



A novel algorithm of cell formation with alternative machines and multiple-operation-type machines

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ABSTRACT

Several different machines can often perform the same type of operation, so an operation can be performed on a part by selecting any of the machines offering that same function. Moreover, many machines are not limited to performing only one type of operation on a part, so a part can be fabricated using a single machine to perform more than one operation. Some papers have discussed alternative routings and machines, but have not considered a machine that can perform more than one operation on a part. The concept of using an alternative machine capable of performing several operation types was only introduced into group technology (GT) in 2014. In this paper, the major purpose is to improve traditional GT with considering alternative machines and multiple-operation-type machines. A novel algorithm is proposed. The result can recommend which machine can be used to provide which type of operation on a specific part. Two numerical examples are presented to compare the algorithm with others. Especially, there are sixty-four resolutions that could be suggested to the manager in numerical example one. The traditional GT algorithm cannot solve this problem. Occasionally, more than one result with the same GT efficiency can be provided.

1. Introduction

A factory leader must achieve the goals of increased productivity and decreased processing time and material wastage. The use of cellular manufacturing (CM) affords numerous advantages, such as a 45.6% decrease in throughput time, 39.3% decrease in material handling time, and it can reduce work-in-process inventory and setup time (Wemmerlov & Hyer, 1989). Thus, the two most fundamental benefits associated with CM are reductions in throughput time and inventory (Hyer & Wemmerlov, 2002). The optimum machine cell formation results in a reduction of the overall processing time and material handling costs (Hazarika & Laha, 2018; Mohammadi & Forghani, 2016). Moreover, “parts movement” wastes time and reduces assembly line efficiency. The concept of group technology (GT) has been implemented in CM to solve this problem (hereafter, the GT problem) (Shahdi-Pashaki, Teymourian, Kayvanfar, Komaki, & Sajadi, 2015; Zohrevand, Raffei, & Zohrevand, 2016; Liu, Wang, & Leung, 2018; Nalluri, Kannan, & Gao, 2019). GT is a manufacturing philosophy and provides a methodology for sorting machines into machine cells and parts into part families (Boe & Cheng, 1991; Parkin & Li, 1997; Gupta, Devika, Valarmathi, Sowmiya, & Shinde, 2014; Danilovic & Ilic, 2019; Won, 2020; Li, 2020; Rahimi,

Arkat, & Farughi, 2020). A GT environment can minimize the makespan (Qin, Zhang, & Bai, 2016; Zhang et al., 2018), reduce resource allocation costs (Liang et al., 2019), and find the optimal job schedule (Lu, Wang, Ji, & He, 2017; Miao, 2019). The benefits derived from the GT manufacturing system also include reductions of setup time, batch size and work-in-process inventory, and an improvement of quality (Singh & Rajamani, 1996). Numerous algorithms have been developed to solve the GT problem, such as heuristic, genetic, and neural network algorithms.

GT is based on the idea of using similarity to group parts (Suzic, 2012; Won & Logendran, 2015; Huang & Yan, 2019). A typical heuristic algorithm used in GT is the similarity coefficient method (McAuley, 1972):

$$s_{ij} = \frac{N_{ij}}{N_i + N_j - N_{ij}}$$

where N_i and N_j represent the number of parts processed by machines i and j , respectively, and N_{ij} represents the number of parts processed by both machines i and j .

Kusiak and Cho (1992) improved the similarity coefficient method and considered bottleneck parts or bottleneck machines in the similarity coefficient algorithm while solving the GT problem. Kumar and Singh

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Nomenclature

m	number of machines
n	number of parts
r	number of operation types
m_i	i^{th} machine
p_i	i^{th} part
o_i	i^{th} operation type
$A = \{a_{ij}\}_{m \times n}$	incidence matrix
$B_{machine} = \{b_{ij}\}_{m \times m}$	closeness matrix for machines
$B_{part} = \{b_{ij}\}_{n \times n}$	closeness matrix for parts
$OP = \{op_{ij}\}_{r \times n}$	operation type-part matrix
$MO = \{mo_{ij}\}_{m \times r}$	machine-operation type matrix

G_i	i^{th} group
g	number of groups
$S = \{s_{ij}\}_{gn}$	group-part matrix
η	group efficiency
e_b	total number of 1's in the major blocks
e_0	total number of 1's in the stray blocks
Q_i	the number of machines in the i^{th} cell
P_i	the number of parts in the i^{th} family
q	weighting factor
v_m	total number of times that machines move to different groups
v_p	total number of times that parts move to different groups

(2017) provided a novel similarity score-based two-phase heuristic approach to solve the dynamic cellular facility layout problem (DCFLP). The first step is to form a machine-cell based on similarity scores between machines.

Laha and Hazarika (2017) developed a heuristic approach based on the Euclidean distance matrix. This method differs from the similarity coefficient algorithm by using distance instead of similarity coefficients. The parts are sorted by considering the smallest Euclidean distance.

A genetic algorithm has also been proposed to solve the GT problem (Agustin-Blas et al., 2011; Boulif & Atif, 2006; Feng, Li, & Sethi, 2018; Hazarika & Laha, 2015; Imran, Kang, Lee, Jahanzaib, & Aziz, 2017). Using the genetic algorithm to solve the GT problem involves at least five steps: initial problem determination, fitness evaluation, population selection, crossover, and mutation (Hazarika & Laha, 2015). The genetic algorithm might find a solution, but it is usually not the best solution.

Although traditional algorithms are limited to solving two-dimensional GT problems, Parkin and Li (1997) attempted to solve GT problems of three or more dimensions by using a heuristic algorithm. The main concept of their algorithm is to consider all incidence matrices as independent and then to combine all closeness matrices. In addition, Bootaki, Mahdavi, and Paydar (2016) considered not only the part-machine incidence matrix, but also the worker-machine task matrix. They tried to minimize the voids of both worker-machine and worker-worker incidence matrices.

2. Problem description

The element in an incidence matrix of the traditional GT is either 1 or 0. The incidence matrix is defined as follows:

$$A = \{a_{ij}\} \text{ (Boe \& Cheng, 1991).}$$

$$\text{Here, } a_{ij} = \begin{cases} 1, & \text{if part } j \text{ visits machine } i \\ 0, & \text{otherwise} \end{cases}$$

Consider the following example.

$$A = \begin{matrix} & p_1 & p_2 & p_3 & p_4 \\ \begin{matrix} m_1 \\ m_2 \\ m_3 \\ m_4 \end{matrix} & \begin{bmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{bmatrix} \end{matrix}$$

where $a_{11} = 1$; this implies that means p_1 must be operated using m_1 . Moreover, $a_{21} = 0$; this implies that p_1 should not be operated using m_2 .

Some articles have discussed alternative routings (Hazarika & Laha, 2018; Mehdizadeh, Niaki, & Rahimi, 2016; Feng, Da, Xi, Pan, & Xia, 2017; Lian, Liu, Li, Evans, & Yin, 2014; Alhourani, 2016; Eguia, Molina, Lozano, & Racero, 2017; Forghani & Fatemi Ghomi, 2020; Rahimi et al., 2020), but papers have seldom mentioned alternative machines and

operation types. It was not until 2014 that Navaei and ElMaraghy (2014) introduced the concept of using an alternate machine with several operation types into GT. In this paper, the operation types are also considered in an incidence matrix.

Suppose two operation types (such as drilling a hole and welding) have to be performed on part δ ; thus, the operation type-part matrix can be defined as follows:

$$OP = \begin{matrix} & \text{part } \delta \\ \begin{matrix} \text{drilling a hole} \\ \text{welding} \end{matrix} & \begin{bmatrix} 1 \\ 1 \end{bmatrix} \end{matrix}$$

Usually, more than one type of machine can be used on some parts to perform the same type of operation. In addition, a part can be fabricated using a single machine to perform more than one operation type. Thus, a single machine with multiple operation types must be considered. For example, a computer numerical control (CNC) milling machine can drill a hole and mill, as shown in Fig. 1.

Thus, the “machine-operation type” matrix can be defined as follows:

$$MO = \begin{matrix} & \begin{matrix} \text{drilling a hole} & \text{milling} \end{matrix} \\ \text{milling machine} & \begin{bmatrix} 1 & 1 \end{bmatrix} \end{matrix}$$

In addition, having alternative machines capable of performing the same operation type means that the operation process (such as drilling a hole) could be completed by any one of them, as shown in Fig. 2.

Thus, in order to explain the question clearer, let's suppose an “operation type-part” matrix as follows:

$$OP = \begin{matrix} & p_1 & p_2 & p_3 & p_4 \\ \begin{matrix} o_1 \\ o_2 \\ o_3 \\ o_4 \end{matrix} & \begin{bmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{bmatrix} \end{matrix}$$

where $op_{11} = 1$ implies that operation type o_1 has to be performed on p_1 , and $op_{21} = 0$ implies that operation type o_2 does not have to be performed on p_1 . Moreover, o_1 , o_2 , o_3 , and o_4 represent drilling a hole, shearing, boring, and welding, respectively.

Suppose the “machine-operation type” matrix can be obtained as follows:

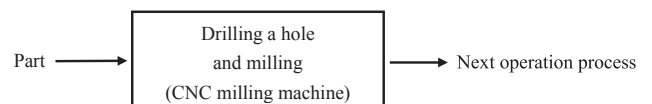


Fig. 1. A part is operated on by a single machine with multiple operation types.

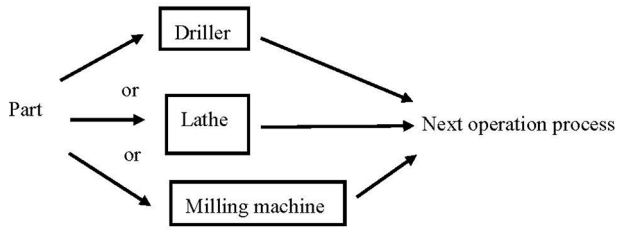


Fig. 2. A part is operated on by one of three types of machine.

$$MO = \begin{matrix} & o_1 & o_2 & o_3 & o_4 \\ \begin{matrix} m_1 \\ m_2 \\ m_3 \\ m_4 \\ m_5 \end{matrix} & \begin{bmatrix} 1 \\ & 1 & & \\ 1 & & 1 & \\ & & & 1 \\ 1 & & 1 & \end{bmatrix} \end{matrix}$$

Here, when mo_{11} , mo_{31} , and mo_{51} are equal to 1, it is implied that operation type o_1 could be performed by machine m_1 , m_3 , or m_5 , respectively.

Thus, p_1 could be operated on by m_1 , m_3 , or m_5 , as shown in Fig. 3.

The machine-operation type solutions for part p_3 are as shown in Fig. 4.

Traditional group technology usually provides only one answer. Although Navaei and ElMaraghy (2014) introduced the concept of an alternative machine with several operation types into GT, their method cannot form machine cells. Li and Parkin (2002) introduced the concept of “OR,” which is the same concept as an alternative machine, but operation types were not considered.

In addition, traditional GT focuses on “1” or “0” in an incidence matrix, but an incidence matrix cannot reflect the problem presented. Thus, this paper proposes a novel algorithm that can recommend both an alternative machine and an operation type.

3. Methodology

The inputs of the algorithm are the operation type-part matrix and the machine-operation type matrix. The outputs are the groups of machines and parts. A flow chart of the algorithm proposed in this article is shown in Fig. 5.

3.1. Operation-part matrix

Consider that a factory comprises m machines, n parts, and r types of

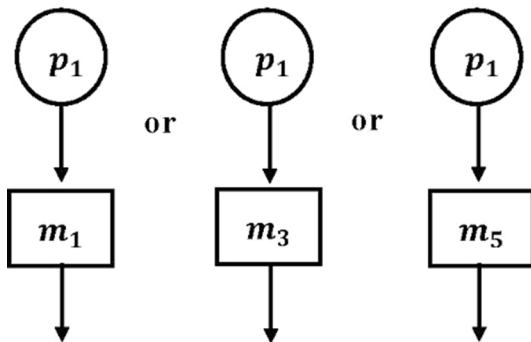


Fig. 3. p_1 could be operated on by one of three processes.

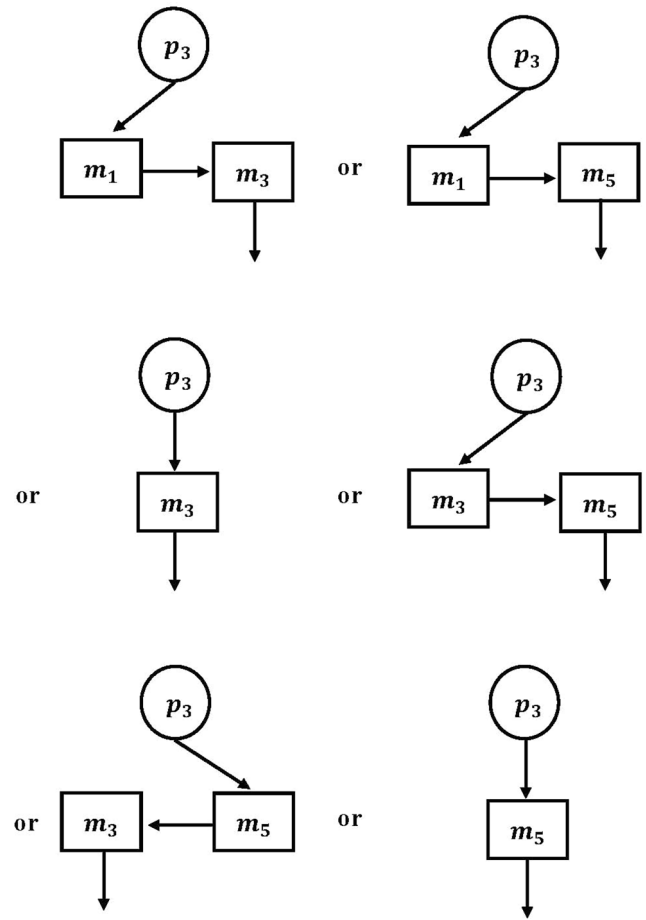


Fig. 4. p_3 could be operated on by one of six processes.

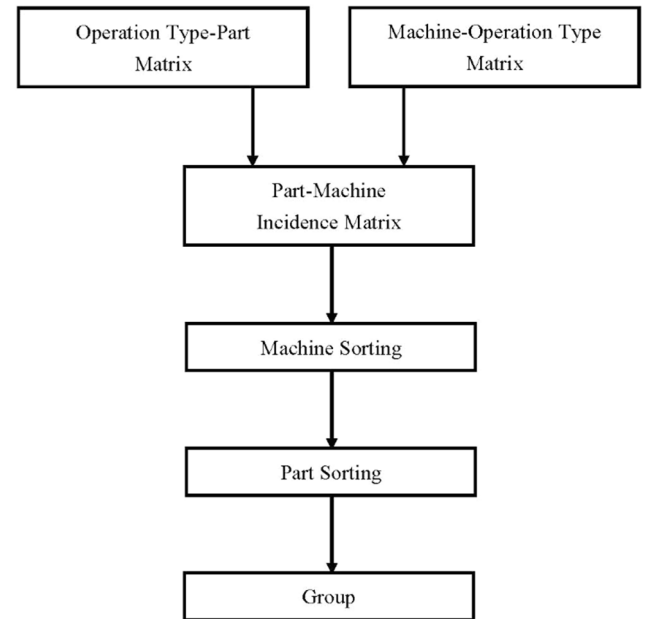


Fig. 5. A flow chart of the algorithm proposed in this article.

operations. Each part must undergo one or more types of operations. Thus, the relation between operation types and parts can be defined as follows:

$$OP = \{op_{ij}\}_{r \times n}$$

$$\text{where } op_{ij} = \begin{cases} 1, & \text{if part } j \text{ needs operation type } i \\ 0, & \text{otherwise} \end{cases}$$

3.2. Machine-operation matrix

There is at least one machine that can perform a type of operation. Occasionally, an operation type may be performed by more than one machine. For this case, the machine-operation matrix can be defined as follows:

$$MO = \{mo_{ij}\}_{m \times r}$$

$$\text{where } mo_{ij} = \begin{cases} 1, & \text{if operation type } j \text{ may be done by machine } i \\ 0, & \text{otherwise} \end{cases}$$

3.3. Incidence matrix

The incidence matrix of the traditional GT is defined as follows:

$$A = \{a_{ij}\}_{m \times n}$$

$$\text{where } a_{ij} = \begin{cases} 1, & \text{if machine } i \text{ operates part } j \\ 0, & \text{otherwise} \end{cases}$$

In this paper, the incidence matrix A must be modified and redefined as follows:

$$A = MO \times OP = \{mo_{ij}\}_{m \times r} \times \{op_{ij}\}_{r \times n} \quad (1)$$

where

$$a_{ij} = \sum_{k=1}^r mo_{ik} op_{kj}$$

The traditional a_{ij} is equal to either 1 or 0 but is defined as follows in this paper:

$$a_{ij} = \{x | x = o_s, mo_{is} op_{sj} \neq 0, 1 \leq s \leq r\} \quad (2)$$

Moreover, a_{ij} is a set, but the symbol $\{\}$ is ignored in the incidence matrix.

3.4. Machine sorting

The closeness matrix of machine $B_{machine} = \{b_{ij}\}_{m \times m}$ is to determine the similarity between machines. Thus,

$$b_{pq} = \sum_{k=1}^n a_{pk} a_{qk}, p \neq q, b_{pp} = 0$$

where $a_{pk} a_{qk}$ is equal to 1 or 0 (Boe & Cheng, 1991).

However, b_{ij} must be modified as follows:

$$b_{ij} = \sum_{k=1}^n a_{ik} a_{jk} \quad (3)$$

where

$$a_{ik} a_{jk} = \begin{cases} 0, & \{ [a_{ik} = a_{jk}] \wedge [n(a_{ik}) = n(a_{jk}) = 1] \} \vee \{ \min. [n(a_{ik}), n(a_{jk})] = 0 \} \\ 1, & \text{otherwise} \end{cases}$$

Forming a machine cell involves three steps:

Step 1: Machine grouping is initiated with the m_i that has the highest number of relations.

Note that $m_i \in G_1$ and has the highest value of $\max. \{b_{iu}\}, 1 \leq u, v \leq m$, in the i^{th} row of $B_{machine}$. A tie is broken by selecting the smallest value of i .

Step 2: Find machine m_k that has the highest value in $B_{machine}$, not including the entries of grouped machines' rows.

$$\begin{cases} m_k \in G_\xi, \text{ where } (b_{kj} = \max. \{b_{kt}\}, 1 \leq t \leq m) \wedge (m_j \in G_\xi) \\ \text{A tie is broken by choosing the smallest } j. \\ m_k \in a \text{ new group, otherwise} \end{cases} \quad (4)$$

Step 3: Repeat step 2 until all machines are grouped.

3.5. Part sorting

First, machine cells must be formed. Subsequently, part families must be formed. Four steps are involved in assigning groups to parts to form part families.

Step 1: After machine groups are formed, the incidence matrix A should be arranged to A' based on the machine cells.

Step 2: A matrix $S = \{s_{ij}\}_{g \times n}$ must be defined. There are g rows and n parts. The rows are G_1, G_2, \dots , and G_g instead of machines.

where

$$s_{ij} = n(a'_{aj} \cup a'_{\beta j} \dots \cup a'_{\sigma j}) \quad (5)$$

where $m_\alpha, m_\beta, \dots, m_\sigma \in G_i$

Step 3:

$$\text{Let } p_u \in G_v, \text{ where, } s_{vu} = \max. (s_{iu}, i = 1, \dots, g) \quad (6)$$

A tie is broken by selecting the highest efficiency.

Step 4: Repeat step 3 until all parts are grouped.

Two efficiency measurements have been proposed. One was defined by Chandrasekharan and Rajagopalan (1986) (Eq. (7)), and the other one was proposed by Li (2007) for two-dimensional GT (Eq. (8)).

$$\eta = q\eta_1 + (1-q)\eta_2 = q \frac{e_b}{\sum Q_i P_i} + (1-q) \left(1 - \frac{e_0}{mn - \sum Q_i P_i} \right) \quad (7)$$

$$\eta = \eta_1 \eta_2 = \left(1 - \frac{\sum Q_i P_i}{mn} \right) \left(1 - \frac{(v_m + v_p)}{(m+n) \times (g-1)} \right) \quad (8)$$

4. Numerical examples

This paper presents two numerical examples to demonstrate the operation of the proposed algorithm.

4.1. Example 1 and a comparison with Navai and ElMaraghy's algorithm

Suppose that there is a factory with 5 machines, 6 parts, and 13 operation types.

$$\begin{aligned}
 & \begin{matrix} & p_1 & p_2 & p_3 & p_4 & p_5 & p_6 \\ \text{OP=} & \begin{bmatrix} o_1 & 1 & & & & & \\ o_2 & 1 & & & & & \\ o_3 & & 1 & & & & \\ o_4 & & 1 & & & & \\ o_5 & & & 1 & & & \\ o_6 & & & 1 & & & \\ o_7 & & & 1 & & & \\ o_8 & & & & 1 & & \\ o_9 & & & & 1 & & \\ o_{10} & & & & & 1 & \\ o_{11} & & & & & 1 & \\ o_{12} & & & & & & 1 \\ o_{13} & & & & & & 1 \end{bmatrix} \end{matrix} \\
 & \begin{matrix} & o_1 & o_2 & o_3 & o_4 & o_5 & o_6 & o_7 & o_8 & o_9 & o_{10} & o_{11} & o_{12} & o_{13} \\ \text{MO=} & \begin{bmatrix} m_1 & 1 & & 1 & & 1 & 1 & & & & 1 & & 1 \\ m_2 & & 1 & & & & 1 & 1 & & & & & 1 \\ m_3 & 1 & & 1 & 1 & 1 & & & 1 & & 1 & & \\ m_4 & & 1 & 1 & & 1 & & 1 & & & & & 1 \\ m_5 & & & & & & & & 1 & & 1 & & \end{bmatrix} \end{matrix}
 \end{aligned}$$

Through Eqs. (1) and (2), for instance, $a_{m_2 p_3}$ or a_{23} can be obtained as follows:

$$a_{23} = m_2 \begin{bmatrix} o_1 & o_2 & o_3 & o_4 & o_5 & o_6 & o_7 & o_8 & o_9 & o_{10} & o_{11} & o_{12} & o_{13} \end{bmatrix} \begin{matrix} p_3 \\ \begin{bmatrix} o_1 \\ o_2 \\ o_3 \\ o_4 \\ o_5 & 1 \\ o_6 & 1 \\ o_7 & 1 \\ o_8 \\ o_9 \\ o_{10} \\ o_{11} \\ o_{12} \\ o_{13} \end{bmatrix} \end{matrix}$$

$$= 0 \times 0 + 1 \times 0 + 0 \times 0 + 0 \times 0 + 0 \times 1 + 1 \times 1 + 1 \times 1 + 0 \times 0 + 0 \times 0 + 0 \times 0$$

$$+ 0 \times 0 + 1 \times 0 + 0 \times 0$$

$$= 0 + 0 + 0 + 0 + 0 + 1 + 1 + 0 + 0 + 0 + 0 + 0$$

There are two none zeros, noted as $\{o_6, o_7\}$, but the symbol $\{\}$ is ignored in this article.

Thus, the incidence matrix A is defined as follows:

$$A = \begin{matrix} & p_1 & p_2 & p_3 & p_4 & p_5 & p_6 \\ \begin{matrix} m_1 \\ m_2 \\ m_3 \\ m_4 \\ m_5 \end{matrix} & \left[\begin{array}{cccccc} o_1 & o_3 & o_5, o_6 & & o_{10} & o_{12} \\ o_2 & & o_6, o_7 & & & o_{12} \\ o_1 & o_3, o_4 & o_5 & o_8 & o_{10} & \\ o_2 & & o_5, o_7 & & & o_{13} \\ & o_4 & & o_9 & o_{11} & \end{array} \right] \end{matrix}$$

Through Eq. (3), the entry $b_{m_1 m_3}$ or b_{13} of closeness matrix $B_{machine}$ is obtained as follows:

$$\begin{matrix} & p_1 & p_2 & p_3 & p_4 & p_5 & p_6 \\ \begin{matrix} m_1 \\ m_3 \end{matrix} & \left[\begin{array}{cccccc} o_1 & o_3 & o_5, o_6 & & o_{10} & o_{12} \\ o_1 & o_3, o_4 & o_5 & o_8 & o_{10} & \\ \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\ 0 & 1 & 1 & 0 & 0 & 0 \end{array} \right] \end{matrix}$$

$$b_{13} = 0 + 1 + 1 + 0 + 0 + 0 = 2$$

Thus, $B_{machine}$ is obtained as follows:

$$B_{machine} = \begin{matrix} & m_1 & m_2 & m_3 & m_4 & m_5 \\ \begin{matrix} m_1 \\ m_2 \\ m_3 \\ m_4 \\ m_5 \end{matrix} & \left[\begin{array}{ccccc} - & 2 & 2 & 3 & 2 \\ 2 & - & 2 & 2 & 0 \\ 2 & 2 & - & 2 & 3 \\ 3 & 2 & 2 & - & 0 \\ 2 & 0 & 3 & 0 & - \end{array} \right] \end{matrix}$$

In step 1, let m_1 belong to G_1 due to it having the highest number in $B_{machine}$.

In step 2, through Eq. (4), let m_3 belong to a new group, called G_2 , due to the highest number in row m_3 being b_{35} , but m_5 does not belong to any group. Next, let m_4 belong to G_1 due to the highest number in row m_4 being b_{41} and m_1 belonging to G_1 . In the same way, two groups are formed: $G_1 = \{m_1, m_4, m_2\}$ and $G_2 = \{m_3, m_5\}$.

In part sorting, the first step is to rearrange incidence matrix A to A'. Thus, the following is obtained:

$$A' = \begin{matrix} & p_1 & p_2 & p_3 & p_4 & p_5 & p_6 \\ \begin{matrix} m_1 \\ m_4 \\ m_2 \\ m_3 \\ m_5 \end{matrix} & \left[\begin{array}{cccccc} o_1 & o_3 & o_5, o_6 & & o_{10} & o_{12} \\ o_2 & & o_5, o_7 & & & o_{13} \\ o_2 & & o_6, o_7 & & & o_{12} \\ o_1 & o_3, o_4 & o_5 & o_8 & o_{10} & \\ & o_4 & & o_9 & o_{11} & \end{array} \right] \end{matrix}$$

Using Eq. (5) yields the following:

$$S = \begin{matrix} & p_1 & p_2 & p_3 & p_4 & p_5 & p_6 \\ \begin{matrix} G_1 \\ G_2 \end{matrix} & \left[\begin{array}{cccccc} 2 & 1 & 3 & 0 & 1 & 2 \\ 1 & 2 & 1 & 2 & 2 & 0 \end{array} \right] \end{matrix}$$

Applying Eq. (6) yields $p_1, p_3, p_6 \in G_1$ and $p_2, p_4, p_5 \in G_2$. Thus, the sorted incidence matrix A is as follows:

$$A_{sort} = \begin{matrix} & p_1 & p_3 & p_6 & p_2 & p_4 & p_5 \\ \begin{matrix} m_1 \\ m_4 \\ m_2 \\ m_3 \\ m_5 \end{matrix} & \left[\begin{array}{ccc|ccc} o_1 & o_5, o_6 & o_{12} & o_3 & & o_{10} \\ o_2 & o_5, o_7 & o_{13} & & & \\ o_2 & o_6, o_7 & o_{12} & & & \\ o_1 & o_5 & & o_3, o_4 & o_8 & o_{10} \\ & & & o_4 & o_9 & o_{11} \end{array} \right] \end{matrix}$$

Thus, o_2 of p_1 could be done by m_4 or m_2 ; o_5 of p_3 could be done by m_1 or m_4 ; o_6 of p_3 could be done by m_1 or m_2 ; o_7 of p_3 could be done by m_4 or m_2 ; o_{12} of p_6 could be done by m_1 or m_2 ; o_4 of p_2 could be done by m_3 or m_5 . There are sixty-four resolutions.

By conducting two measurements of GT efficiency, namely Chandrasekharan's measurement (with $q = 0.5$) and Li's measurement, and if the operation type or loading in each workstation is balanced, one resolution is suggested as follows:

		p_1	p_3	p_6	p_2	p_4	p_5
$A_{sort} =$	m_1	o_1 o_2			o_5		
	m_4		o_7	o_{13}			
	m_2		o_6	o_{12}			
	m_3				o_3	o_8	o_{10}
	m_5				o_4	o_9	o_{11}

Or rewritten as follows:

		p_1	p_3	p_6	p_2	p_4	p_5
$A_{sort} =$	m_1	1	1				
	m_4	1	1	1			
	m_2		1	1			
	m_3				1	1	1
	m_5				1	1	1

Chandrasekharan's η is equal to

$$\eta = 0.5 \times \frac{13}{3 \times 3 + 2 \times 3} + 0.5 \times \left(1 - \frac{0}{5 \times 6 - (3 \times 3 + 2 \times 3)}\right) = 0.933$$

Li's η is equal to

$$\eta = \left(1 - \frac{(3 \times 3 + 2 \times 3)}{5 \times 6}\right) \left(1 - \frac{0}{(5 + 6) \times (2 - 1)}\right) = 0.5$$

By considering the higher GT efficiency, one resolution is suggested as follows in this article:

		p_1	p_3	p_6	p_2	p_4	p_5
$A_{sort} =$	m_1	<div>o_1 o_5, o_6 o_{12}</div>					
	m_4	<div>o_2 o_7 o_{13}</div>					
	m_2						
	m_3				<div>o_3 o_8 o_{10}</div>		
	m_5				<div>o_4 o_9 o_{11}</div>		

Or rewritten as follows:

$$A_{sort} = \begin{matrix} & p_1 & p_3 & p_6 & p_2 & p_4 & p_5 \\ \begin{matrix} m_1 \\ m_4 \\ m_2 \\ m_3 \\ m_5 \end{matrix} & \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ & & & 1 & 1 & 1 \\ & & & 1 & 1 & 1 \\ & & & & & & 1 & 1 & 1 \end{bmatrix} \end{matrix}$$

In this resolution, m_2 could be a spare machine, and the GT efficiency is as follows:

Chandrasekharan's η is equal to

$$\eta = 0.5 \times \frac{12}{2 \times 3 + 2 \times 3} + 0.5 \times \left(1 - \frac{0}{5 \times 6 - (2 \times 3 + 2 \times 3)}\right) = 1$$

Li's η is equal to

$$\eta = \left(1 - \frac{(2 \times 3 + 2 \times 3)}{5 \times 6}\right) \left(1 - \frac{0}{(5 + 6) \times (2 - 1)}\right) = 0.6$$

However, there is only one resolution for part families, and the machine cells have not been formed by Navaei and ElMaraghy (2014) algorithm. Their method only suggested $p_3, p_6, p_1, p_2 \in G_1$ and $p_4, p_5 \in G_2$, as shown in Fig. 6.

4.2. Example 2 and a comparison with Li and Parkin's algorithm

Another example was demonstrated in the study by Li and Parkin (2002), and it is described as follows:

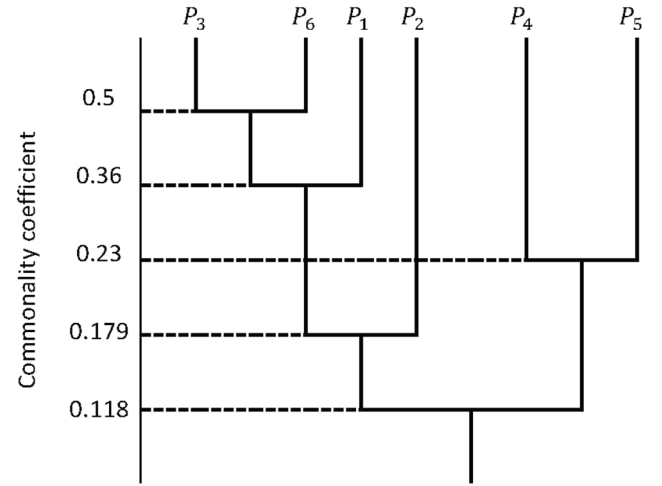


Fig. 6. Dendrogram presentation by Navaei and ElMaraghy's algorithm.

$$A = \begin{matrix} & p_1 & p_2 & p_3 & p_4 & p_5 & p_6 & p_7 & p_8 & p_9 & p_{10} \\ \begin{matrix} m_1 \\ m_2 \\ m_3 \\ m_4 \\ m_5 \\ m_6 \\ m_7 \end{matrix} & \begin{bmatrix} 1 & & 1 & & & & 1 & & & & C \\ & 1 & & 1 & & 1 & & D & & & A \\ 1 & 1 & 1 & & & & 1 & 1 & & & A \\ & & & & 1 & & & D & 1 & & A \\ & & & 1 & & 1 & & E & & & C \\ 1 & & 1 & & & & 1 & & & & B \\ & & & & 1 & & & E & 1 & & B \end{bmatrix} \end{matrix}$$

This example demonstrates the logical “OR” operation in GT. For example, p_8 must be operated by m_3 , either m_2 or m_4 , and either m_5 or m_7 . Operation types were not considered in the study by Li and Parkin, which suggested only one resolution, as follows:

	p_{10}	p_1	p_3	p_7	p_2	p_8	p_4	p_6	p_5	p_9
$A_{sort} = m_3$	A	1	1	1	1	1				
m_1	C	1	1	1						
m_6	B	1	1	1						
m_5						E	1	1		
m_2						D	1	1		
m_7									1	1
m_4									1	1

Or rewritten as follows,

	p_{10}	p_1	p_3	p_7	p_2	p_8	p_4	p_6	p_5	p_9
$A_{sort} = m_3$	1	1	1	1	1	1				
m_1	1	1	1	1						
m_6	1	1	1	1						
m_5						1	1	1		
m_2						1	1	1		
m_7									1	1
m_4									1	1

However, this problem could be also solved using the method suggested in this paper. The problem-solving process can be initiated using the incidence matrix A as follows:

Solving this problem through the algorithm presented in this paper reveals three machine cells and three part families. The sorted incidence matrix is as follows.

	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}
$A = m_1$	o_1		o_5				o_{14}			o_{22}
m_2				o_8		o_{12}		o_{17}		o_{23}
m_3	o_2	o_4	o_6				o_{15}	o_{18}		o_{23}
m_4					o_{10}			o_{17}	o_{20}	o_{23}
m_5				o_9		o_{13}		o_{19}		o_{22}
m_6	o_3		o_7				o_{16}			o_{24}
m_7					o_{11}			o_{19}	o_{21}	o_{24}

$$A_{sort} = \begin{matrix} & p_1 & p_2 & p_3 & p_7 & p_{10} & p_4 & p_6 & p_8 & p_5 & p_9 \\ \begin{matrix} m_1 \\ m_3 \\ m_6 \\ m_2 \\ m_5 \\ m_4 \\ m_7 \end{matrix} & \begin{bmatrix} o_1 & o_4 & o_5 & o_{14} & o_{22} & & & & & & \\ o_2 & & o_6 & o_{15} & o_{23} & & & & o_{18} & & \\ o_3 & & o_7 & o_{16} & o_{24} & & & & & & \\ & & & & o_{23} & o_8 & o_{12} & o_{17} & & & \\ & & & & o_{22} & o_9 & o_{13} & o_{19} & & & \\ & & & & o_{23} & & & o_{17} & o_{10} & o_{20} & \\ & & & & o_{24} & & & o_{19} & o_{11} & o_{21} & \end{bmatrix} \end{matrix}$$

However, two resolutions are suggested because these two results have the same highest GT efficiency levels, as defined by Chandrasekharan and Li, shown in Table 1 and Table 2.

Chandrasekharan's η is equal to

$$\eta = 0.5 \times \frac{23}{3 \times 5 + 2 \times 3 + 2 \times 2} + 0.5 \times \left(1 - \frac{1}{7 \times 10 - 25}\right) = 0.95$$

Li's η is equal to

$$\eta = \left(1 - \frac{(3 \times 5 + 2 \times 3 + 2 \times 2)}{(7 \times 10)}\right) \left(1 - \frac{(1 + 1)}{(7 + 10) \times (3 - 1)}\right) = 0.61$$

The two sorted incidence matrices A_{sort} are as follows:

$$A_{sort} = \begin{matrix} & p_1 & p_2 & p_3 & p_7 & p_{10} & p_4 & p_6 & p_8 & p_5 & p_9 \\ \begin{matrix} m_1 \\ m_3 \\ m_6 \\ m_2 \\ m_5 \\ m_4 \\ m_7 \end{matrix} & \begin{bmatrix} o_1 & o_4 & o_5 & o_{14} & o_{22} & & & & & & \\ o_2 & & o_6 & o_{15} & o_{23} & & & & o_{18} & & \\ o_3 & & o_7 & o_{16} & o_{24} & & & & & & \\ & & & & & o_8 & o_{12} & o_{17} & & & \\ & & & & & o_9 & o_{13} & o_{19} & & & \\ & & & & & & & & o_{10} & o_{20} & \\ & & & & & & & & o_{11} & o_{21} & \end{bmatrix} \end{matrix}$$

Table 2

One resolution of example 2 and a comparison with Li and Parkin's algorithm.

	Algorithm proposed in this study	Li and Parkin's algorithm
Machine cells	$\{m_1, m_3, m_6\}, \{m_2, m_5\}, \{m_4, m_7\}$	$\{m_3, m_1, m_6\}, \{m_5, m_2\}, \{m_7, m_4\}$
Part families	$\{p_1, p_2, p_3, p_7, p_{10}\}, \{p_4, p_6\}, \{p_8, p_5, p_9\}$	$\{p_{10}, p_1, p_3, p_7, p_2\}, \{p_8, p_4, p_6\}, \{p_5, p_9\}$
Chandrasekharan's η , $q = 0.5$	0.95	0.95
Li's η	0.61	0.61

Table 1

One resolution of example 2 and a comparison with Li and Parkin's algorithm.

	Algorithm proposed in this study	Li and Parkin's algorithm
Machine cells	$\{m_1, m_3, m_6\}, \{m_2, m_5\}, \{m_4, m_7\}$	$\{m_3, m_1, m_6\}, \{m_5, m_2\}, \{m_7, m_4\}$
Part families	$\{p_1, p_2, p_3, p_7, p_{10}\}, \{p_4, p_6, p_8\}, \{p_5, p_9\}$	$\{p_{10}, p_1, p_3, p_7, p_2\}, \{p_8, p_4, p_6\}, \{p_5, p_9\}$
Chandrasekharan's $\eta, q = 0.5$	0.95	0.95
Li's η	0.61	0.61

and

		p_1	p_2	p_3	p_7	p_{10}	p_4	p_6	p_8	p_5	p_9														
$A_{sort} =$	m_1	<table> <tr><td>o_1</td><td>o_4</td><td>o_5</td><td>o_{14}</td><td>o_{22}</td></tr> <tr><td>o_2</td><td></td><td>o_6</td><td>o_{15}</td><td>o_{23}</td></tr> <tr><td>o_3</td><td></td><td>o_7</td><td>o_{16}</td><td>o_{24}</td></tr> </table>	o_1	o_4	o_5	o_{14}	o_{22}	o_2		o_6	o_{15}	o_{23}	o_3		o_7	o_{16}	o_{24}								
	o_1		o_4	o_5	o_{14}	o_{22}																			
	o_2			o_6	o_{15}	o_{23}																			
	o_3		o_7	o_{16}	o_{24}																				
	m_3							o_{18}																	
	m_6																								
	m_2						o_8	o_{12}																	
m_5						o_9	o_{13}																		
m_4								o_{17}	o_{10}	o_{20}															
m_7								o_{19}	o_{11}	o_{21}															

Or rewritten as follows,

	p_1	p_2	p_3	p_7	p_{10}	p_4	p_6	p_8	p_5	p_9
--	-------	-------	-------	-------	----------	-------	-------	-------	-------	-------

$A_{sort} =$

m_1	1	1	1	1	1					
m_3	1		1	1	1			1		
m_6	1		1	1	1					

m_2						1	1	1		
m_5						1	1	1		

m_4									1	1
m_7									1	1

and

	p_1	p_2	p_3	p_7	p_{10}	p_4	p_6	p_8	p_5	p_9
--	-------	-------	-------	-------	----------	-------	-------	-------	-------	-------

$A_{sort} =$

m_1	1	1	1	1	1					
m_3	1		1	1	1			1		
m_6	1		1	1	1					

m_2						1	1			
m_5						1	1			

m_4								1	1	1
m_7								1	1	1

5. Result and discussion

This work considers both an alternative machine and operation types, which sometimes can provide more than one result with the same group technology efficiency. If an alternative machine and operation types are considered in GT, it is more complicated, and the manager is faced with a greater number of selections in deciding which part should be operated on by which machine and which operation type. For instance, there are sixty-four resolutions in example 1, and although p_1 could be operated on by m_1 or m_3 with the same operation type, the method proposed in this article selected m_1 , because p_1 does not need to move between two groups, thus yielding a higher GT efficiency. In addition, one resolution is to let p_3 be operated on by m_1 with operation type 5 (o_5). Another resolution is to let p_3 be operated on by m_1 with operation types 5 and 6 (o_5, o_6). The manager has the possibility of selecting which resolution is suitable for the production line, while still benefiting from the GT. In example 2, p_8 yields the same GT efficiency whether it is assigned to part family $\{p_4, p_6\}$ or part family $\{p_5, p_9\}$. A manager in a factory could select either family based on the machine load or the real situation.

6. Conclusion

CM or GT has many advantages. A major advantage is that the distance or time required for transferring parts is reduced. Many algorithms, such as heuristic, genetic, and neural network algorithms, have been derived in previous studies to realize this reduction. All these traditional GT algorithms focus on “1” or “0,” which means that when a machine can operate on a part, then the value is 1; otherwise, the value is 0. Several different machines have the capability to perform the same type of operation. Many machines are not limited to perform only one type of operation. Thus, a suitable machine can be selected to perform more than one type of operation on a part based on the requirement. In this paper, the method of using alternative machines and the method of using a single machine to perform multiple functions are considered. Thus, machine–operation type and operation type–part matrices are introduced. The main step of the algorithm is to form machine cell groups by using a series of logical operations and concepts, and then part families are formed. Two numerical examples are presented to demonstrate the proposed algorithm. It can help the manager to decide which part should be operated on by which machine and which operation type. The results may reveal more than one answer. Thus, two GT efficiency measurements are conducted for testing the proposed algorithm to enable a manager to select the best layout or machines in a factory.

Usually, GT considers only machines and parts, but workers should also be considered. Thus, future work could examine a multi-dimensional GT efficiency that incorporates machines, parts, operation types, and workers.

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