Journal of Industrial and Systems Engineering
Vol. 1, No. 4, pp 318-344
Winter 2008

JISE

Machine Cell Formation Based on a New Similarity Coefficient

Ibrahim H. Garbie[1*], Hamid R. Parsaei[2] and Herman R. Leep[3]

[1] Department of Mechanical Engineering, Helwan University, Helwan, Cairo, 11792, EGYPT.
ibrahim68@helwan.edu.eg

[2]Department of Industrial Engineering, University of Houston, Houston, TX, 77204, USA.
[3]Department of Industrial Engineering, University of Louisville, Louisville, KY, 40292, USA.

ABSTRACT

One of the designs of cellular manufacturing systems (CMS) requires that a machine population be partitioned into machine cells. Numerous methods are available for clustering machines into machine cells. One method involves using a similarity coefficient. Similarity coefficients between machines are not absolute, and they still need more attention from researchers. Although there are a number of similarity coefficients in the literature, they do not always incorporate the important properties of a similarity coefficient satisfactorily. These important properties include alternative routings, processing time, machine capacity (reliability), machine capability (flexibility), production volume, product demand, and the number of operations done on a machine. The objectives of this paper are to present a review of the literature on similarity coefficients between machines in CMS, to propose a new similarity coefficient between machines incorporating all these important properties of similarity, and to propose a machine cell heuristic approach to group machines into machine cells. An example problem is included and demonstrated in this paper.

Keywords: Cellular manufacturing, Similarity coefficients, Machine cells

1. INTRODUCTION

Cluster analysis has been used to study similarity measures and coefficients. Similarity coefficient approaches, which were used in grouping machines into cells, have received considerable attention in the literature. The machine–part incidence matrix is the input for most problems involving machine clustering. The machine-part incidence matrix is a zero-one matrix, [A], where element a_{ij} =1 indicates that part j is processed on machine *i*. Although several methods are available in the literature to cluster machines into machine cells, similarity coefficient approaches represent a well-known methodology in grouping machines, and they are more flexible in incorporating various types of manufacturing data. A wide range of similarity coefficient measures between machines will be explained in the review.

This paper is structured as follows. Section 2 reviews most of the papers published in the area of similarity coefficients between machines. Section 3 presents the proposed similarity coefficient between two machines. The heuristic approach which was used to group machines into machine

* Corresponding Author

cells is presented in Section 4. Section 5 describes the analytical example. Section 6 presents the conclusion.

2. LITERATURE REVIEW

This section presents a comprehensive review of the research work of similarity coefficients between machines are related to the problem of finding similarity between two machines.

Viswanathan (1996) proposed similarity coefficient between two machines for P-median formulation as follows:

$$S_{ij} = \sum_{k=1}^{n} \delta(a_{ik}, a_{jk}) \tag{1}$$

$\delta(a_{ik,}a_{jk}) = 2$, if element $a_{ik} = a_{jk} = 1$

$\delta(a_{ik,}a_{jk}) = -1$, if $a_{ik} \neq a_{jk}$

$\delta(a_{ik,}a_{jk}) = 0$, otherwise

k = subscript of part, $k = 1,\ldots, n$ (parts)

Viswanathan (1996) used positive and negative values, revealing the extent of similarity as well as dissimilarity. The machines were first clustered by solving for the P-median, and then the parts were assigned to the cells so as to minimize the number of voids inside the cells and the number of ones outside the cells. In this case, he ensured that each cell has at least two parts and two machines.

Jaccard's similarity coefficient equation (McAuley, 1972) is defined as follows:

$$S_{ij} = \frac{N_{ij}}{N_i + N_j - N_{ij}} \tag{2}$$

S_{ij} similarity coefficient between machines *i* and *j*.

N_{ij} number of common parts processed by both machines i and j.

N_i number of parts processed by machine *i* only.

N_j number of parts processed by machine *j* only.

Aljaber et al. (1997) modified Jaccard's similarity measure (McAuley, 1972) between two machines by subtracting it from its upper bound of 1, and it can be defined as follows:

$$S_{ij} = 1 - \frac{N_{ij}}{N_i + N_j - N_{ij}} \tag{3}$$

Won and Kim (1997) modified Jaccard's similarity coefficient between two machines to produce a generalized similarity coefficient including alternative routings (process plans) of parts. They defined the generalized machine similarity coefficient between two machines *i* and *j* as follows:

$$gsc_{ij} = \frac{\delta_{ij}}{\delta_i + \delta_j - \delta_{ij}} \tag{4}$$

gsc_{ij} generalized similarity coefficient between machines *i* and *j*.

δ_{ij} number of common parts with multiple process routings processed by both machines *i* and *j*.

δ_i number of parts with multiple process routing processed by machine *i* only.

δ_j number of parts with multiple process routing processed by machine *i* only.

$$\delta_i = \sum_{k=1}^{n} \alpha(i,k) \quad , \quad \delta_j = \sum_{k=1}^{n} \alpha(j,k)$$

$\alpha(i,k) = 1$ if $a_{ikr} = 1$ for some $r \in R_k$

$\alpha(i,k) = 0$ otherwise

$\alpha(j,k) = 1$ if $a_{jkr} = 1$ for some $r \in R_k$

$\alpha(j,k) = 0$ otherwise

$k = 1,\ldots, n$ (parts)

R_k set of process routings of part *k*

$$\delta_{ij} = \sum_{k=1}^{n} B(i,j,k)$$

$B(i,j,k) = 1$ if $a_{ikr} = a_{jkr}$ for some $r \in R_k$, $i \neq j$

$B(i,j,k) = 0$ otherwise

Yin and Yasuda (2002) modified the similarity coefficient of Won and Kim (1997) by incorporating a sequence ratio (SR_{ij}) and machine load ratio (MLR_{ij}) into equation (4). Then, they defined a new similarity as follows:

$$gsc_{ij} = \frac{\delta_{ij}}{\delta_i + \delta_j - \delta_{ij}} * SR_{ij} * MLR_{ij} \tag{5}$$

SR_{ij} sequence ratio $= \frac{X_{ij}}{D_{ij}}$

MLR_{ij} machine load ratio $= \frac{Y_{ij}}{E_{ij}}$

X_{ij} number of actual movements of parts between machines *i* and *j*

D_{ij} number of possible movements of parts between machines *i* and *j*

Y_{ij} minimum production volume factor between machine *i* and *j*

E_{ij} maximum production volume factor between machines *i* and *j*

Yin and Yasuda (2002) suggested also another similarity coefficient between machine cells (*P* and *Q*) as follows:

$$S_{PQ} = \frac{\sum_{i \in P} \sum_{j \in Q} gsc_{ij}}{NM_P \times NM_Q} \tag{6}$$

NM_P number of machines in cell *P*.

NM_Q number of machines in cell *Q*.

Won (2000) suggested two similarity coefficients between two machines for the P-median of machine cell formation under the assumption that each part may be processed by alternative process plans. The first coefficient reflects the extent of similarity between machines *i* and *j*, and it is defined as follows:

$$S_{ij}^1 = \sum_{k=1}^{n} \alpha(i, j, k) \tag{7}$$

if $i \neq j$, i , $j = 1,\ldots, m$

$S_{ij}^1 = 0$ otherwise

$\alpha(i, j, k) = 1$, if $a_{ikr} = a_{jkr} = 1$ for some $r \in R_k$ $k = 1,\ldots, n$ $\alpha(i, j, k) = 0$, otherwise

The second coefficient reflects the extent of similarity as well as dissimilarity between two machines as follows:

$$S_{ij}^2 = \sum_{k=1}^{n} \beta(i, j, k) \tag{8}$$

if $i \neq j$, $i, j = 1,\ldots, m$

$S_{ij}^2 = 0$ otherwise

$\beta(i,j,k) = n$ if $a_{ikr} = a_{jkr} = 1$ for some $r \in R_k$

$\beta(i, j, k) = -1$ if $a_{ikr} \neq a_{jkr}$ for all $r \in R_k$

$\beta(i, j, k) = 0$ if otherwise

n number of parts, m = number of machines

Nair and Narendran (1998) defined a new similarity coefficient and incorporated production sequence and product volume to form cells. Then, the similarity coefficient between machines *i* and *j* can be described as the ratio of the sum of the moves common to machines *i* and *j*, and the sum of the total number of moves to and from machines *i* and *j* as follows:

$$S_{ij}(0) = \frac{C_i + C_j}{t_i + t_j} \tag{9}$$

$$t_i = \sum_{k=1}^{n} \sum_{p=1}^{n_{iki}} w_k t_{kip} \ , \ t_j = \sum_{k=1}^{n} \sum_{p=1}^{n_{kj}} w_k t_{kjp} \ ,$$

$$C_i = \sum_{k=1}^{n} \sum_{p=1}^{n_{ki}} w_k c_{kip} \ , \ \ C_j = \sum_{k=1}^{n} \sum_{p=1}^{n_{kj}} w_k c_{kjp}$$

t_i accounts for the total number of moves to and from machine *i* by components which visit it.

t_j accounts for the total number of moves to and from machine *j* by components which visit it.

C_i takes into account the total number of moves to and from machine *i* made by all components which visit machines *i* and *j*.

C_j takes into account the total number of moves to and from machine *j* made by all components which visit machines *i* and *j*.

$t_{kip} = 0$ if $b_{kip} = 0$

$t_{kip} = 1$ if $b_{kip} = 1$ or r_k

$t_{kip} = 2$ otherwise

$t_{kjp} = 0$ if $b_{kjp} = 0$

$t_{kjp} = 1$ if $b_{kjp} = 1$ or r_k

$t_{kjp} = 2$ otherwise

$c_{kip} = 0$ if $b_{kip} = 0$ or $b_{kjp} = 0$

$c_{kip} = 1$ if $b_{kip} = 1$ or $b_{kjp} = 1$ or r_k

$c_{kip} = 2$ otherwise

$c_{kjp} = 0$ if $b_{kip} = 0$ or $b_{kjp} = 0$

$c_{kjp} = 1$ if $b_{kip} = 1$ or $b_{kjp} = 1$ or r_k

$c_{kjp} = 2$ otherwise

w_k weight of component *k*

n number of parts, *m* = number of machines

r_k maximum number of operations for component *k*

b_{kip} operation sequence number if the *k*th $(1 \le k \le n)$ component visits the *i*th $(1 \le i \le m)$ machine for the *p*th $(1 \le p \le n_{ki})$ time, zero

b_{kjp} operation sequence number if the *k*th $(1 \le k \le n)$ component visits the *j*th $(1 \le j \le m)$ machine for the *p*th $(1 \le p \le n_{ki})$ time, zero

n_{ki} number of times the *k*th component visits the *i*th machine

n_{ki} number of times the *k*th component visits the *j*th machine

Probhakaran et al. (2002) proposed a combined dissimilarity coefficient measure by mixing a SINE dissimilarity coefficient with the sequence similarity coefficient which was created by Nair and Narendran (1998) (see equation (9)). The SINE dissimilarity coefficient between machines *i* and *j* ($S_{ij}(r)$) is defined as the SINE of the angle between the pair of vectors that represent the machines as follows:

$$S_{ij}(r) = Sin_{ij}(\theta) = (1 - Cos^2_{ij}(\theta))^{1/2} \tag{10}$$

$$Cos_{ij}(\theta) = \frac{i.j}{|i|.|j|}$$

From equation (9) we have $S_{ij}(0) = \frac{C_i + C_j}{t_i + t_j}$.

The combined dissimilarity coefficient for a pair of machines *i* and *j* is defined as follows:

$$S_{ij} = \frac{S_{ij}(r)}{j + S_{ij}(0)} \tag{11}$$

Seifoddini and Wolfe (1986) suggested a similarity coefficient. Their similarity coefficient can be described as follows:

$$S_{ij} = \frac{HAND}{NOR} \tag{12}$$

NOR and NAND number of non-zero bits in MVO and MVA, respectively

MVO MVi OR MVj
MVA MVi AND MVj
MVi machine vector *i*
MVj machine vector *j*

Seifoddini and Djassemi (1991 and 1996) compared the performance of Jaccard's similarity coefficient with the performance of a production-data-based similarity coefficient by using intercellular and intracellular material handling costs and group efficiencies. Jaccard's similarity coefficient is given as follows:

$$S_{ij} = \frac{\sum_{k=1}^{n} X_{ijk}}{\sum_{k=1}^{n} Y_{ijk}} \tag{13}$$

The production data-based similarity coefficients are given as follows

$$S_{ij} = \frac{\sum_{k=1}^{n} V_k X_{ijk}}{\sum_{k=1}^{n} V_k Y_{ijk}} \tag{14}$$

S_{ij} similarity coefficient between machines *i* and *j*
V_k production volume for part type *k*
n number of part types
$X_{ijk} = 1$ if part type *k* visits both machines *i* and *j*
$X_{ijk} = 0$ otherwise
$Y_{ijk} = 1$ if part type *k* visits either machine *i* or *j*
$Y_{ijk} = 0$ otherwise

Seifoddini and Tjahana (1999) modified the production-data-based similarity coefficient (equation (14)) between two machines *i* and *j* based on the batch size. This similarity coefficient (BS_{ij}) can be described as follows:

$$BS_{ij} = \frac{\sum_{k=1}^{n} (\frac{V_k}{b_k}) * X_{ijk}}{\sum_{k=1}^{n} (\frac{V_k}{b_k}) * Y_{ijk}} \tag{15}$$

BS_{ij} batch similarity coefficient
b_k batch size

Seifoddini (1988) modified the similarity coefficient between machines *i* and *j* as follows:

$$S_{ij} = \frac{\sum_{k=1}^{n} m_k n_k X_k}{\sum_{k=1}^{n} m_k n_k Y_k} \tag{16}$$

S_{ij} similarity coefficient between machines *i* and *j*
n number of parts
m_k production volume of part type *k*
n_k number of times part type *k* moves between machines *i* and *j*
X_k numerator entry (0 or 1) in vector V_{ij}
Y_K denominator entry (0 or 1) in vector V_{ij}'
V_{ij} vector containing information on parts visiting both machines *i* and *j*

$V_{ij}^{\setminus}$ vector containing information on parts visiting either machine *i* or *j*

Gupta (1991) and Gupta and Seifoddini (1990) created a similarity coefficient between two machines *i* and *j* as follows:

$$S_{ij} = \frac{\sum_{k=1}^{n} [X_k t_{ij}^k + \sum_{o=1}^{n_k} Z_{ko}] m_k}{\sum_{k=1}^{n} [X_k t_{ij}^k + \sum_{o=1}^{n_k} Z_{ko} + Y_k] m_k} \tag{17}$$

S_{ij} similarity coefficient between machines *i* and *j*

m_k planned production volume during a period for part type $k \ \forall k, k = 1,\ldots, n$

n_k number of times part type *k* visits machines *i* and *j* consecutively

$X_k = 1$ if part type *k* visits both machines *i* and *j*

$X_k = 0$ otherwise

$Y_k = 1$ if part type *k* visits either machine *i* or *j*

$Y_k = 0$ otherwise

$Z_k = 1$ if part type *k* visits both machines *i* and *j* consecutively

$Z_k = 0$ otherwise

$$t_{ij}^k = \frac{\min \ (\sum_{o=1}^{n_{ki}} t_{ki}, \sum_{o=1}^{n_{kj}} t_{kj})}{\max \ (\sum_{o=1}^{n_{ki}} t_{ki}, \sum_{o=1}^{n_{ki}} t_{kj})}$$

t_{ij}^k ratio of smaller unit operation time to larger unit operation time for machine pair *i,j*

n_{ki} number of visits part type *k* makes to machine *i*

n_{kj} number of visits part type *k* makes to machine *j*

t_{ki} unit operation time for part type *k* on machine *i* during *o*th visit

t_{kj} unit operation time for part type *k* on machine *j* during *o*th visit

Seifoddini (1989) proposed a similarity coefficient to eliminate improper machine assignment by assigning a higher weight to parts having common operations on both machines. This similarity coefficient is defined as follows:

$$S_{ij} = \frac{\sum_{k=1}^{n} f_{bk} X_{ijk}}{\sum_{k=1}^{n} f_{bk} X_{ijk} + \sum_{k=1}^{n} f_{ek} Y_{ijk}} \tag{18}$$

S_{ij} similarity coefficient between machines *i* and *j*

n total number of parts

X_{ijk} = 1 if part type *k* visits both machines *i* and *j*

X_{ijk} = 0 otherwise

Y_{ijk} = 1 if part type *k* visits either machine *i* or *j*

Y_{ijk} = 0 otherwise

f_{bk} weighting factor for parts visiting both machines *i* and *j*

f_{ek} weighting factor for parts visiting either machine *i* or *j*, but not both

Gupta (1993) modified his previous similarity coefficients Gupta (1991) and Gupta and Seifoddini (1990) to incorporate an alternative routing sequence in addition to production volumes and operation times for each part in the formation of part families and machine cells as follows:

$$S_{ij} = \frac{\sum_{k=1}^{n}\left[\sum_{r=1}^{r_k}\left(X_{kr}t_{kr} + n_{kr}\right)P_{kr}\right]m_k}{\sum_{k=1}^{n}\left[\sum_{r=1}^{r_k}\left(X_{kr}t_{kr} + n_{kr} + Y_{kr}\right)P_{kr}\right]m_k} \tag{19}$$

r_k number of alternative routes for part type *k*

P_{kr} usage factor of route r for part type *k*

n_{kr} number of trips part type *k* makes between machines *i* and *j* for consecutive operations on the *r*th route

Lee et al. (1997) and Luong et al. (2001) proposed a similarity coefficient between machines. They called it a machine chain similarity coefficient (MCS_{ij}) between machines *i* and *j* depending on the processing sequences, production volumes, and alternative routing.

$$MCS_{ij} = \frac{\sum_{l=1}^{m}\left(\min\left(\sum_{k=1}^{n}P_{il}^{k}, \sum_{k=1}^{n}P_{ji}^{k}\right)\right)}{\sum_{l=1}^{m}\sum_{k=1}^{n}\left(V_{kl} + V_{kl}^{'}\right)} \tag{20}$$

V_{kl} number of units of *k* coming from machine l

$V_{kl}^{'}$ number of units of part type *k* going to machine l

n number of parts, *m* = number of machines

$$P_{il}^{k} = \frac{\#\ of\ units\ of\ part\ k\ moved\ between\ machines\ i\ and\ l\ if\ i \neq l}{\#\ of\ units\ of\ part\ k\ moved\ between\ machines\ i\ and\ l\ if\ i = l}$$

$$P_{jl}^{k} = \frac{\#\ of\ units\ of\ part\ k\ moved\ between\ machines\ j\ and\ l\ if\ j \neq l}{\#\ of\ units\ of\ part\ k\ moved\ between\ machines\ j\ and\ l\ if\ j = l}$$

Mosier (1989) developed three different types of similarity coefficients between machines. The first similarity coefficient between machines *i* and *j* can be described as follows:

$$S_{ij} = \frac{a_{ij} - b_{ij} c_{ij}}{a_{ij} d_{ij} + b_{ij} c_{ij}} \tag{21}$$

The second similarity coefficient is as follows:

$$S_{ij} = \frac{(a_{ij} + d_{ij}) - (b_{ij} + c_{ij})}{(a_{ij} + d_{ij}) + (b_{ij} + c_{ij})} \tag{22}$$

The last similarity coefficient is as follows:

$$S_{ij} = \frac{a_{ij} + (a_{ij} d_{ij})^{1/2}}{a_{ij} + b_{ij} + c_{ij} + (a_{ij} d_{ij})^{1/2}} \tag{23}$$

a_{ij} count of parts processed on machines *i* and *j*

d_{ij} number of parts processed on neither machine *i* or *j*

b_{ij} and c_{ij} number of parts processed on machine *i* only, and machine *j* only, respectively

Islam and Sarker (2000) modified similarity coefficient (23) to form machine cells (equation (23)) by adding the new term d_{ij} in the denominator to form cohesive cells. It is defined as follows:

$$S_{ij} = \frac{a_{ij} + (a_{ij} d_{ij})^{1/2}}{a_{ij} + b_{ij} + c_{ij} + d_{ij} + (a_{ij} d_{ij})^{1/2}} \tag{24}$$

Gunasingh and Lashkari (1989) proposed a similarity coefficient between two machines based on the similarity in the processing of parts. The similarity coefficient S_{ij} between machines *i* and *j* can be described as follows:

$$S_{ij} = \frac{\sum_{k \in cp_{ij}} [NCT_{ki} + NCT_{kj}]}{\sum_{k}^{n} [NCT_{ki} + NCT_{kj}]} \tag{25}$$

NCT_{ki} number of common tools between part *k* and machine *i*

NCT_{kj} number of common tools between part *k* and machine *j*

cp_{ij} set of parts requiring both machines *i*, *j*

n number of parts

Waghodekar and Sahu (1984) proposed three similarity coefficients between machines *i* and *j*. The first one was for the additive type, and it will be described as follows:

$$SC_{ij} = \frac{NCC_{ij}}{TNC_i + TNC_j - NCC_{ij}} \tag{26}$$

NCC_{ij} number of common components using both machines *i* and *j*

TNC_i total number of components using machine *i*

TNC_j total number of components using machine *j*

The second similarity coefficient was used for product type based on the total number of components processed by each machine *i* and machine *j* as follows:

$$PSC_{ij} = \frac{NCC_{ij} \times NCC_{ij}}{TNC_i \times TNC_j} \tag{27}$$

The last coefficient was based on total flow of common components processed by a machine as follows:

$$SCTF_{ij} = \frac{NCC_{ij} \times NCC_{ij}}{TFC_i \times TFC_j} \tag{28}$$

TFC_i total flow of common components processed by machine *i*

TFC_j total flow of common components processed by machine *j*

$$TFC_i = \sum_{k=1}^{n} NCC_{ij}, TFC_j = \sum_{k=1}^{n} NCC_{ij} \text{ for } i \# j$$

Leem and Chen (1996) used a similarity coefficient between two machines to form machine cells based on a fuzzy set approach. The new similarity coefficient can be described as follows:

$$S_{ij} = \frac{\sum_{k=1}^{n} (\mu_{ik} \cap \mu_{jk})}{\sum_{k=1}^{n} (\mu_{ik} \cup \mu_{jk})} \tag{29}$$

$0 \le \mu_{ik} \le 1$ and $0 \le \mu_{jk} \le 1$

$\sum_{k=1}^{n} \mu_{ik} \succ 0$ for $i = 1,\ldots, n$; $\sum_{k=1}^{n} \mu_{jk} \succ 0$

for $j = 1,\ldots, n$; for i and $j = 1,\ldots, n$

n number of parts

Ponnambalam and Aravindan (1994) used a similarity coefficient between two machines *i* and *j* as follows:

$$S_{ij} = \sum_{k=1}^{n} d_k \tag{30}$$

$d_k = 1$ if $a_{ik} = a_{jk}$

$d_k = 0$ otherwise

$S_{jj} = 0$ if k = index for part, $k = 1,\ldots, n$

Luong (1993) proposed a similarity coefficient which considered the similarity between machines cells rather than individual machines. The new similarity coefficient will be described as follows:

$$S_{PQ} = \frac{\sum_{i=1}^{m_q} \sum_{j=1}^{m_p} X_i Y_j}{\min(n, m)} \tag{31}$$

S_{PQ} similarity coefficient between machine cells P and Q.

$X_i Y_j = 1$ if $X_i = Y_j$; $X_i Y_j = 0$, if $X_i \neq Y_j$

$\min(m_p, m_q) = m_p$, if $m_p < m_q$; $\min(m_p, m_q) = m_q$ if $m_p > m_q$

m_p number of machines in cell P

m_q number of machines in cell Q

Nazarlo and Ramirez (2000) proposed a new similarity coefficient between two machines. The proposed similarity coefficient can be defined as follows:

$$S_{ij} = \frac{1}{4}\left(\Pi_i - \Pi_j\right) * \left(1 + e^{-\delta_{ij}}\right) \tag{32}$$

S_{ij} similarity coefficient between machines i and j

Π_i proportion of common time that parts spend on machine i

$$\Pi_i = \frac{\sum_{k \in A} P_{ik}}{\sum_{k \in B} P_{ik}}$$

Π_j proportion of common time that parts spend on machine j

$$\Pi_j = \frac{\sum_{k \in A} P_{ik}}{\sum_{k \in C} P_{ik}}$$

A set of parts that are processed on machines i and j

B set of parts that are processed on machine i

C set of parts that are processed on machine *j*

P_{ik} processing time of part *k* on machine *i*

δ_{ij} distance proportion between machines *i* and *j*

$$\delta_{ij} = \frac{h_{ij}}{H}$$

H max { h_{ij} }, if $h_{ij} \neq 0$

H=1 if $h_{ij} = 0$

h_{ij} distance between machines *i* and *j* (assume locations of machines *i* and *j* are known).

Chang and Lee (2000) suggested a similarity coefficient between two machines *i* and *j* as follows:

$$S_{ij} = \sum_{k=1}^{N} (1 - |a_{ik} - a_{jk}|) \quad \text{if } i \neq j \tag{33}$$

$$S_{ij} = 0, \quad \text{if } i = j$$

Lozano et al. (2001) suggested a similarity coefficient between two machines *i* and *j* as follows:

$$S_{ij} = n_{ij} + n_{ji} \tag{34}$$

n_{ij} total number of part movements from machine *i* to machine *j*

n_{ji} total number of part movements from machine *j* to machine *i*

$$n_{ij} = \sum_{k=1}^{n} \sum_{l}^{o_j} D_k \delta_{ijkl}$$

D_k demand for part type k

δ_{ijkl}=1 if $m_{kl} = 1$

δ_{ijkl}=0 otherwise

m_{kl} machine on which operation l of part type *k* is performed

Yasuda and Yin (2001) proposed a system representing the dissimilarity of a pair of machine groups and part families based on the calculation of an average voids value (AVV).

$$AVV = \frac{\sum_{m=1}^{M_i} (vc_{im}{}^{j} - vc_{im})}{M_i} + \frac{\sum_{n=1}^{M_j} (vc_{jn}{}^{i} - vc_{jn})}{M_j} \tag{35}$$

c_i machine group i in the problem

c_{im} machine m of c_i

$c_{im}{}^{j}$ machine m of c_i in $c_i{}^{j}$

vc_{im} number of voids produced by machine m of c_i

$vc_{im}^{\ j}$ number of voids produced by machine *m* of c_i in $c_i^{\ j}$

vc_{jm} number of voids produced by machine *m* of c_j

vc_{jm}^{i} number of voids produced by machine *m* of c_j in $c_j^{\ i}$

$c_i^{\ j} = c_j^{\ i}$ (the machine group formed by c_i and c_j)

M_i number of machines in c_i

M_j number of machines in c_j

m subscript of machine in c_i

n subscript of machine in c_j

Shaferm and Rogers (1993) suggested a similarity coefficient between two machines as follows:

$$MAXSC_{ij} = \max\left[\frac{M_{ij}}{M_i}, \frac{M_{ij}}{M_j}\right] \tag{36}$$

M_{ij} number of components that visit both machine types *i* and *j*

M_i number of components that visit machine type *i*

M_j number of components that visit machine type *j*

3. THE PROPOSED SIMILARITY COEFFICIENT BETWEEN MACHINES

A comprehensive new similarity coefficient between machines will be created by considering alternative routings, processing time, machine capacity (reliability), machine capability (flexibility), production volume, product (part) demand, and number of operations done on each machine (figure 1). A relationship between machines can be calculated by using their similarity coefficient. The relationship between machines usually ranges from 0 to 1, as most researchers range as a function of the definition of a coefficient. As the value of the similarity coefficient approaches 1 , the two machines become more similar. If this value is equal to 0, there is no similarity between them. The main objective for creating the new similarity coefficient between machines is to take both direct and indirect relations between them into consideration.

The mathematical expression for the new similarity coefficient between machines i and j, which was based on machine capacity, machine flexibility (maximum number of operations available per machine), part (product) volume and demand, number of operations performed by machines, and processing time, will be explained as follows (see equations (37) and (38)).

Assumptions:

The model assumes that the following information has been collected and screened for accuracy or specified by the user.

1. The processing times for all part type operations with associated process plans on different machine types are known.
2. The capacity of each machine type is known and constant over time.

3. The capability of each machine type is also known and constant over time.
4. Each machine type can perform one or more operations.
5. The production volume of each part type in a specific period is known.
6. The demand for each part type in the specific period is also known.
7. The production volume per part is greater than part demand.

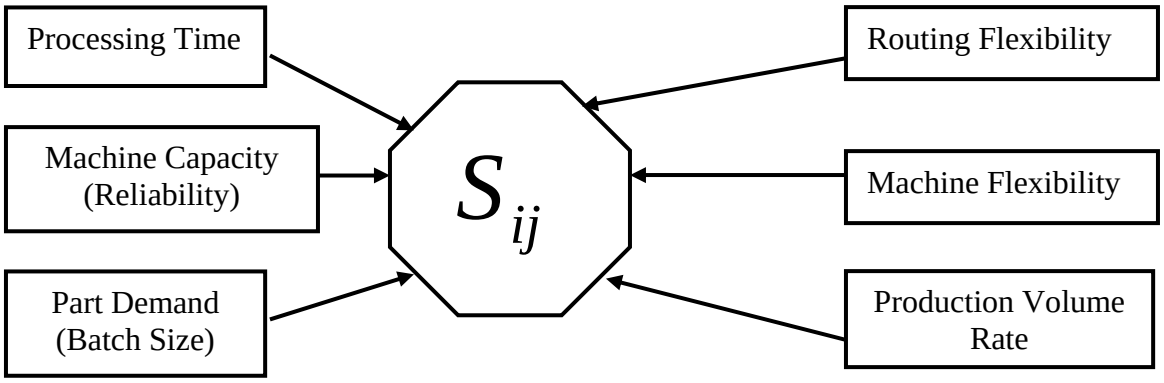

Figure 1. Issues that will be used to create a new similarity coefficient between machines.

$$S_{ij} = \frac{\sum_{k=1}^{n_{X_{ijkr}}} \sum_{\substack{r\in ki \\ and \\ r\in kj}}^{R} \left[\max\left(\frac{t_{kir}}{C_i} \times \frac{n_{o_i}}{N_{o_{i\max}}}, \frac{t_{kjr}}{C_j} \times \frac{n_{o_j}}{N_{o_{j\max}}} \right) X_{ijkr} \right] \frac{V_k}{D_k}}{\sum_{k=1}^{n_{X_{ijkr}}} \sum_{\substack{r\in ki \\ and \\ r\in kj}}^{R} \left[\max\left(\frac{t_{kir}}{C_i} \times \frac{n_{o_i}}{N_{o_{i\max}}}, \frac{t_{kjr}}{C_j} \times \frac{n_{o_j}}{N_{o_{j\max}}} \right) X_{ijkr} \right] \frac{V_k}{D_k} + \sum_{k=1+n_{X_{ijkr}}}^{n-n_{X_{ijkr}}} \sum_{\substack{r\in ki \\ or \\ r\in kj}}^{R^{l}} \left[\left(\frac{t_{kir}}{C_i} \times \frac{n_{o_i}}{N_{o_{i\max}}} OR \frac{t_{kjr}}{C_j} \times \frac{n_{o_j}}{N_{o_{j\max}}} \right) Y_{ijkr} \right] \frac{V_k}{D_k}} \tag{37}$$

or

$$S_{ij} = \frac{\sum_{k=1}^{n_{X_{ijkr}}} \sum_{\substack{r\in ki \\ and \\ r\in kj}}^{R} \left[\max\left(\frac{t_{kir}}{C_i} \times \frac{n_{o_i}}{N_{o_{i\max}}}, \frac{t_{kjr}}{C_j} \times \frac{n_{o_j}}{N_{o_{j\max}}} \right) X_{ijkr} \right] (BS_k)}{\sum_{k=1}^{n_{X_{ijkr}}} \sum_{\substack{r\in ki \\ and \\ r\in kj}}^{R} \left[\max\left(\frac{t_{kir}}{C_i} \times \frac{n_{o_i}}{N_{o_{i\max}}}, \frac{t_{kjr}}{C_j} \times \frac{n_{o_j}}{N_{o_{j\max}}} \right) X_{ijkr} \right] (BS_k) + \sum_{k=1+n_{X_{ijkr}}}^{n-n_{X_{ijkr}}} \sum_{\substack{r\in ki \\ or \\ r\in kj}}^{R^{l}} \left[\left(\frac{t_{kir}}{C_i} \times \frac{n_{o_i}}{N_{o_{i\max}}} OR \frac{t_{kjr}}{C_j} \times \frac{n_{o_j}}{N_{o_{j\max}}} \right) Y_{ijkr} \right] (BS_k)} \tag{38}$$

S_{ij} similarity coefficient between machines *i* and *j*

t_{kir} processing time part *k* takes on machine *i* including setup time with process plan *r*

t_{kjr} processing time part *k* takes on machine *j* including setup time with process plan *r*

n_{o_i} number of operations done on machine *i*

n_{o_j} number of operations done on machine *j*

$N_{o_{i\max}}$ maximum number of operations available on machines *i*

$N_{o_{j\max}}$ maximum number of operations available on machine *j*

C_i capacity of machine *i*

C_j capacity of machine *j*

V_k part volume of part type *k* per period

D_k part demand of part type *k* per period

BS_k batch size of part *k*

X_{ijkr} =1 if part type *k* visits both machines *i* and *j* with process plan *r*

X_{ijkr} =0 otherwise

Y_{ijkr} =1 if part type *k* visits either machine *i* or machine *j* with process plan *r*

Y_{ijkr} =0 otherwise

k = 1,…, *n* (parts), l = 1,…, *m* (machines), *r* = 1,…, *R* (routings)

R number of part routings that can be processed on both machines *i* and *j*

$R^{\backslash}$ number of part routings that can processed on either machine *i* or machine *j*

m number of machines in the machine-part incidence matrix.

n number of parts *R* in the machine-part incidence matrix.

$n_{X_{ijkr}}$ number of parts that can visit both machines *i* and *j* with process routings *r*

$\frac{t_{kir}}{C_i}$ fraction of processing time which part *k* will take from the capacity of machine *i*

$\frac{t_{kjr}}{C_j}$ fraction of processing time which part *k* will take from the capacity of machine *j*

$\frac{n_{o_i}}{N_{o_{i\max}}}$ number of operations done on machine *i* with respect to the maximum number of operations available on that machine. This term represents the flexibility of machine *i*

$\frac{n_{o_j}}{N_{o_{j\max}}}$ number of operations done on machine *j* with respect to the maximum number of operations available on that machine. This term represents the flexibility of machine *j*

$\frac{V_k}{D_k}$ ratio of production volume rate to demand per part

4. HEURISTIC APPROACH FOR MACHINE CELL FORMATION

Machines are assigned to machine cells based on our new similarity coefficient. The procedure to group machines into cells is given by the following steps:

Step 1: Check the Machine Work Load (MWL) of each machine type capacity ($C_i,...,C_m$) to produce all production volumes for all parts ($V_1,...,V_n$) by these machines in the machine-part incidence matrix. The MWL of machine *i* is based on production volumes and processing times of all parts assigned to machine *i*. The equation for computing the MWL for machine *i* is shown as follows:

$$MWL_i = \sum_{k=1}^{n}\left(\sum_{r_1,r_2,r_r \in ki}^{k_{ir_r}} \max\left(t_{ki_{r_1}}V_k + t_{ki_{r_2}}V_k + ... + t_{ki_{r_r}}V_k\right)\right) \quad (39)$$

Step 2: Compute the similarity coefficient matrix between all machine pairs according to equations (37) and (38).

Step 3: Determine the desired number of machines cells (NMC) by the following equation:

$$NMC \geq \frac{m}{m_{\max}}$$

m number of machines in machine-part incidence matrix.

$m_{\max}$ pre-determinable maximum number of machines in the machine cell (at least two machines per cell)

Step 4: Select the largest similarity coefficient between machine i and machine (*j*,…,*m*) from the similarity coefficient matrix in each row directly.

Step 5: Sort the similarity coefficients from highest to lowest value and record the values of S_h and the corresponding sets of $m_h\{i, j\}$, where h represents the level of the similarity value.

Step 6: Start forming the first machine cell MC_1 by selecting the highest similarity coefficient. value S_1. Then, this pair of machines $m_1\{i, j\}$ will be clustered into the first machine cell.

Step 7: Check the minimum machine cell size constraint (at least two machines per cell).

Step 8: Increase the value of *h* (*h* = 2,…, *H*).

Step 9: If $m_h \bigcap MC_1 \neq 0$. Then, modify MC_1 by the new $MC_1 = MC_1 \bigcup m_h$.

Otherwise, form a new machine cell $MC_n\,(n = 2,..., NMC)$.

Step 10: If any set m_h intersects two cells MC_I and MC_J, then, discard the corresponding S_h and go back to Step 8.

Step 11: Check for the maximum number of machines allowed in a machine cell.
If the number of machines in this machine cell does not exceed the desired number of machines, then, add to this cell.
Otherwise, stop adding to this cell and go back to Step 8.

Step 12: If all the machines have not been assigned to machine cells, go back to Step 8. Otherwise, go to Step 13.

Step13: If the number of machine cells formed exceeds the desired number of machine cells NMC, join two machine cells into one machine cell. All these steps will be shown in Figures 2 and 3.

5. ANALYTICAL EXAMPLE

In order to demonstrate the proposed approach, the following numerical example will illustrate the procedure, including the similarity coefficients and formation of machines into machine cells. It is composed of 10 types of machines and seven types of parts with different process plans. The incidence matrix between machines and parts is presented in table 1. The part information including operation sequence and processing times for each process plan, and production volume and part demand is also presented in table 2. Information about machine availability, including the capacities of the machines, number of operations that will be done on machines, and maximum number of operations available on machines, is shown in table 3.

Table 1. Incidence matrix between machines and parts.

		Parts													
		P1		**P2**			**P3**		**P4**	**P5**		**P6**		**P7**	
		r11	**r12**	**r21**	**r22**	**r23**	**r31**	**r32**	**r41**	**r51**	**r52**	**r61**	**r62**	**r71**	**r72**
Machine	**M1**	1	0	1	1	0	1	0	0	0	1	0	1	0	0
	M2	0	1	1	0	1	0	0	1	0	1	1	0	0	1
	M3	0	1	0	1	1	0	1	0	1	0	0	0	1	0
	M4	1	0	1	1	0	1	0	1	0	0	1	0	0	1
	M5	1	0	1	0	1	0	1	0	0	0	0	0	0	0
	M6	0	1	1	1	0	0	0	1	1	0	0	0	0	1
	M7	1	0	0	0	1	1	0	0	1	1	1	0	0	0
	M8	0	1	0	0	1	1	1	0	1	0	0	1	1	0
	M9	0	1	0	1	0	1	1	1	0	1	0	1	0	1
	M10	1	0	1	0	1	0	1	0	1	0	1	0	1	0

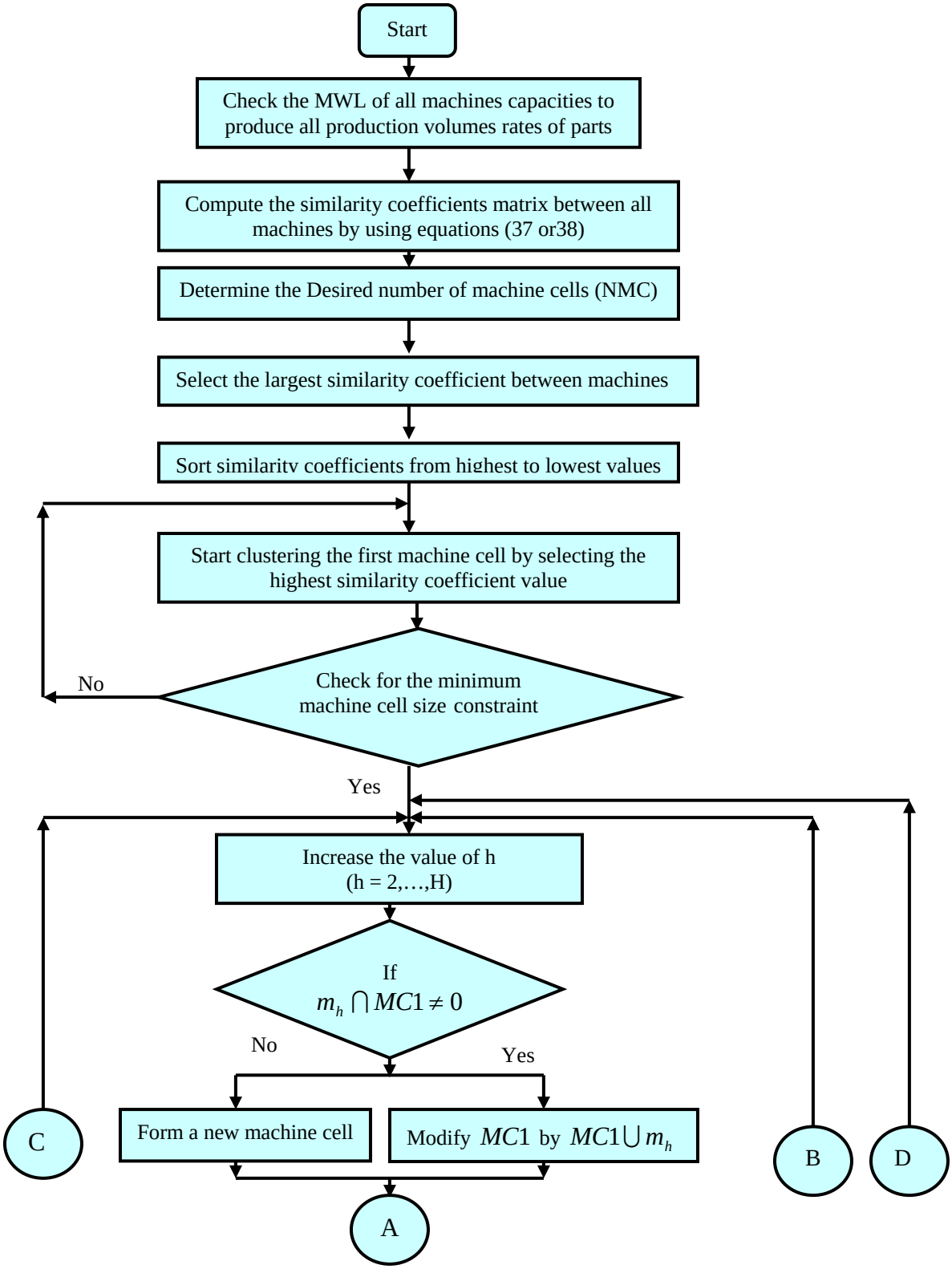

Figure 2. Flow chart of grouping machines into machine cells (Part 1).

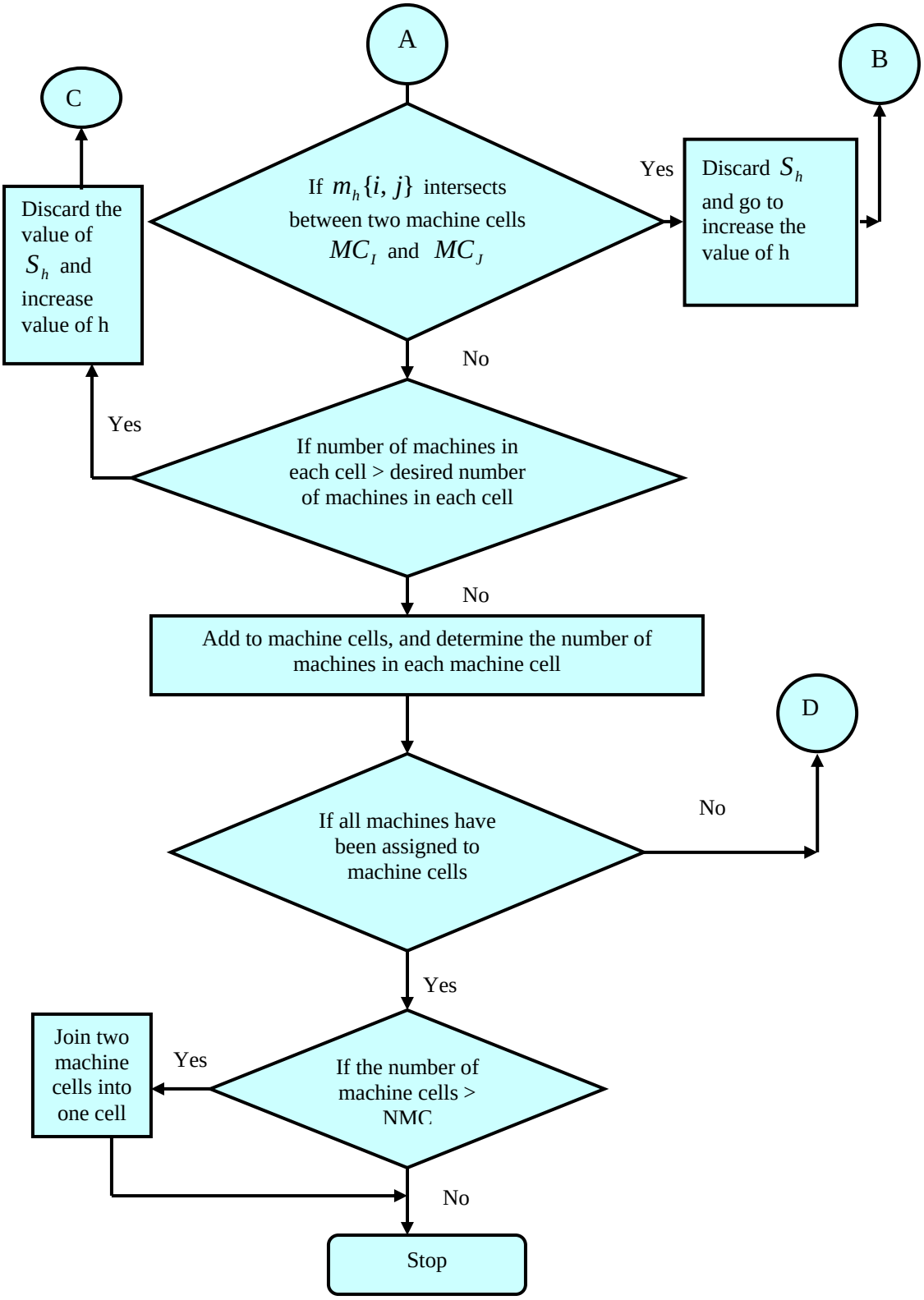

Figure 2. Flow chart of grouping machines into machine cells (Part 2).

Table 2. Parts information.

Part Type		Operation Sequence	Processing Time (Minutes)	Production Volume	Number of Operations per Part	Part Demand
P1	r11	M1-M4-M5-M7-M10	2.0- 3.2- 0.9- 2.5- 0.6	2000	5	1800
	r12	M2-M3-M6-M8-M9	2.7- 3.0- 4.0- 1.35- 0.71		5	
P2	r21	M1-M2-M4-M5-M6-M10	3.0- 2.5- 0.8- 1.1- 1.7- 2.35	2100	6	2000
	r22	M1-M3-M4-M6-M9	2.5- 1.8- 2.2- 3.1- 2.11		5	
	r23	M2-M3-M5-M7-M8-M10	2.0- 1.2- 3.0- 1.3- 4.4- 1.8		6	
P3	r31	M1-M4-M7-M8-M9	1.1- 1.8- 2.6- 1.5- 1.35	900	5	650
	r32	M3-M5-M8-M9-M10	3.6- 0.6- 2.6- 0.11- 1.93		5	
P4	r41	M2-M4-M6-M9	3.0- 3.65- 0.5- 1.95	2400	4	2000
P5	r51	M3-M6-M7-M8-M10	4.4- 2.83- 1.1- 2.32- 2.0	1800	5	1700
	r52	M1-M2-M7-M9	4.83- 0.9- 0.7- 2.28		4	
P6	r61	M2-M4-M7-M10	1.6- 2.1- 0.9- 1.8	1900	4	1700
	r62	M1-M8-M9	2.0- 2.3- 0.7		3	
P7	r71	M3-M8-M10	2.0- 3.1- 3.0	2700	3	2100
	r72	M2-M4-M6-M9	0.8- 1.9- 2.5- 4.2		4	

Table 3. Machine information.

Machine Type	Capacity of machine (Hours)	Number of Operations done on machine (n_o)	Maximum number of operations available on machine ($N_{\max}$)
1	2400	6	6
2	2000	7	7
3	2300	6	6
4	3000	7	10
5	1800	4	4
6	1900	6	9
7	2700	6	8
8	1300	7	10
9	2500	8	9
10	2100	7	10

5.1. Similarity Coefficient between Machines

The similarity coefficient between machines has been coded in the C programming language and executed on a Pentium IV processor. The result of similarity coefficients between machines is illustrated in table 4.

5.2. Machine Cells Formation

Step 1: Check the capacity of each machine type (availability of time per machine) to produce all parts that require processing on the machine.

For machine one (M1), the capacity for M1 equals 2400 hours.
The total consumed time taken from M1 will be calculated as follows:

$$\frac{1}{60}\begin{bmatrix} 2(2000)+\max[3.0(2100)+ \\ 2.5(2100)+1.1(900)+ \\ 4.83(1800)+2.0(1900)] \end{bmatrix} = \frac{23,784}{60} = 396.4 \ \textit{hours}$$

The slack of time on machine (M1) is 2400-396 = 2004 hours. So, M1 is OK.
The slack of time on machine (M2) is 2000-412 = 1588 hours. So, M2 is OK.
The slack of time on machine (M3) is 2300-439 = 1861 hours. So, M3 is OK.
The slack of time on machine (M4) is 3000-509 = 2491 hours. So, M4 is OK.
The slack of time on machine (M5) is 1800-144 = 1656 hours. So, M5 is OK.
The slack of time on machine (M6) is 1900-453 = 1447 hours. So, M6 is OK.
The slack of time on machine (M7) is 2700-229 = 2471 hours. So, M7 is OK.
The slack of time on machine (M8) is 1300-440 = 860 hours. So, M8 is OK.
The slack of time on machine (M9) is 2500-475 = 2025 hours. So, M9 is OK.
The slack of time on machine (M10) is 2100-383 = 1716 hours. So, M10 is OK.

The capacities of all machines are satisfy to all production volumes for all parts.

Step 2: Compute the similarity coefficient matrix between all machines according to the similarity coefficient (37).

Table 4. Similarity coefficients between machines.

	M1	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**
M1	0.0000	0.1856	0.0739	0.4613	0.2422	0.2219	0.5072	0.1501	0.4751	0.1996
M2		0.0000	0.1816	0.4218	0.3305	0.5031	0.2510	0.2560	0.5466	0.3057
M3			0.0000	0.0698	0.3928	0.4293	0.2458	0.7618	0.3653	0.6190
M4				0.0000	0.2308	0.3287	0.5097	0.0779	0.3326	0.3339
M5					0.0000	0.0751	0.4640	0.3568	0.0511	0.6015
M6						0.0000	0.1312	0.1909	0.6068	0.1942
M7							0.0000	0.3954	0.2516	0.4381
M8								0.0000	0.3363	0.6110
M9									0.0000	0.0821
M10										0.0000

Step 3: Determine the desired number of machine cells, NMC. The maximum number of machines assigned to cells ranged from 3 to 7 machines (Wilhelm et al. 1998) and from 5 to 10 machines (Ramabhatta and Nagi 1998). Four machines per cell are recommended for easy management and control.

$NMC \geq \frac{10}{4} \geq 2.5$. Therefore, the number of machine cells can start with three cells.

Three machine cells will be chosen.

Step 4: Select the largest similarity coefficient between machine *i* and machine (*j*,…,*m*) from Table 4 as follows:

$m_1 - m_7$	0.5072
$m_2 - m_9$	0.5466
$m_3 - m_8$	0.7618
$m_4 - m_7$	0.5097
$m_5 - m_{10}$	0.6015
$m_6 - m_9$	0.6068
$m_7 - m_{10}$	0.4381
$m_8 - m_{10}$	0.6110
$m_9 - m_{10}$	0.0821

Step 5: Sort the similarity coefficients from the highest to lowest value and record the values of S_h and the corresponding sets of $m_h\{i, j\}$

H	$m_h\{i, j\}$	S_h
1	$m_3 - m_8$	0.7618
2	$m_8 - m_{10}$	0.6110
3	$m_6 - m_9$	0.6068
4	$m_5 - m_{10}$	0.6015
5	$m_2 - m_9$	0.5466
6	$m_4 - m_7$	0.5097
7	$m_1 - m_7$	0.5072
8	$m_7 - m_{10}$	0.4381

Step 6: For S_1 = 0.7618 (between Machines 3 and 8).

Then, MC_1 = **{3, 8}**

Step 7: Check the minimum machine cell size constraint (at least two machines per cell).

Step 8: S_2 = 0.6110 (between Machines 8 and 10).
m_2 = {8, 10}

Step 9: There is an intersection between Machine 8 and MC_1.

The new machine cell is $MC_1 \bigcup m_2$.
Then, the revised machine cell MC_1 = **{3, 8, 10}**
S_3 =0.6068 (between Machines 6 and 9)
m_3 = {6, 9} and $MC_1 \bigcap m_3 = 0$
S_3 does not intersect with MC_1
Then, form a new machine cell MC_2 = **{6, 9}**
S_4 = 0.6015 (between Machines 5 and 10)
m_4 = {5, 10}
There is an intersection between Machine 10 and MC_1, but there is no intersection with MC_2.
The new machine cell is $MC_1 \bigcup m_4$.
Then, the revised machine cell
MC_1 = **{3, 5, 8, 10}**

Step 10: Check for the maximum number of machines a machine cell.

Machine Cell 1 contains four machines. Therefore, no more machines are added to MC_1.
S_5 = 0.5466 (between Machines 2 and 9)
m_5 = {2, 9}
There is an intersection between Machine 9 and MC_2, but this is no intersection with MC_1. The new machine cell is $MC_2 \bigcup m_5$.
Then, the revised machine cell MC_2 = **{2, 6, 9}**
S_6 = 0.5092 (between Machines 4 and 7)
m_6 ={4,7}, $MC_1 \bigcap m_6 = 0$,and $MC_2 \bigcap m_6 = 0$
There is no intersection between Machines 4 or 7 with either MC_1 or MC_2.
Then, forms a new machine cell MC_3 = **{4, 7}**
S_7 = 0.5072 (between Machines 1 and 7)
m_7 = {1, 7}
There is an intersection between Machine 7 and MC_3, but this is no intersection with MC_1 or MC_2. The new machine cell is $MC_3 \bigcup m_7$.
Then, the revised machine cell MC_3 = **{1, 4, 7}**

Step 11: All the machines have been assigned to machine cells. Stop.

Machine Cells are as follows:

MC_1 **= {3, 5, 8, and 10}**

MC_2 **= {2, 6, and 9}**

MC_3 **= {1, 4, and 7}**

6. CONCLUSIONS

This paper proposed a new similarity coefficient for grouping machines into machine cells. Similarity coefficients between machines were reviewed through this paper. These similarity coefficients show that there are several factors or issues to be used in determining the similarity between machines. Some of them concentrated on the machine–part incidence matrix, and the rest of them depend on one or two production and/or flexibility issues like production volume, operation sequence, part demand, and number of intercellular moves. This variation will lead to suggest a new comprehensive similarity coefficient between machines including the most important production and flexibility issues. The main difference between the proposed similarity coefficient and those which already existed in the literature is the lack of them to incorporate all the real world issues. The results in table 4 showed how each value of the similarity coefficient is different. The heuristic based similarity approach was used to group machines into machine cells.

REFERENCES

[1] Aljaber N., Baek W., Chen C.L. (1997), A Tabu search approach to the cell formation problem; *Computers & Industrial Engineering* 32; 169-185.

[2] Chang P. T., Lee E.S. (2000), A multisolution method for cell formation-exploring practical alternatives in group technology manufacturing; *Computers and Mathematics with Applications* 40; 1285-1296.

[3] Gunasingh K.R., Lashkari R.S. (1989), Machine grouping problem in cellular manufacturing systems: An integer programming approach; *International Journal of Production Research* 27; 1465-1473.

[4] Gupta T. (1991), Clustering algorithms for the design of a cellular manufacturing system-An analysis of their performance; *Computers & Industrial Engineering* 20; 461-468.

[5] Gupta T. (1993), Design of manufacturing cells for flexible environmental considering alternative routing; *International Journal of Production Research* 31; 1259-1273.

[6] Gupta T., Seifoddini H. (1990), Production data based similarity coefficient for machine-component grouping decisions in the design of a cellular manufacturing system; *International Journal of Production Research* 28; 1247-1269.

[7] Islam K.M.S., Sarker B.R. (2000), A similarity coefficient measure and machine-parts grouping in cellular manufacturing systems; *International Journal of Production Research* 38; 699-720.

[8] Lee M.K., Luong H.S., Abhary K. (1997), A genetic algorithm based cell design considering alternative routing; *Computer Integrated Manufacturing Systems* 10**;** 93-107.

[9] Leem C.-W., Chen J.J. G. (1996), Fuzzy-set-based machine-cell formation in cellular manufacturing; *Journal of Intelligent Manufacturing* 7; 355-364.

[10] Lozano S., Canca D., Guerrero F., Garcia J.M. (2001), Machine grouping using sequence based similarity coefficients and neural network; *Robotics and Computer Integrated Manufacturing* 17; 399-404.

[11] Luong L.H.S. (1993), A cellular similarity coefficient algorithm for the design of manufacturing cells; *International Journal of Production Research* 31; 1757-1766.

[12] Luong L.H.S., Kazerooni M., Abhary K. (2001), Genetic algorithms in manufacturing system design. In Computational Intelligence in Manufacturing Handbook, edited by Jun Wang et al., Boca Raton, FL (CRC Press LLC).

[13] McAuley J. (1972), Machine grouping for efficient production; *The Production Engineer* 52; 53-57.

[14] Mosier C. (1989), An experiment investigating the application of clustering procedures and similarity coefficients to the GT machine cell formation problem; *International Journal of Production Research* 27; 1811-1835.

[15] Nair G.J., Narendran T.T. (1998), CASE: A clustering algorithm for cell formation with sequence data; *International Journal of Production Research* 36; 157-179.

[16] Nazarlo D., Ramirez B. (2000), Application of mixed integer programming to cellular manufacturing; *Engineering Valuation and Cost Analysis* 2; 373-386.

[17] Ponnambalam S.G., Aravindan P. (1994), Design of cellular manufacturing systems using objective functional clustering algorithms; *International Journal of Advanced Manufacturing Technology* 9; 390-397.

[18] Probhakaran G., Janakiraman T.N., Sachithanandam M. (2002), Manufacturing data-based combined dissimilarity coefficient for machine cell formation; *International Journal of Advanced Manufacturing Technology* 19; 889-897.

[19] Ramabhatta V., Nagi R. (1998), An integrated formulation of manufacturing cell formation with capacity planning and routing; *Annals of Operations Research* 77; 79-95.

[20] Seifoddini H. (1988), *Incorporation of the production volume in machine cells formation in group technology applications*. Recent Developments in Production Research, edited by A. Mital, (Elsevier Science Publishers B.V., Amsterdam), 562-570.

[21] Seifoddini H. (1989), *A probabilistic approach to machine cell formation in group technology*. International Conference of Institute of Industrial Engineers, Toronto, Ontario, Canada, May 14-17, 625-629.

[22] Seifoddini H., Djassemi M. (1991), The production data-based similarity coefficient versus Jaccard"s similarity coefficient; *Computers & Industrial Engineering* 21; 263-266.

[23] Seifoddini H., Djassemi M. (1996), Merits of the production volume based similarity coefficient in machine cell formation; *Journal of Manufacturing Systems* 14; 35-44.

[24] Seifoddini H., Wolfe P.M. (1986), Application of the similarity coefficient method in group technology; *IIE Transactions*; 271-277.

[25] Seifoddini H., Tjahana B. (1999), Part-family formation for cellular manufacturing: A case study at Harnischfeger; *International Journal of Production Research* 37**;** 3263-3273.

[26] Shaferm S.M., Rogers D.F. (1993), Similarity and distance for cellular manufacturing. Part II: An extension and comparison; *International Journal of Production Research* 31; 1315-1326.

[27] Viswanthan S. (1996), A new approach for solving the P-median problem in group technology; *International Journal of Production Research* 34; 2691-2700.

[28] Waghodekar P.H., Sabu S. (1984), Machine-component cell formation in group technology: MACE; *International Journal of Production Research* 22; 937-948.

[29] Wilhelm W.E., Chiou C.C., Chang D.B. (1998), Integrating design and planning considerations in cellular manufacturing; *Annals of Operations Research* 77; 97-107.

[30] Won Y. (2000), New P-median approach to cell formation with alternative process plans; *International Journal of Production Research* 38; 229-240.

[31] Won Y., Kim S. (1997), Multiple criteria clustering algorithm for solving the group technology problem with multiple process routings; *Computers & Industrial Engineering* 32; 207-220.

[32] Yasuda K., Yin Y. (2001), A dissimilarity measure for solving the cell formation problem in cellular manufacturing; *Computers & Industrial Engineering* 39; 1-17.

[33] Yin Y., Yasuda K. (2002), Manufacturing cells design in consideration of various production factors; *International Journal of Production Research* 40; 885-906.