



POLAR COORDINATES APPLIED FOR SOLVING PART-MACHINE CELL FORMATION PROBLEM

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<https://doi.org/10.30572/2018/KJE/170113>

ABSTRACT

Cell Formation (CF) is regarded as critical aspect of a Cellular Manufacturing System (CMS). It focuses on the creation of part families and machine cells. There are numerous methods, algorithms and models suggested to deal with solving the CF problem. However, there are several drawbacks to some existing CF methods such as, their inability deal with large size datasets, ill structured datasets, the simultaneous creation of clusters of parts and machines, lack of ability to find optimum solutions, and increased material handling costs. Thus, the suggested polar coordinates effectively address the CF problem by clustering parts and machines to reduce the material handling costs. It offers efficient initial clustering, and adapts to different production environments. While not globally optimal, it provides good starting solutions for further optimization, excelling in cost reduction and efficiency. A polar coordinates-based approach combines the repetition of parts and machines with angles and then the resulting pattern is used for checking similarity criteria. The purpose is to improve the Grouping Efficacy (GC), decrease the travel time of parts inside and outside cells and enhance Machine Utilization (MU). GC is applied as a performance measure to identify the quality of the suggested CF approach. After the polar-based approach is applied, it enhanced the proportion of exceptional elements and machine utilization. On the other hand, it showed better results for GC when compared with Rank Order Clustering (ROC). For some datasets, it recorded (60, 90) compared with (53.33, 71.93) for the traditional ROC.



KEYWORDS

Cell formation, polar coordinates-based approach, cellular manufacturing system, grouping efficacy, machine utilization.

1. INTRODUCTION

The cellular manufacturing system (CMS) is counted among the most effective approaches to address the challenges posed by the constantly changing product designs and customer demands. CMS works on the foundation of group technology rule. It has confident effect Pertaining to increasing productivity and enhancing quality. Cell formation (CF) is a paramount major step in the CMS. It tackles the Grouping similar products into clusters referred to as families, and various machines are similarly grouped into clusters known as cells. Numerous approaches have been suggested in the literature for addressing the CF problem, encompassing methods built on artificial intelligence, array clustering, similarity coefficients, heuristic/meta-heuristic techniques, mathematical programming, and more.

[Rajesh et al. \(2017\)](#) proposed a novel CF approach in CMS based on similarities and dissimilarities, addressing key drawbacks of older methods. Compared to the traditional ROC method, the proposed method outperformed it in terms of performance measures like PEE, MU, GE, and CE. ([Rajesh et al., 2017](#)).

[Rajesh et al. \(2018\)](#) proposed a time-efficient method based on voids, overcoming limitations of traditional methods. When compared to the Rank Order Clustering (ROC) approach, the results show its effectiveness in solving CF problems ([Rajesh et al., 2018](#)).

[Golmohammadi et. al., \(2019\)](#) employed two recent natures - inspired algorithms (Red Deer Algorithm RDA, Keshtel Algorithm KA and GA Algorithm). Additionally, they proposed a novel hybrid metaheuristic algorithm. The proposed algorithms solve certain numerical problems. The outcomes indicate that the results of the introduced hybrid algorithm are more effective than those of the individual methods ([Golmohammadi et. al., 2019](#)).

[Raja \(2020\)](#) suggested a novel heuristic approach for solving the CF problem, utilizing a new similarity coefficient-based approach and determining the intra-cell machine layout by considering alternative routings and operation sequence. The efficiency of the proposed approach validated by some assessment cases from literature. The Findings showed that the suggested procedure provides equal or superior solution than the existing methods ([Raja, 2020](#)).

[Shunmugasundaram, et.al \(2021\)](#) proposed combined algorithms to enhance the CF. The aim of their study is to increase production and decrease travelling time of products. grouping efficacy and grouping efficiency were used as performance measures. The results refer to increase machine utilization and decrease the total travelling time of the products ([Shunmugasundaram, et.al , 2021](#)).

[Nugroho \(2022\)](#) used Sorting Algorithms to rearranging the layout of production facilities based on cellular manufacturing concept. He applied Visual Studio 2012 software to rearrange

the layout of facilities, for this purpose, he used 20 machines and 11 parts. The results showed that the material handling is reduced by 61.61% (Nugroho, 2022).

Saeidi, and Nikakhtar (2022) have used a meta-heuristic algorithm relying on the Gray Wolf Optimization (GWO) method. It has been designed to solve the modified model using test cases, and the outcomes are then compared. The outcomes after simulation referred that the suggested approach led to a 3% reduction in manufacturing system costs. Additionally, an enhancement in performance was shown in the simulation results of five problems, comparing the recommended method with PSO and Lingo (Saeidi, and Nikakhtar, 2022).

Hakeem, et.al. (2022) presented a review of different methods and approaches that used for solving CF problems such GA, SA, PSO, TS and ACO (Hakeem, et.al., 2022).

Al-Zuheri et. al., (2022) presented heuristic approach based on genetic algorithms and group technology, which is used to reduce the material handling cost, inter/intra-cellular movements. However, increasing group efficacy and efficiency. The proposed heuristic method, identifies the best solution for flexible CF and machine layout inside each cell (Al-Zuheri et. al., 2022).

Cáceres-Gelvez et. al., (2022) applied, a simulation approach to assess the performance of the CMS for the sewing section of a sportswear industrial company. Improvements of 50.65% in average machine setup times and 51.46% in average flow time were observed in the outcomes of the suggested model, compared with the existing state of the manufacturing company (Cáceres-Gelvez et. al., 2022).

Urazel and Buruk Şahin (2023) concentrated on the issue of a cubic cellular manufacturing which take into account (workers, parts and machines) as an incidence matrix. The objective of their study is to decreasing the exceptional and void elements, for this reason they employed a hybrid (GA and SA) based approach (Urazel and Buruk Şahin, 2023).

Raja and Vignesh (2023) utilized eigenvalues and Kaiser's law to identify machine cells and part families based on their similarities. Moreover, the proposed method takes into account the inter-intra cellular movements, exceptional and void elements. From the obtained result, it could be showed that the proposed method offers equal (or) better solution than the usual method (Raja and Vignesh, 2023).

Vinitha, et.al., (2023) introduced an application for a design of cellular manufacturing system in manufacturing industries. The proposed design based on the operation sequences for totally designing machine cells, part families, best cells layout and best machines layout in each cell (Vinitha, et.al., 2023).

Liu et, al., (2023) Presented a method to solve product scheduling and cell formation at the same time in multi-factory manufacturing systems. This research study the influence of the

proposed method on the raw material cost, total manufacturing time of each product and labor cost (Liu et al., 2023).

Figuroa-Torrez et al. (2024) introduced study suggestions visions into existing trends in solving the cell formation problem with machine reliability and alternative routings, assisting researchers and experts in the field to enhance the quality of their studies (Figuroa-Torrez et al., 2024).

Sellitto (2025) applied similarity coefficients in group technology and cellular layout in industrial factories. This article takes into consideration multicellular manufacturing. The aim of the article is to offer some benefits in the manufacturing industries such as enhance the quality, improve efficiency of the operations and decrease the production costs (Sellitto, 2025). There are numerous drawbacks to some present CF methods such as, their inability to handle large size problems, ill structured problems, creating groups of machines and parts simultaneously, lack of the capability to find optimal solutions, lack of flexibility and increased material handling cost. Thus, the contribution of the proposed method excels in handling the similarity in part-machine relationships which minimizes inter-cell material handling costs, provides a simple and efficient initial clustering method, Additionally, and can handle non-square part-machine matrices. Although it may not always yield the globally optimal solution, it provides good-quality initial solutions that can serve as starting points for further optimization using more advanced techniques.

In the current paper researchers tried to use angles to identify the numbers of parts related to certain machine and vice versa by denoting angles to parts and machines in such a way that the involved parts and machines will have specific pattern which will be used for similarity check. The structure of the current research includes seven sections. Section 1 provides the introduction, section 2 explains the polar coordinate-based method, while section 3 describes the research method. Section 4 explains the performance measure results. On the other hand, section 5 displays the results and discussion. However, section 6 focuses on the conclusion. Finally, the references are displayed in section 7.

2. METHOD BASED ON POLAR COORDINATES

The polar coordinate system is a flat coordinate system, specifies each point on a coordinate space by its distance from a reference point and its angle relative to a reference direction. It is widely used where angles and distances clearly illustrate the relationship between two points. In contrast, when using the Cartesian or rectangular coordinate system, trigonometric formulas are necessary to represent this relationship. in this two-dimensional coordinate system, two polar coordinates will determine each point these are:

2.1. The Radial Coordinate

The distance from a central point (similar to the origin of the cartesian system) called the pole to the points represents the radial coordinate (r).

2.2. The Angular Coordinate

The azimuth angle or the polar angle (θ) which represents the angle in either the positive or anticlockwise (counterclockwise) direction is the angular coordinate required to reach the point from the 0° ray or polar axis. Generally degrees or radians are used to express angles in polar notation (2π rad being equal to 360°) (Serway and Jewett, 2014). Fig. 1 refers to the angular coordination in degrees.

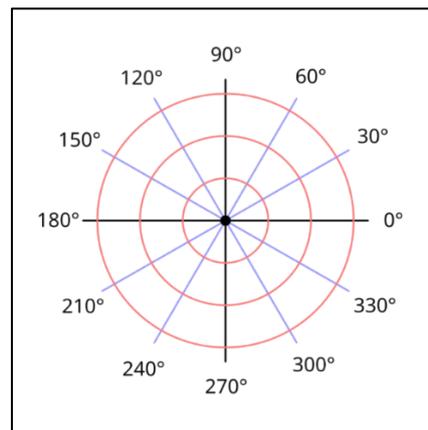


Fig. 1: refers to the angular coordination in degrees.

A multiple angles polar grid increasing in positive orientation using degrees labeling.

In this paper only four distinctive angles will be used to represent the parts and machines these are 90, 180, 270 and 360. Each with one color to increase the suggested method visually these are red, green, blue and yellow respectively. The four angles were initially chosen to demonstrate proof of concept for the suggested method because they offer a balanced and manageable approach for initial testing and validation. Using four angles allows for a clear, focused analysis that can effectively illustrate the principles of the proposed method without overwhelming the model with excessive complexity. The selection of four angles represents a compromise between simplicity and functionality, providing enough variability to assess the effectiveness of the method while maintaining clarity in the results. However, it is important to note that the method is not restricted to just four angles. In future work, the analysis can be extended to investigate the impact of using more than four angles, which could provide a deeper understanding of the method's scalability and performance in more complex scenarios. The choice of four angles serves as an initial benchmark, but exploring a wider range of angles could potentially yield more nuanced insights. Regarding the color code used in this study, the primary goal was to enhance the visualization of the method, with the colors being arbitrarily

chosen for differentiation. The use of colors helps to clearly distinguish between the different angles, making the graphical representation more intuitive and visually appealing. However, as more than four angles are introduced in future studies, it would be necessary to implement additional colors, ensuring each angle is represented by a distinct color for clarity and effective differentiation. This extension would maintain the visual integrity of the representation while accommodating the increased complexity brought about by additional angles. Fig. 2 illustrates the suggested polar grid with the four angles used.

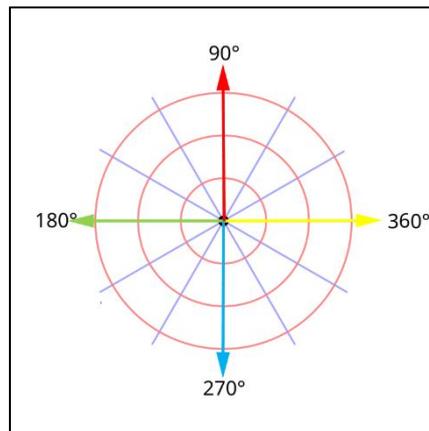


Fig. 2: The suggested polar grid with the four angles used.

Although Cartesian and polar coordinates are distinct systems, they are equivalent in that any point in the plane can be represented in both, with the ability to convert between them. Polar coordinates were chosen because they allow the cells with a value of 1 to be mapped to an angle, which is easier to determine and access in polar coordinates compared to Cartesian coordinates.

The polar system was used to represent the accruing of part machine bond in specific range depending on virtual horizontal or vertical line and denoting one angle (color) only in this range represents numbers 1, 2, 3 or 4.

The suggested method, while effective in its initial form, does have certain limitations, particularly when applied to larger or sparse matrices. In the case of large matrices, the need to use more than four angles may arise, which, although adding complexity to the method, does not necessarily compromise its accuracy. However, the increase in the number of angles introduces additional computational overhead and could potentially complicate the analysis and interpretation of results. This added complexity might require more sophisticated techniques to manage and visualize the data, potentially reducing the efficiency of the method in large-scale applications. On the other hand, when applied to sparse matrices (those with a significant lack of 1's), the method faces challenges due to the limited information available. Sparse matrices inherently lack the dense connectivity of data points, which may reduce the reliability of the

results. The absence of 1's in key positions could lead to incomplete or less accurate representations, affecting the overall robustness of the method. As a result, the method's performance in sparse environments may be less reliable, and additional strategies may be needed to address these limitations and improve its robustness in such scenarios.

3. METHODOLOGY:

The methodology that followed in this research is as mentioned below:

3.1. The Selected Datasets

Some well-known datasets from open literature were selected, which arranged as (0-1) matrix, (1) means the part need the machine to operate while (0) otherwise. The dataset sizes are (5*7, 6*8, 7*11, 10*15), (Waghodekar and Sahu,1984; Kusiak, 1987; Boctor, 1991; Chan and Milner,1982) respectively.

3.2. The Application of the Proposed Algorithm

The steps of the proposed algorithm are outlined in the following points, using Structured English to describe the algorithm with basic control structures (e.g., IF-THEN-ELSE, FOR, WHILE).

1. First, we assume a horizontal line placed in the middle which divide's the matrix into two equal sections upper section and lower section.
2. If the number of the rows was odd which makes it hard to divide the matrix into two equal sections upper section and lower section, we add slack machine which will not process any part, this will guarantee that even numbers of cells will be above and under the horizontal line which is consists with the four angles suggested.
3. For each part we replaced each four 1's with the following angles (90,180,270 and 360) respectively and periodically to cover all the machines.
4. To make it easier to track the cells and their corresponding numbers in each row, we use a color code for the angles in the matrix. The colors represent specific angles: red for 90°, green for 180°, blue for 270°, and yellow for 360°. This color coding is applied only to the last cell contains 1 in each cycle.
5. If the part has to be processed by more than 4 machines, then we use same angles and color code repeatably until all the machines are covered.
6. The color code used once in each group of 1's (one, two, three and four) and only with the last one in the group to indicate the limits
7. After giving angles to the 1's and use color coding in the matrix we start the arrangement process.

8. The parts arranged according the angles as follows:

- Parts with angles only marked above the line: in this case we start to arrange parts descendingly from highest angles to the lowest angles and from the farthest from the middle line to the closest to the line.
- Parts with angles only marked under the line: in this case we start to arrange parts descendingly from closest to the middle line to the farthest from the line and from highest angles to the lowest angles.
- If two parts were equal in angles and both have the same distance to the horizontal line, we use the following criteria the part with distance between the first cell contains 1 and the last cell contains 1 greater than the distance between the middle horizontal line and the last cell contains 1 is preferred.

After parts were arranged now, we start to rearrange machines according to the following:

1. First, we assume a vertical line is placed in the middle which divide's the matrix into two equal sections left section and right section.
2. If the number of the columns was odd which makes it hard to divide the matrix into two equal sections, then we add slack part which will not be processed by any machine, this will guarantee that even numbers of cells will be on the left and the right of the vertical line which is consists with the four angles suggested.
3. For each machine we replaced each four 1's with the following angles (90,180,270 and 360) respectively and periodically to cover all the parts.
4. To make it easier to track the cells and their corresponding numbers in each column, we use a color code for the angles in the matrix. The colors represent specific angles: red for 90°, green for 180°, blue for 270°, and yellow for 360°. This color coding is applied only to the last cell contains 1 in each cycle.
5. If the machine is processing more than 4 parts, we use same angles and color code repeatably until all the parts processed by this machine are covered.
6. The color code used once in each group of 1's (one, two, three and four) and only with the last one in the group to indicate the limits.
7. After giving angles to the 1's and use color coding in the matrix we start the arrangement process.

8. The parts arranged according the angles as follows:

Machines with angles only marked on the left of the line: in this case we start to arrange machines descendingly from highest angles to the lowest angles and from the farthest from the middle line to the closest to the line.

Machines with angles only marked to the right of the line: in this case we start to arrange machines descendingly from closest to the middle line to the farthest from the line and from highest angles to the lowest angles.

If two parts were equal in angles and both have the same distance to the vertical line, we use the following criteria the machine with distance between the first cell contains 1 and the last cell contains 1 greater than the distance between the middle vertical line and the last cell contains 1 is preferred.

Fig. 3 refers to the research methodology flowchart.

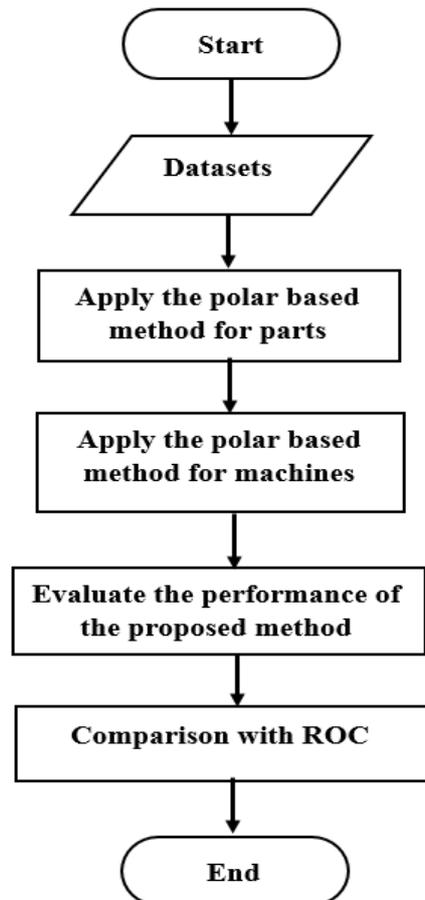


Fig. 3: The methodology flowchart.

The proposed polar based method was employed as in below (one dataset 5*7) was selected as an example to explain the proposed method, one problem (matrix) with (0-1) entries was used as in the followings noting that the binary numbers will remain unchanged; instead, the positions of the cells containing 1 will be mapped to angles based on the number of cells containing 1 in a particular column or row.

Dataset (5*7):

Number 5 refers to the machines, while number 7 corresponds to the parts [Table 1](#).

Table 1: Dataset (5*7)

| | P1 | P2 | P3 | P4 | P5 | P6 | P7 |
|----|----|----|----|----|----|----|----|
| M1 | 0 | 1 | 0 | 1 | 1 | 1 | 0 |
| M2 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| M3 | 1 | 0 | 1 | 0 | 0 | 1 | 1 |
| M4 | 0 | 1 | 0 | 1 | 0 | 1 | 0 |
| M5 | 1 | 0 | 0 | 0 | 1 | 0 | 1 |

The proposed method as explained in section (3.2) was applied for the above matrix (5*7) in the following steps: -

Step 1: Apply color code to the parts to show angles [Table 2](#).

Table 2

| | P1 | P2 | P3 | P4 | P5 | P6 | P7 |
|----|----|----|----|----|----|----|----|
| M1 | 0 | 1 | 0 | 1 | 1 | 1 | 0 |
| M2 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| M3 | 1 | 0 | 1 | 0 | 0 | 1 | 1 |
| M4 | 0 | 1 | 0 | 1 | 0 | 1 | 0 |
| M5 | 1 | 0 | 0 | 0 | 1 | 0 | 1 |

Step 2: Adding slack machine, horizontal line placed in the middle and re-arrange parts [Table 3](#).

Table 3

| | P6 | P2 | P4 | P3 | P1 | P5 | P7 |
|----|----|----|----|----|----|----|----|
| M1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 |
| M2 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| M3 | 1 | 0 | 0 | 1 | 1 | 0 | 1 |
| M4 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| M5 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| MS | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Step 3: Adding slack part, vertical line placed in the middle and re-arrange machines [Table 4](#).

Table 4

| | P6 | P2 | P4 | P3 | P1 | P5 | P7 | PS |
|----|----|----|----|----|----|----|----|----|
| M1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 |
| M2 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| M3 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 |
| M4 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| M5 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |

Step 4: Final Part-Machine Cell Formation [Table 5](#).

Table 5

| | P6 | P2 | P4 | P3 | P1 | P5 | P7 |
|----|----|----|----|----|----|----|----|
| M1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 |
| M4 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| M3 | 1 | 0 | 0 | 1 | 1 | 0 | 1 |
| M2 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| M5 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |

4. PERFORMANCE MEASURES RESULTS:

Before recognize the performance measures results, it will identify the number of cells as follows:

4.1. Number of Cells

The number of obtained cells after applied the proposed method for the selected datasets is as displayed in [Table 6](#).

Table 6: Find number of cells

| Matrix size | Number of cells (C) |
|-------------|---------------------|
| 5*7 | 2 |
| 6*8 | 2 |
| 7*11 | 3 |
| 10*15 | 3 |

4.2. Number of Voids and Exceptional Elements

Voids represent the count of zero entries in the final assembled cells, signifying that certain machines remain idle and do not fully utilize the available capacity. However, the positive off-diagonal ones (1's), referred to as exceptional elements (EE) in the final CF solution, are utilized to assess the effectiveness of the chosen CF method. EE can be computed as demonstrated in [Eq.1 \(King, 1980\)](#):

$$EE = eo \quad (1)$$

[Table 7](#) Relates to the exceptional elements and voids within the chosen datasets.

Table 7: The exceptional elements and voids

| Matrix size | Number of void elements | Number of exceptional elements |
|-------------|-------------------------|--------------------------------|
| 5*7 | 4 | 2 |
| 6*8 | 4 | 2 |
| 7*11 | 9 | 3 |
| 10*15 | 5 | 0 |

4.3. Percentage of Exceptional Elements and Machine Utilization

The quality of the grouping can be determined by counting the number of ones located outside the diagonal block. PE is represented by the formula in [Eq.2. \(Chandrasekharan and Rajagopalan, 1986a, 1986b\)](#):

$$PE = \frac{EE}{UE} * 100 \quad (2)$$

EE represents the number of 1's located outside the block diagonal, the total count of 1's present in an incidence matrix, known as UE.

However, utilizing the machines percentage within the cells during production are referred by the machine utilization. MU is calculated using [Eq.3](#) as follows. [\(Chandrasekharan and Rajagopalan, 1986a, 1986b\)](#):

$$MU = \frac{N1}{\sum_{K=1}^K m_K n_K} * 100 \quad (3)$$

Where:

- (N1) represents the total number of ones within the clusters.
- (K) denotes the number of groups.
- (m) indicates the number of machines in the k th group.
- (n) refers to the number of products in the k th group.

Table 8 Refers to the present of exceptional elements and machine utilization within the selected datasets.

| Matrix size | Percent of PE | Machine Utilization MU |
|-------------|---------------|------------------------|
| 5*7 | 12.50 | 77.77 |
| 6*8 | 9.09 | 75.00 |
| 7*11 | 14.28 | 66.66 |
| 10*15 | 0.00 | 90.00 |

4.4. Comparisons of the GC of the Proposed Polar and ROC Based Methods

The performance parameter that used to assess the proposed polar method and compared with ROC based method in the present article known as Grouping Efficacy (GC). ROC and GC are explained in the following:

ROC based method:

ROC is one of the array-based clustering methods which is used to create machine cells and corresponding part families at the same time. This method was proposed initially by [King \(1980\)](#). The ROC algorithm is mainly based on binary value (value to power 2), which allows shifting and reorganizing rows and columns in the original (0-1) matrix to form cells along the matrix diagonal. Even though, there are numerous CF methods, ROC was cohesion in the current article for comparison because it leads to achieve machine cells and part families simultaneously. It allowed to shift and rearrange rows and columns in the origin (0-1) matrix, so it is easy to form blocks (cells) along the matrix diagonal. Even though ROC algorithm has some drawbacks but it still considered as the simplest and accepted algorithm for solving CFP to create cells and families concurrently.

Grouping Efficacy (GC)

GC possesses certain positive traits, for instance, (i) it provides positive values (ii) its values traces from zero to one and (iii) it hasn't any hindrance alongside the dimension of the (0, 1) part- machine matrix. [Tariq et al., \(2007\)](#) reported that the cell formation problem is solved by simultaneously minimizing outside cells movements and maximizing machine utilization inside cells. To achieve these two objectives concurrently, GC is selected as a performance measure due to its ability to contain the intercellular movements and the within cell machine utilization. Furthermore, it has a high ability to distinguish between ill-structured and well-structured

matrices (Tariq et al.,2007). GC expressed as in Eq. 4 (Tariq et al., 2007).

$$GC = \frac{N_1 - N_1^{\text{out}}}{N_1 + N_0^{\text{in}}} * 100 \quad (4)$$

Where, N_1 : denotes to the 1's in the machine-part matrix; N_1^{out} : indicates the whole number of 1's located outside the groups; N_0^{in} : denotes to the whole count of 0's found within groups.

Table 9 and Fig. 4 Denotes to the GC values within the selected datasets.

| Matrix size | Proposed polar based method | ROC based method |
|--------------------|------------------------------------|-------------------------|
| 5*7 | 70.00 | 73.68 |
| 6*8 | 76.92 | 76.92 |
| 7*11 | 60.00 | 53.33 |
| 10*15 | 90.00 | 71.93 |

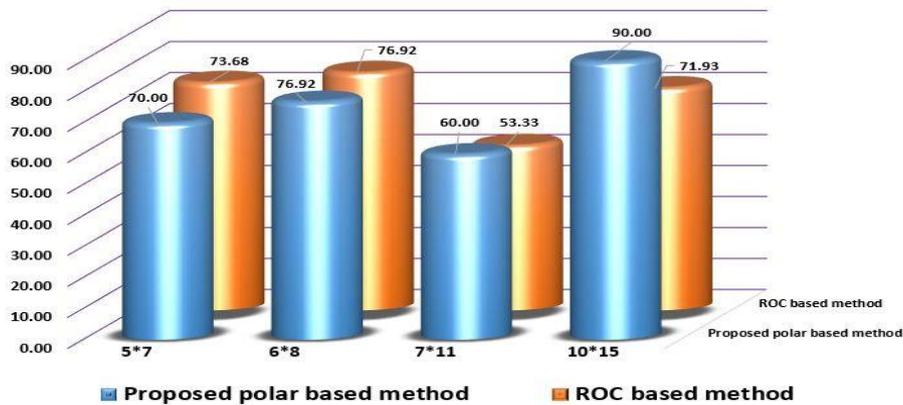


Fig. 4: Comparisons of the GC of the proposed Polar and ROC

5. RESULTS AND DISCUSSION:

To verify the effectiveness of the pertaining to the introduced polar-based method, four problems were addressed after been selected from the open literature. Initially, by using the introduced procedures outlined for the suggested method in Section 3.2 all the assessment cases were solved. Subsequently, the quantity of machine cells, C , was established. Furthermore, a several effectiveness measures such as (MU, PE, V, EE, GC) were considered and calculated. The EE needs to operate in more than one machine cell, and the corresponding machine is called a bottleneck machine because it processes two or more-part families. The large number of EEs leads to increased material handling costs between machine cells, which results in increased production costs. Thus, a small number of EEs is preferred. On the other hand, machine utilization, which refers to the percentage of machines used inside cells during production, is important. A higher value of MU indicates better clustering results, while a lower value suggests that some machines have idle time and do not utilize all the available capacity. The number of voids (0's) inside cells represents the idle time of machines, where a higher number of voids

denotes a poor solution, and vice versa.

Table 9 and Fig. 4 revealed that the results of the proposed polar based technique better than ROC based method in terms of the grouping efficacy, where it recorded results either equivalent or better than ROC. For the first matrix, ROC recorded GC (73.68) higher than the value of the proposed method (70.00). While both of the two methods resulted the same value of the second matrix (76.92). However, the proposed method recorded higher values of GC for the last two matrices, where it recorded (60.00), (90.00) respectively comparing with (53.33, 71.93) for ROC.

6. CONCLUSIONS

In the current study, four benchmark datasets were selected from literature. A polar based method was applied for all the selected problems. It has been found that the results of the proposed polar method had a significant impact on the most of the performance parameters. However, GC was applied as an evaluation criterion for comparison between polar and ROC based methods. The outcomes of the proposed method could lead to the conclusions below:

1. There is a significant improvement in the voids and exceptional elements for the majority of datasets
2. The results of the polar based method is better than ROC based method in terms of the grouping efficacy.
3. The recommended polar based method had a positive outcome relating to the PE and MU.

Overall, the suggested method offers a solid foundation for solving CFP particularly in terms of cost reduction, computational efficiency, and adaptability to different manufacturing contexts.

For future work, it is suggested to:

- a. Use other CF methods for comparison with the proposed polar coordinates-based method, such as similarity coefficient-based methods, heuristic-based methods, artificial intelligence-based methods, and mathematical programming-based methods.
- b. Employ other performance measures, such as grouping efficiency and grouping capability index.
- c. Apply the proposed method to large-size datasets.
- d. Utilize more than four angles, which could provide a deeper understanding of the method's scalability and performance in more complex scenarios.

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