Evaluating layout design efficiency: a proposed model based on matrix formulation.

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This paper presents a model to evaluate layout design efficiency. The proposed model is based on matrix formulation. Layout efficiency is determined comparing layout design conditions with current layout utilization, for different periods. A case study in an auto parts manufacturing company is presented and the results are analyzed using a performance index defined by the authors: Layout Design Efficiency (LDE). The LDE index uses matrix formulation model for layout design and compares the values of grouping efficiency (GE) for different conditions. From the calculation of the efficiency of clusters for different conditions of use, the efficiency of the project is determined, and it is possible to decide about layout reconfigurable demands. The relevance of using LED for the decision to reconfigure a layout is based on a quantitative and objective criterion, based on the application of this metric to the production system. This is the main contribution of this proposal to the operations management area. Results of a case study showed LDE can be used to evaluate layout design in a quantitative criterion, comparing layout efficiency for different conditions of use for manufacturing systems. For the case studied, obtained values of LDE indicated that is not necessary a reconfiguration effort.

Keywords: Layout Design, Layout Efficiency, Matrix Formulation, Reconfigurable Layout

1 Matrix Formulation and Layout Design Principles

A good industrial layout is critical for the success of any industrial operation, as it can have a significant impact on productivity, efficiency, safety, and the overall success of the business. Matrix formulation is a method for designing a layout that involves creating a matrix that identifies the relationships between various work areas and departments. This can help identify opportunities for consolidation, and optimize the flow of materials, personnel, and equipment. It is particularly useful in situations where there are many departments or work areas that need to be considered.
Cluster analysis, on the other hand, is a statistical method that involves grouping similar items or objects together into clusters. This technique is useful for designing layouts that maximize efficiency by grouping together areas or departments that have similar

requirements, equipment, or workflows. It is particularly useful in situations where there are clear similarities between different areas of the industrial operation.
Both of these techniques can be effective for designing industrial layouts.
Matrix Formulation is used to model industrial layouts since decade of 80 [1]. An incidence matrix uses the following rule to represent a manufacturing system, composed by machines and pieces or components:

$$a_{ij} = \begin{cases} 1, \text{ when component (i) is processed in machine (j)} \\ 0, \text{ when component (i) is not processed in machine (j)} \end{cases}$$

Using matrix formulation is possible to define production flow analysis in a manufacturing system and identify the best configuration of machines and pieces to reduce movements and lead times [2]. Early applications of matrix formulation were used to design cellular layouts based on grouping algorithms for cluster analysis [3]. A typical layout model design by cluster analysis techniques is showed in Figure 1.

	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**
M1	0	1	0	1	1	0	0	0
M2	1	0	0	1	0	0	0	1
M3	0	0	1	0	0	0	1	0
M4	0	0	0	0	0	1	0	1
M5	0	0	0	0	0	0	1	0
M6	0	0	1	0	0	0	1	0
M7	0	1	0	0	1	0	0	0

(a)

	P3	**P7**	**P5**	**P4**	**P2**	**P1**	**P6**	**P8**
M3	1	1	0	0	0	0	0	0
M5	0	1	0	0	0	0	0	0
M6	1	1	0	0	0	0	0	0
M1	0	0	1	1	1	0	0	0
M7	0	0	1	0	1	0	0	0
M2	0	0	0	***1***	0	1	0	1
M4	0	0	0	0	0	0	1	1

(b)

Fig.1: Incidence Matrix for initial condition of production flow (a) and Incidence Matrix reordered by grouping algorithm (b)

Figure 1 illustrates a block diagonal structure (BDS) formed by 3 groups of pieces (P) and machines (M): the first group is composed by machines M3, M5, M6, and by pieces P3, P7; the second group is formed by machines M1, M7 and pieces P5, P4, P2 and the third group is composed by machines M2, M4 and pieces. The element 1 represented by processing P4 in machine M2 is defined as an “exception element”, because in the solution showed in (b) configuration, this element is out of the BDS.

The presence of exception elements in BDS difficult the perfect cluster formation and the layout design is not ideal for this condition [4]. Therefore, is necessary to evaluate grouping efficiency layout. There are several measures proposed for this issue [5]. Figure (2) presents the widely known and used.

DEFINITION	CHARACTERISTICS
Effectiveness Measure (ME)	Proposed for Bond Energy Algorithm (BEA) application
Exception Elements Percentual (%EE)	Used to identify exception elements in clusters formation %EE = (number of exceptional elements) / (total number of elements “1” in incidence matrix)
Machine Utilization (MU)	Used to identify “0” elements in block diagonal structure (BDS)
Grouping Efficiency (GE)	Used to evaluate simultaneously the presence of “0” elements in block diagonal structure (BDS) and “1” elements out of block diagonal structure (BDS)
Grouping Efficacy (GEF)	Used to compare the number of exception elements and “0” elements in block diagonal structure (BDS)
Grouping Measure (C)	Used to determine the distances between “1” elements in the matrix and main diagonal

Figure 2: Evaluation measures for layout grouping efficiency [6],[7].

The proposed method in this article uses GE [8]. to compare different configurations of formulation matrix. GE is considered more effective than other efficiency measures because it considers simultaneously the presence of exception elements (%EE) and machine utilization (MU).

GE (Grouping Efficiency) is determined by:

$$GE = q\,(n1/nt1) + (1-q)\,(n2/nt2)$$

where:

q is a weight factor defined with values between (0,1 and 0,9) and usually assuming 0,5. [9],[10].

n1 is the number of “1” elements in BDS.

nt1 is the total number of elements inside the BDS structure.

n2 is the number of “0” elements outside the BDS structure.

nt2 is the total number of elements outside the BDS structure.

Perfect conditions of clusters formation consider an ideal and complete BDS structure, which means n1 = nt1 and n2 = nt2. For this condition, GE = 1 (100%).

Applying GE for the matrix configuration of Figure (1)b results:

GE = 0,5 (14/18) + (1-0,5) (37/38) = 0,875 (87,5%)

For industrial applications, GE values above 85% are considered highly performed. [10]

2 Layout reconfigurable conditions

Next step of a new layout design is its implementation. Machines are relocated in the shop floor according to the logical conditions defined by BDS structure and the mix of pieces or components are processed in each formed cluster. [11].

For each period (usually months) lots of production are planned, processed, and controlled, according to manufacturing demands. Figure (3) shows a hypothetic production plan that considers a scenario of six months and represents the pieces (or components) processed. This scenario simulates a real condition, where not always all the pieces are processed in each period. It is based on Figure (1)b incidence matrix reordered.

Period	Processed pieces	Non-Processed pieces
1	P1, P3, P4, P6	P2, P5, P7, P8
2	P1, P2, P3, P5, P7	P4, P6, P8
3	P2, P4, P7, P8	P1, P3, P5, P6
4	P1, P2, P3, P4, P5, P8	P6, P7
5	P1, P3, P4	P2, P5, P6, P7, P8
6	P1, P2, P6	P3, P4, P5, P7, P8

Figure 3: Processed pieces per period

For period (1), where P2, P5, P7 and P8 were non-processed, the configuration of incidence matrix is showed in Figure 4.

	P3	**P4**	**P1**	**P6**
M3	1	0	0	0
M5	0	0	0	0
M6	1	0	0	0

M1	0	1	0	0
M7	0	0	0	0
M2	0	***1***	1	0
M4	0	0	0	1

Figure 4: Matrix configuration for period 1

Grouping Efficiency (GE) for this period is determined by:

$$GE = 0{,}5\ (5/9) + (1-0{,}5)\ (18/19) = 0{,}752\ (75{,}2\%)$$

Therefore, for period 1, GE assumes value 75,2% and the efficiency of grouping decreases, comparing with design conditions.

Figure 5 presents GE values for periods 1 to 6 and GE for design layout condition

Period	1	2	3	4	5	6	Design
GE	0,752	0,917	0,918	0,868	0,75	0,833	0,875

Figure 6 shows a control chart comparing GE for design condition and GE for each period.

Analyzing the results, in periods 2 and 3 GE assumes values major than GE Design. However, for periods 1, 4,5 and 6, the values for GE are less than GE Design.

Therefore, after implement a new layout design, it is necessary to monitoring its current utilization. For different periods, the mix of pieces processed are always distinct.

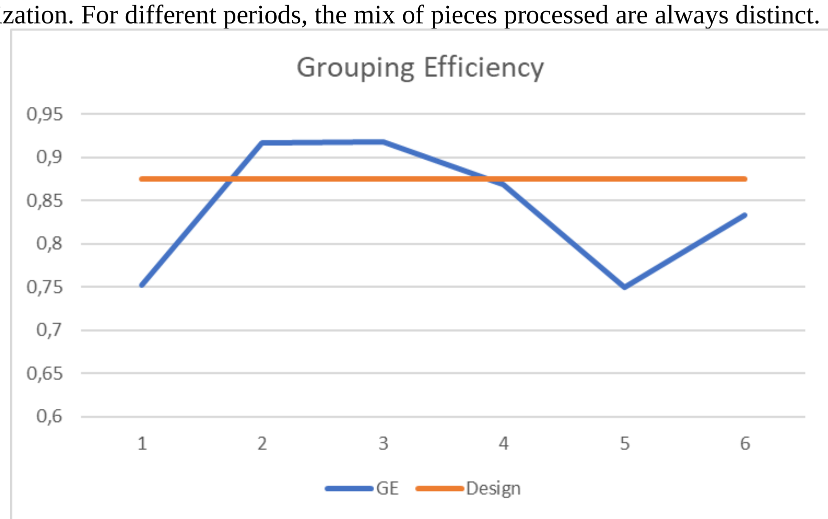

Figure 5: GE for periods 1 a 6

It can occur by different reasons, like pieces of new products being introduced, spare parts of products, pieces of MTS (Make to Stock) products, pieces of MTO (Make to Order) products.

This dynamic condition of layout utilization can result in inadequate values of GE, and underutilization of layout design. [12].

Values of GE constantly less than GE Design may indicate a demand to reevaluate layout efficiency. It is necessary control GE values to determine if design requisites are changing and reconfigure the layout if it is necessary to assure high values of GE.

3 Evaluating Layout Efficiency

This paper proposes the use of LDE (Layout Design Efficiency) to evaluate layout efficiency and to decide based on a quantitative criterion, if it is necessary redesign efforts.

Figure 6 shows the proposed procedure, step by step. First step is layout design, using matrix formulation model and cluster analysis. Second step is determined GE for design conditions. Next step is the implementation of layout. After implementation, it is necessary measure and control GE values, to assure results like GE Design.

A similarity range of 15% (up or down GE Design) may be consider adequate to maintain layout design initial conditions. Values of GE out the limits must be monitored during six periods. The maintenance of GE out of limits during six periods demand reconfiguration layout analysis.

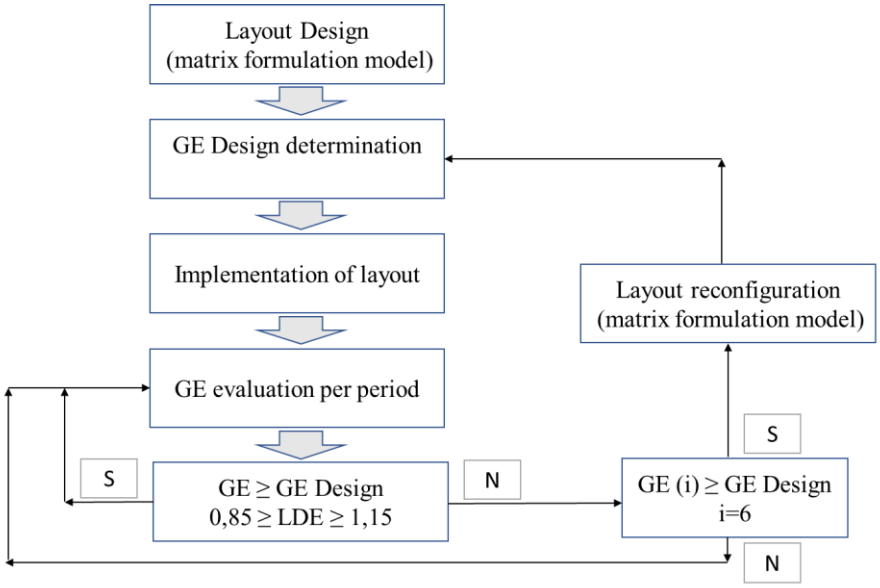

Figure 6: Steps for layout design evaluation using GE and LDE

LDE (Layout Design Efficiency) evaluate the utilization of layout. It compares GE Design with GE per period (usually months).
The range of variation is limited to +/- 15% of GE Design. This range was adopted based on operational efficiency measure, used in Operations Management.

Therefore, monitoring LDE and GE values, it is possible to evaluate layout design using a quantitative criterion, and analyses layout reconfigurations demands.

LDE is calculated by:

LDE (per period) = GE (period)/ GE Design

The ideal value of LDE occurs when GE Design = GE (period), resulting LDE = 1,0. Considering the same limits used for GE, the range for optimal values of LDE is (0,85; 1,15).

4 Case study of LDE (Layout Design Evaluation)

To analyze the LDE application, a case study was carried out. An auto parts manufacturing plant sited in Sao Paulo state was studied.

This plant produces brake systems, and its layout is organized in cellular manufacturing units.
There are 10 production units, for heavy and light brake systems. This paper analyses one production unit for light vehicles, composed by 32 different types of machines and 22 parts (pieces or components).

Figure 7 presents the layout design for the production unit studied. It is composed by 4 clusters: cells G, M, E, and K.

	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P 10**	**P 11**	**P 12**	**P 13**	**P 14**	**P 15**	**P 16**	**P 17**	**P 18**	**P 19**	**P 20**	**P 21**	**P 22**
M1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M2	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M3	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M4	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M5	1	1	1	0	Cell G				0	0	0	0	0	0	0	0	0	0	0	0	0	0
M6	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M7	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M8	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M9	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M10	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M11	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M12	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M13	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M14	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M15	0	0	0	1	1	0	0	0	Cell M				0	0	0	0	0	0	0	0	0	0
M16	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M17	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M18	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M19	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M20	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
M21	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
M22	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
M23	0	0	0	0	0	0	0	1	1	1	1	1	0	Cell E				0	0	0	0	0
M24	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
M25	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
M26	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
M27	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
M28	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
M29	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
M30	0	0	0	0	0	0	0	Cell K				0	1	1	1	1	1	1	1	1	1	1
M31	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
M32	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1

Figure 7: Layout Design for Light Vehicles Production Unit

The first step is calculated GE Design.

GE Design = 0,5 (147/162) + (1 – 0,5) (1) = 0,954 (95,4%)

For upper and lower limits:

UL (Upper Limit) = 0,85 (0,954) = 0,811

LL (Lower Limit) = 1,15 (0,954) = 1,097

Figure 8 presents the results for GE per period, for 4 months. The production plan for each month is showed.

Month	**Cell G**	**Cell M**	**Cell E**	**Cell K**	**GE (i)**
1	**P1, P2**	**P4, P5**	**P8, P9, P11**	**P13, P14, P15, P16, P17**	**0,966**
2	**P1, P3**	**P4, P5**	**P8**	**P13, P14, P15, P18, P19**	**0,987**
3	**P2, P3**	**P4, P6, P7**	**P8, P9, P12**	**P20, P21, P22**	**0,943**
4	**P1, P2, P3**	**P6**	**P8, P11, P12**	**P20**	**0,923**
5	**P1, P2**	**P6, P7**	**P11, P12**	**P21**	**0,888**

Figure 8: GE for 5 periods (months)

Figure 9 shows the matrix configuration for month 1.

Figure 10 shows values of LDE for the same periods.

Period	1	2	3	4	5
LDE	1,012	1,034	0,988	0,968	0,930

Figure 10: Values of LDE

	1	**2**	**4**	**5**	**8**	**9**	**11**	**13**	**14**	**15**	**16**	**17**

1	1	1	0	0	0	0	0	0	0	0	0	0
2	1	1	0	0	0	0	0	0	0	0	0	0
3	1	1	0	0	0	0	0	0	0	0	0	0
4	1	1	0	0	0	0	0	0	0	0	0	0
5	1	1	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0
8	1	0	0	0	0	0	0	0	0	0	0	0
9	1	1	0	0	0	0	0	0	0	0	0	0
10	0	0	1	1	0	0	0	0	0	0	0	0
11	0	0	1	1	0	0	0	0	0	0	0	0
12	0	0	1	1	0	0	0	0	0	0	0	0
13	0	0	1	1	0	0	0	0	0	0	0	0
14	0	0	1	1	0	0	0	0	0	0	0	0
15	0	0	1	1	0	0	0	0	0	0	0	0
16	0	0	1	1	0	0	0	0	0	0	0	0
17	0	0	1	1	0	0	0	0	0	0	0	0
18	0	0	1	1	0	0	0	0	0	0	0	0
19	0	0	1	1	0	0	0	0	0	0	0	0
20	0	0	0	0	1	1	1	0	0	0	0	0
21	0	0	0	0	1	1	1	0	0	0	0	0
22	0	0	0	0	1	1	1	0	0	0	0	0
23	0	0	0	0	1	1	1	0	0	0	0	0
24	0	0	0	0	1	1	1	0	0	0	0	0
25	0	0	0	0	1	1	0	0	0	0	0	0
26	0	0	0	0	1	1	1	0	0	0	0	0
27	0	0	0	0	0	0	0	1	1	1	1	1
28	0	0	0	0	0	0	0	1	1	1	1	1
29	0	0	0	0	0	0	0	1	1	1	1	1
30	0	0	0	0	0	0	0	1	1	1	1	1
31	0	0	0	0	0	0	0	1	1	1	1	1
32	0	0	0	0	0	0	0	1	1	1	1	1

Figure 9: Matrix configuration for period 1

Figure 11 presents the obtained values of LDE for 5 months.

For each month, distinct production plans change layout configuration and GE values can varies.

Analyzing the obtained results, all LDE values are inside the range defined by the limits of control chart showed in Figure 11.

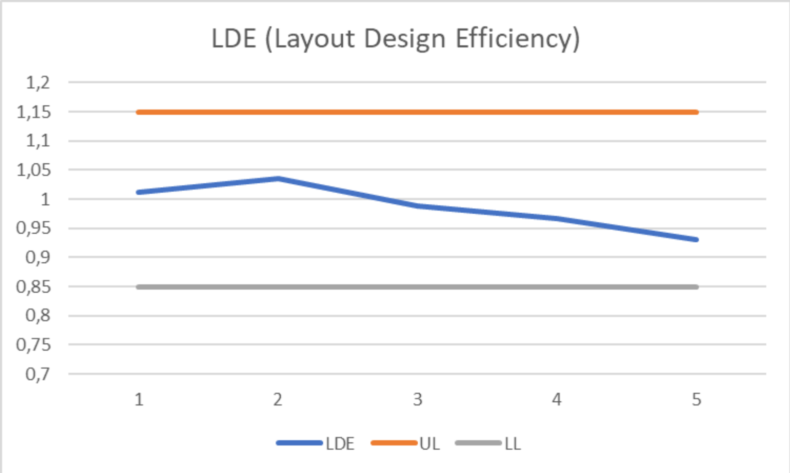

Figure 10: LDE values for 5 periods

In this case, according to the obtained results, reconfiguration of layout design is not necessary. The values of LDE and GE are always inside the limits of the control chart.

5 Final Considerations

The LDE index uses matrix formulation model for layout design. It compares the values of grouping efficiency (GE) for different conditions. From the calculation of the efficiency of clusters for different conditions of use, the efficiency of the project is determined, and it is possible to decide about layout reconfigurable demands.
Results of a case study showed LDE can be used to evaluate layout design in a quantitative criterion, comparing layout efficiency for different conditions of use for manufacturing systems.
LDE values for case study showed the layout reconfiguration is not necessary, during the five periods evaluation. In this case, all the obtained results presented LDE values inside the planned range.
The calculation of Grouping Efficiency (GE) can be changed, if it is necessary to consider the presence of exceptional pieces (%EE) more relevant than the presence of elements “0” inside the BDS. In this case, the weight factor q must assume values major than 0,5.

References

1. ZHAO, Yanlin; LU, Jiansha; YI, Wenchao. A new cellular manufacturing layout: multi-floor linear cellular manufacturing layout. International Journal of Advanced Robotic Systems, [S.L.], v. 17, n. 3, p. 172988142092530, 1 maio 2020. SAGE Publications. http://dx.doi.org/10.1177/1729881420925300.
2. RAMPASSO, Izabela S.; ANHOLON, Rosley; SILVA, Dirceu da; ORDÓÑEZ, Robert E. C.; QUELHAS, Osvaldo L. G.. Maturity analysis of manufacturing cells. Production Planning & Control, [S.L.], v. 30, n. 15, p. 1250-1264, 14 maio 2019. Informa UK Limited.
3. AALAEI, Amin; DAVOUDPOUR, Hamid. A robust optimization model for cellular manufacturing system into supply chain management. International Journal Of Production Economics, [S.L.], v. 183, p. 667-679, jan. 2017. Elsevier BVLNCS Homepage, http://www.springer.com/lncs, last accessed 2016/11/21.
4. ARORA, P K; A HALEEM,; SINGH, M K. Recent development of cellular manufacturing systems. Sadhana, [S.L.], v. 38, n. 3, p. 421-428, jun. 2013. Springer Science and Business Media LLC.
5. BORTOLINI, Marco; GALIZIA, Francesco Gabriele; MORA, Cristina; PILATI, Francesco. Reconfigurability in cellular manufacturing systems: a design model and multi-scenario analysis. The International Journal Of Advanced Manufacturing Technology, [S.L.], v. 104, n. 9-12, p. 4387-4397, 21 ago. 2019. Springer Science and Business Media LLC.
6. DEFERSHA, Fantahun M.; CHEN, Mingyuan. A comprehensive mathematical model for the design of cellular manufacturing systems. International Journal Of Production Economics, [S.L.], v. 103, n. 2, p. 767-783, out. 2006. Elsevier BV.
7. DELGOSHAEI, Aidin; DELGOSHAEI, Armin; ALI, Ahad. Evolution of clustering techniques in designing cellular manufacturing systems: a state-of-art review. International Journal of Industrial Engineering Computations, [S.L.], p. 177-198, 2019. Growing Science.
8. ERNAWATI, D; RAHMAWATI, N; PUDJI, E; SARI, Nk; A WIANTO,. Layout Design in Group Technology Using Cellular Manufacturing System. Journal Of Physics: Conference Series, [S.L.], v. 1569, p. 032012, jul. 2020. IOP Publishing.
9. JAVADIAN, Nikbakhsh; AGHAJANI, Aydin; REZAEIAN, Javad; SEBDANI, Mohammad Javad Ghaneian. A multi-objective integrated cellular manufacturing systems design with dynamic system reconfiguration. The International Journal Of Advanced Manufacturing Technology, [S.L.], v. 56, n. 1-4, p. 307-317, 2 fev. 2011. Springer Science and Business Media LLC.
10. KUSIAK, Andrew. Intelligent Manufacturing Systems. Prentice-Hall. 1990. ISBN = 9780134722344
11. BORTOLINI, Marco; FERRARI, Emilio; GALIZIA, Francesco Gabriele; REGATTIERI, Alberto. An optimisation model for the dynamic management of cellular reconfigurable manufacturing systems under auxiliary module availability constraints. Journal Of Manufacturing Systems, [S.L.], v. 58, p. 442-451, jan. 2021. Elsevier BV.
12. PAPAIOANNOU, Grammatoula; WILSON, John M.. The evolution of cell formation problem methodologies based on recent studies (1997–2008): review and directions for future research. European Journal Of Operational Research, [S.L.], v. 206, n. 3, p. 509-521, nov. 2010. Elsevier BV.