekar and Sahu (1984). The final problem originates from the hypothetical example of Gupta *et al.* (1996). Figure 3 shows the basic cell layouts of two different types with equal distance between two continuous cells (Logendran 1991). Hence, the distance between any pair of cells can be calculated. For instance, the distances are 1 and 2 units for cells 1, 2 and cells 1, 3 in the linear single-row cellular layout. However, the distances are 1 and $\sqrt{2}$ units for cells 1, 2 and cells 1, 3 in the linear double-row cellular layout. Notably, the capacity of each machine is 8 (hours/day) and cannot be duplicated in the original studies. Each machine's investment cost is set to be an extremely large number, e.g. 1000. Moreover, all function-identical machines in each workstation must be grouped in the same manufacturing cell. Hence, each workstation is treated as a machine type with capacity which is the sum of the capacities of all machines in

Table 4. Results of minimizing total cost (Problem 4).

| Literature problem | Total number of cells | Layout type | Total moves | Workstations in cell *i*: Cell 1 | Cell 2 | Cell 3 | Cell 4 | Cell 5 | Cell 6 |
|---|---|---|---|---|---|---|---|---|---|
| 4 | 4 | 1 | 37·60* | 14 | 11 | 1, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13 | 2 | | |
| | | 2 | 34·85* | 2 | 1, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13 | 14 | 11 | | |
| | 5 | 1 | 44·20* | 14 | 11 | 3, 4, 5, 6, 7 8, 9, 10, 12, 13, 15 | 2 | 1 | |
| | | 2 | 37·54* | 14 | 11 | 2 | 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 15 | 1 | |
| | 6 | 1 | 53·30* | 1 | 2 | 3, 4, 5, 6, 7, 8, 9, 10, 12, 13 | 15 | 11 | 14 |
| | | 2 | 40·92* | 14 | 15 | 3, 4, 5, 6, 7, 8, 9, 10, 2, 13 | 11 | 2 | 1 |

*The proposed GA-based procedure is better than Gupta *et al.*'s (1996).

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Table 5. Results of minimizing total cost and intracell machine loading unbalance.

| Literature problem | Total number of cells | Type 1 layout: Total move | Type 1 layout: *IALU* | Type 2 layout: Total move | Type 2 layout: *IALU* |
|---|---|---|---|---|---|
| 1 | 2 | 3·80 | 0·15 | 3·80 | 0·15 |
| | 3 | 5·00 | 0·05 | 5·00 | 0·05 |
| | 4 | 6·90 | 0·00 | 6·49 | 0·00 |
| 2 | 2 | 6·30 | 0·13 | 7·50 | 0·07 |
| | 3 | 7·50 | 0·07 | 7·50 | 0·07 |
| | 4 | 9·70 | 0·04 | 8·88 | 0·04 |
| 3 | 2 | 3·50 | 0·09 | 3·50 | 0·09 |
| | 3 | 4·30 | 0·06 | 4·30 | 0·06 |
| | 4 | 6·50 | 0·03 | 5·68 | 0·03 |
| 4 | 4 | 50·3 | 0·15 | 59·40 | 0·04 |
| | | 50·4 | 0·14 | 65·70 | 0·04 |
| | | 53·9 | 0·15 | 71·40 | 0·04 |
| | 5 | 54·3 | 0·11 | 76·10 | 0·03 |
| | | 55·6 | 0·13 | 74·80 | 0·03 |
| | | 59·2 | 0·13 | 72·80 | 0·02 |
| | 6 | 62·5 | 0·07 | 73·70 | 0·02 |
| | | 66·6 | 0·10 | 79·10 | 0·02 |
| | | 67·0 | 0·10 | 80·20 | 0·03 |

that workstation. The unit intercell and intracell part transportation costs are set to be 0·7 and 0·3, respectively (Logendran 1991). Tables 3 and 4 compare our results with previous work. According to these results, our proposed procedure cannot only adapt well for problems of different scales, but also yields satisfactory results. Tables 5 and 6 indicate that simultaneously optimizing multiple objectives is difficult and some tradeoffs must be made. The above results suggest that the total moves grow with an increase in the total number of cells. In most cases, the total moves of the linear double-row cellular layout is equal to or less than the total moves of a linear single-row cellular layout. Moreover, less total moves generally lead to more *IALU*. *IALU* and *IRLU* do not have significant relationships with the total number of cells and layout types. Some flexible different results are given and a decision can be made according to one's own need for problem 4.

## 7. Conclusions

In this work, we have proposed a procedure based on GA to solve the MCG problem. The proposed procedure attempts to simultaneously minimize total cost and intracell and intercell machine loading imbalances. The study also considers many realistic aspects such as operation sequences, setup times, operation times, and intercell and intracell transportation costs of parts. Important factors regarding the investment costs, duplications and capacities of machines are involved. The impact of the layout of manufacturing cells is also included. The MCG problem is first formulated into a multi-criteria

Table 6. Results of minimizing total cost, and intracell and intercell machine loading imbalances.

| Literature problem | Total number of cells | Type 1 layout | | | Type 2 layout | | |
|---|---|---|---|---|---|---|---|
| | | Total move | *IALU* | *IRLU* | Total move | *IALU* | *IRLU* |
| 1 | 2 | 3·80 | 0·15 | 0·02 | 3·80 | 0·15 | 0·02 |
| | 3 | 5·00 | 0·05 | 0·30 | 5·00 | 0·07 | 0·20 |
| | 4 | 7·60 | 0·02 | 0·30 | 6·78 | 0·02 | 0·03 |
| 2 | 2 | 7·10 | 0·21 | 0·01 | 7·10 | 0·21 | 0·01 |
| | 3 | 8·20 | 0·08 | 0·25 | 8·20 | 0·08 | 0·25 |
| | 4 | 10·10 | 0·04 | 0·34 | 8·88 | 0·04 | 0·35 |
| 3 | 2 | 3·50 | 0·09 | 0·04 | 3·50 | 0·09 | 0·04 |
| | 3 | 4·30 | 0·06 | 0·15 | 4·30 | 0·06 | 0·15 |
| | 4 | 6·50 | 0·03 | 0·22 | 5·68 | 0·03 | 0·22 |
| 4 | 4 | 56·50 | 0·21 | 0·11 | 45·10 | 0·20 | 0·14 |
| | | 59·40 | 0·21 | 0·09 | 48·70 | 0·22 | 0·07 |
| | | 62·30 | 0·22 | 0·05 | 49·46 | 0·21 | 0·06 |
| | 5 | 58·10 | 0·16 | 0·14 | 51·55 | 0·16 | 0·11 |
| | | 60·00 | 0·16 | 0·10 | 51·92 | 0·16 | 0·10 |
| | | 65·00 | 0·16 | 0·13 | 51·95 | 0·17 | 0·10 |
| | 6 | 68·70 | 0·12 | 0·15 | 50·06 | 0·10 | 0·24 |
| | | 68·80 | 0·13 | 0·13 | 53·08 | 0·13 | 0·14 |
| | | 71·70 | 0·13 | 0·14 | 55·04 | 0·12 | 0·16 |

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mathematical programming model. Next, three objectives of different scales and units are normalized and combined into one weighted objective function. A procedure based on GA which is quite appropriate for the MCG problems is then developed to solve the problem. A sample example of 35 part types and 18 machine types is solved to test the procedure; a satisfactory result is subsequently obtained. Four different scaled problems from the literature are also considered and the numerical results are compared with those of the original authors. According to this comparison, our proposed procedure is better in most situations. We can conclude not only that simultaneously minimizing several objectives is difficult, but also some tradeoffs must be made. Moreover, in using this procedure, decision makers have flexibility in determining the priorities of the three different ojectives. The procedure is extremely adaptive, flexible, efficient and can be used to solve real MCG problems in factories by providing a robust manufacturing cell formation in a short execution time.

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## Appendix A: The proposed GA-based procedure for cell formation problems

*Step* 1. Calculate the minimum required number for each machine type, and compute maximum and minimum cost.

*Step* 2. Create initial solutions to group the machine into manufacturing cells.

*Step* 2.1. Calculate corrective strengths ($CS$) between machine types.

$CS_{m,m'}$ = correlative strength between machine types $m$ and $m'$

$$= \sum_{i \in \text{Parts}} (IRTC_i - IATC_i) \times \sum_{l=1} OSI_{i,l,m,m'}$$

$OSI_{i,l,m,m'}$ = 1, if the $l$th operation of part type $i$ is operated on machine type $m$ and the $(l+1)$th operation is operated on machine type $m'$
= 0, otherwise.

*Step 2.2.* Calculate the initial total number of machines ($IN_k$) for each manufacturing cell.
$IN_k$ = total number of initial machines in cell $k$. For cell $k = 1, 2, \ldots, NC - 1$,

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$IN_k$ must satisfy

$$MAXINT\left(\sum_{m \in \text{Machine types}} N_{\min,m}/NC\right) \le IN_k \le MININT\left(\sum_{m \in \text{Machine types}} N_{\min,m}/NC\right)$$

where $MAXINT(a)$ rounds down $a$ to the nearest integer.

$$IN_{NC} = \sum_{m \in \text{Machine types}} N_{\min,m} - \sum_{k=1} IN_k$$

must satisfy limitations of total number of machines in each cell.

*Step 2.3.* Let all machines be unassigned.
DO {
Assign an unassigned machine to the current manufacturing cell.
DO {
Find an unassigned machine which has the largest correlative strength ($CS$) with the last machine assigned to the current manufacturing cell. Assign this unassigned machine to the current manufacturing cell.
} WHILE (The current manufacturing cell is not full.)
} WHILE (There is any empty manufacturing cell.)

*Step 2.4.* Represent the initial solution of grouping machines by a chromosome. Duplicate this initial solution (chromosomes) and increase the diversity of initial solutions by mutation function of GA to form an initial population of solutions with predetermined size.

*Step* 3. Assign each operation of parts to an appropriate machine subject to the constraints of machine capacities.
For each part:
DO {
List all possible combinations of assignments subject to the constraints of machine capacities.
Allow all combinations of assignments with the same least sum of intercell and intracell part transportation costs to be the candidates.
Select the candidate which inspires the least 'shock' ($SK$)* to the machine loading imbalance.
*For part type $i$, the shock that a possible combination of assignments inspires is defined as follows:

$$SK = \sum_{l \in \text{Operations}} SOH_{i,l}/AC_j$$

where
$SOH_{i,l}$ = the sum of setup time and operation time of the $l$th operation of part type $i$
$AC_j$ = currently available capacity of machine $j$ which operates the $l$th operation of part type $i$.

*Step* 4. Remove all superfluous machines. Calculate fitness for each result of grouping machines/assigning parts.

*Step 4.1.* For each result, remove the machine with zero machine loading.

*Step 4.2.* Calculate fitness for each result of grouping machines/assigning parts.

$$\text{Fitness}\,F_{\text{overall}} = (w_1 \times (1 - F_1) + w_2 \times (1 - F_2) + w_3 \times (1 - F_3))/(w_1 + w_2 + w_3) - penalty$$

where $F_1$, $F_2$, $F_3$, $w_1$, $w_2$ and $w_3$ are defined as those in the previous section; and $penalty$ refers to an extremely large positive number for the violation of limitations of total number of machines in each cell.

*Step* 5. Generate more candidate solutions by adding machines to manufacturing cells, crossover and mutation.
For each result of grouping machines/assigning parts, perform step 5.1 and step 5.2.

*Step 5.1.* For each machine type, calculate its potential to reduce total cost if this machine type duplicates one more machine.
Where the potential of machine type $m$ is defined as 'the reduced intercell part transportation costs – the reduced intracell part transportation costs – the increased investment cost of the duplicated machine, if machine type $m$ duplicates one more machine under current result of grouping machines/assigning parts.'

*Step 5.2.* Duplicate one more machine with the optimum potential for the original result to generate one more candidate solution.

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*Step 5.3.* Generate more candidate solutions by performing crossover and mutation functions of GA to the original solutions.

*Step* 6. Assign each operation of parts to an appropriate machine subject to the constraints of machine capacities. Remove superfluous machines. Calculate fitness for each result of grouping machines/assigning parts.

*Step* 7. Go to step 9 if satisfying the stopping criteria of GA.

*Step* 8. Select surviving chromosomes (solutions) of grouping machines. Selecting surviving chromosomes, i.e. the original solutions of the next generation of grouping machines, according to the principle of GA. Go to step 5.

*Step* 9. Go to step 10 if the basic cell layout design exists. Otherwise, go to step 11.

*Step* 10. Arrange each manufacturing cell to an appropriate position. Allow the modified total part transportation cost to be

$$MTC_{\text{total}} = \sum_{i \in \text{parts}} \sum_{l=1} (T_{i,l} \times IRTC_i + (1 - T_{i,l}) \times IATC_i) \times DIST_{i,l}$$

where $DIST_{i,l}$ = the linear part transportation distance between two cells or within a cell where the $l$th and the $(l+1)$th operations of part type $i$ must be operated, respectively.

By sequentially exchanging the layouts of paired manufacturing cells, a final arrangement of cells with the criterion of minimizing the modified total part transportation costs ($MTC_{\text{total}}$) could be found.

*Step* 11. Stop.

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