Decision Science Letters 11 (2022) 545–562

Contents lists available at GrowingScience

Decision Science Letters

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Selection of optimum plant layout using AHP-TOPSIS and WASPAS approaches coupled with Entropy method

Anand S. Shivade[a] and Sagar U. Sapkal[a*]

[a]*Department of Mechanical Engineering, Walchand College of Engineering, Sangli. 416415, Shivaji University, Vidyanagar, Kolhapur. 416 004 (MH), India*

C H R O N I C L E

Article history:
Received August 28, 2021
Received in revised format: September 20, 2021
Accepted May 5 2022
Available online May 5, 2022

Keywords:
Unequal area plant layout
MCDM
AHP
TOPSIS
WASPAS
Entropy method
Rank Reversal

A B S T R A C T

Layout design and selection often have notable effects on the performance of the manufacturing industry. This research investigates the Multi-Criteria Decision Making (MCDM) approach to find out the optimum plant layout design. The proposed methodology is demonstrated through the real-life setting for the gearbox manufacturing industry. Manual and computerized layout generation approach is used efficiently and accordingly, six layout designs are generated. The approach takes into account qualitative as well as quantitative performance criteria for the selection of layout design. Analytical Hierarchy Process (AHP) is applied to obtain the weight of qualitative measures. Ranking of alternatives is obtained through the application of Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Weighted Aggregated Sum-Product Assessment (WASPAS) both integrated with the Entropy method. Empirical findings indicate that the rank acquired using the TOPSIS method is perfectly parallel to those acquired through the WASPAS method, which confirms the applicability and potential of these methods. Also, the effect of the parameter λ in WASPAS method on performance score is stable. At the same time, this paper analyses the rank reversal phenomenon and proves that the ranking proposed by TOPSIS satisfies ranking stability.

1. Introduction

Plant layout is an arrangement of sections, subsections, departments, stations and storage space within the existing or proposed facility. The effective layout of the industry is of enormous significance for its effective use. Therefore to meet the required effectiveness, setup should be able to quickly shift gears from one product to another without major alterations regarding available resources. Manufacturing industries producing the standard product such as gearbox require a lot of variation in the product and at the same time should be able to fulfil the growing demands in the market. The layout is classified as static, dynamic, multi-objective, multi-floor, equal area and unequal area. Among these, the design and selection of unequal area facility layout problems are the most critical task. This problem considers a set of rectangular areas and rectangular sub-areas (manufacturing facilities) and should be positioned so that they do not overlap in the production region. The selection of appropriate layout design is a Multi-Criteria Decision Making (MCDM) approach. This approach requires consideration of the qualitative and quantitative criteria, jointly. Qualitative measures include layout flexibility, maintenance, accessibility, human issue, plant safety and information flow while quantitative measures include layout cost or material handling cost, adjacency score i.e. closeness request, distance score, aspect ratio and production volume (Aiello et al., 2012; Yang & Kuo, 2003). A proper plant layout can improve efficiency and reduce material handling costs. Singh & Sharma (2006) focused on current and future research trends on layout problems of formulations and solution

* Corresponding author.
E-mail address: sagarus1201@gmail.com (S. U. Sapkal)

doi: 10.5267/dsl.2022.5.002

methodologies. Pérez-Gosende et al. (2021) reviewed literature and performed an analysis based on manufacturing facility characteristics by configuring layout types, layout planning steps, material handling systems, and generation and evaluation of alternatives. Systematic Layout Planning (SLP) is a procedural approach and is successfully applied to solve real life problems of manufacturing industries to improve plant layout (Naqvi et al., 2016; Wiyaratn & Watanapa, 2010).

The construction algorithmic approach such as Automated Layout Design Program (ALDEP), Computerised Relationship Layout Planning (CORELAP) and BLOCPLAN has been proposed to create layout design alternatives (Hakim & Istiyantri, 2015; Rajesh et al., 2016; Tambunan et al., 2018). Hari Prasad et al. (2014) tackled the existing layout situation using the Computerized Relative Allocation of facilities Technique (CRAFT) approach for layout cost optimization. In addition commercial software like spiral and algorithms, Plant Layout Analysis and Evaluation Technique (PLANET), Computerised Facility Design (COFAD) were developed to resolve single floor layout problem whereas for multi floor design, Multi-floor Plant Layout Evaluation (MULTIPLE), Micro CRAFT (MCRAFT), Layout Optimization with Guillotine Induced Cuts (LOGIC) have been introduced by Hadi-vencheh & Mohamadghasemi (2013) and Moatari-Kazerouni et al. (2015).

Abdul-Hamid et al. (1999) presented AHP approach to select an appropriate layout design by considering three objectives viz. flexibility, production volume and manufacturing costs. Yang & Kuo (2003) in their YK model, proposed AHP and Data Envelopment Analysis (DEA) approach for ranking layout design. Also, Ertay et al. (2006) presented a similar methodology to rank the facility layout design. Case studies on railway system improvement and optimization using AHP/DEA methodology with computer simulation are reported by Azadeh et al. (2008). Yang & Hung (2007) applied the TOPSIS & fuzzy TOPSIS approach for layout design ranking and compared their results with the YK model. Sharma & Singhal (2017) applied fuzzy TOPSIS for selection of the best procedural approach of layout design. Agarwal & Singholi (2018) analysed AHP-TOPSIS and Fuzzy AHP- Fuzzy TOPSIS approach for alternative layout designs and compared with the existing design. Yang et al. (2013) used rough set theory, AHP and TOPSIS to choose the best energy efficient layout design alternative among the proposed layouts. Hadi-vencheh & Mohamadghasemi (2013) proposed NonLinear Programming model (NLP) in correlation with AHP to solve the facility layout problem. Kong (2011) studied the causes of rank reversal in TOPSIS and proposed subjective preferences set by decision-makers that helps for more scientific decision-making. Aires & Ferreira (2019) defined a framework to evaluate the TOPSIS method and suggested models related to the different cases of rank reversal. García-Cascales & Lamata (2012) studied the causes of rank reversal in the TOPSIS related to the normalization method. There is a scope for applying improved methods such as AHP-TOPSIS and WASPAS by integrating with the Entropy method for selection of optimum layout design for the problem under consideration i.e. modification of plant layout of the gearbox manufacturing industry. It is worth mentioning that no literature reported on rank reversal related to layout selection. The present study is focused on finding the optimum layout design for the unequal area and irregular shape department of a gearbox manufacturing plant by considering both qualitative and quantitative measures. Section 1 consists of an introduction and literature survey. Section 2 includes data collection and analysis of existing layout. Section 3 articulates generation of alternative layouts. In Section 4, the details of performance measures and application of the AHP approach are presented. Section 5 analyses two MCDM approaches for optimum layout selection. Section 6 proposes a rank reversal study. Section 7 highlights the conclusion related to this study.

2. Data collection and existing plant layout

The industry manufactures standard as well as custom range planetary gearbox of various models. The list of various departments and the area requirement for each department is summarized in Table 1. A block layout of the existing plant layout of these 14 departments is as shown in Fig. 1. The industry is facing a shortage of supply of products that lead to not satisfying the demands and thus the scope is identified in terms of modification and optimization of the layout. It has been analysed that there is a necessity for improving the existing plant layout by applying systematic approaches that will lead to improving productivity with effective utilization of resources. Various alternatives have been studied for comparison and for suggesting the optimum solution.

Table 1
Departments and their area

Sr. No.	Name of Department	Area
0	Office	660.00
1	Raw material store-A	2625.00
2	Raw material store-B	450.00
3	Fabrication shop	392.00
4	Machine shop	9646.00
5	Quality control	1802.00
6	Store	3131.25
7	Cleaning and lapping	148.50
8	Assembly shop	1772.25
9	Test Running	1002.00
10	Painting shop	420.75
11	Packing shop	198.00
12	Dispatch	357.00

13	Maintenance	470.25

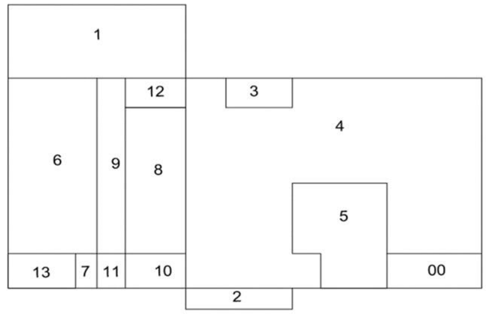

Fig. 1. Existing plant layout

3. Generation of alternative layout designs

3.1 SLP approach

By using the SLP approach the layout is generated as mentioned below. For different sections/ activities of production of a single gearbox, From-To-Chart as shown in the Table 2 is constructed which represents the interaction between departments and rectilinear distance. By the addition of these, flow distance in the existing situation is 960.11 feet.

Table 2
From-To-Chart for existing layout

From/To	1	2	3	4	5	6	7	8	9	10	11	12	13
1.Raw material store-A	0	0	0	159.68	0	0	0	0	0	0	0	0	0
2.Raw material store-B	0	0	0	88.04	0	0	0	0	0	0	0	0	0
3.Fabrication shop	0	0	0	66.68	0	0	0	0	0	0	0	0	0
4.Machine shop	0	0	0	0	35.01	0	0	0	0	0	0	0	0
5.Quality control	0	0	0	35.01	0	154.19	0	0	0	0	0	0	0
6.Store	0	0	0	0	0	0	64.25	50.5	0	0	0	0	0
7.Cleaning and lapping	0	0	0	0	0	64.25	0	0	0	0	0	0	0
8.Assembly shop	0	0	0	0	0	0	0	0	25.75	0	0	0	0
9.Test Running	0	0	0	0	0	0	0	25.75	0	68.75	0	0	0
10.Painting shop	0	0	0	0	0	0	0	0	0	0	18.75	0	0
11.Packing shop	0	0	0	0	0	0	0	0	0	0	0	103.5	0
12.Dispatch	0	0	0	0	0	0	0	0	0	0	0	0	0
13.Maintenance	0	0	0	0	0	0	0	0	0	0	0	0	0

In the present study, for identifying the relative importance between the departments and for selecting the reasons of the closeness for the departments, the opinions of industry experts are taken into account. Table 3 summarizes the different reasons for closeness of the departments.

Table 3
Reasons for closeness

Sr. No.	Reason
1	Material flow
2	Supervision and control
3	Share the same personnel
4	Communication need

To decide the ranking of the relationship between departments, the ranking system mentioned by Muther & Hales (2015) is used and is reported in Table 4.

Table 4
Closeness values and their rating of the relationship chart

Value	Closeness	Rating	Colour Code	Meaning
A	Absolutely necessary	6		Must be next to each other
E	Especially important	5		Need to be very close
I	Important	4		Need to be on same floor, side or wing
O	Ordinary closeness Okay	3		Occasional interaction.
U	Unimportant	2		Infrequent interaction.

X	Not Desirable	1		Keep separate and away

Based on the reasons for closeness, the relationship chart is presented in Fig. 2.

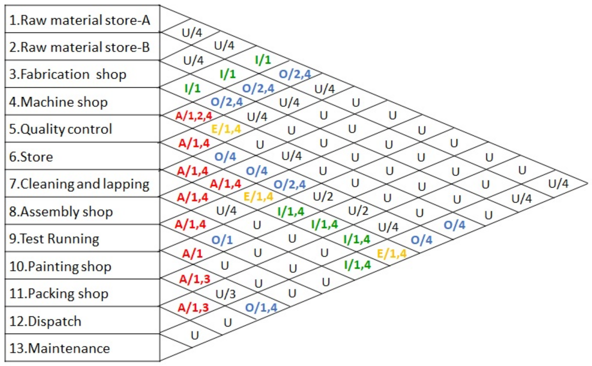

Fig. 2. Relationship chart

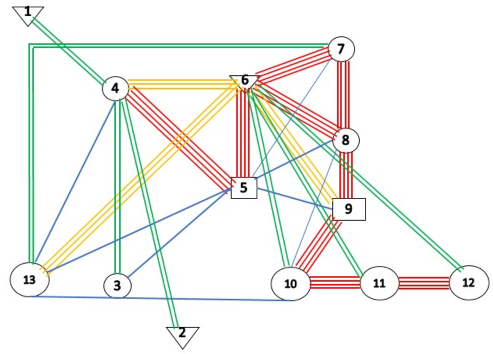

Fig. 3. Activity relationship diagram

Accordingly, activity relationship diagram (Fig. 3) and space relationship diagram (Fig. 4), are developed.

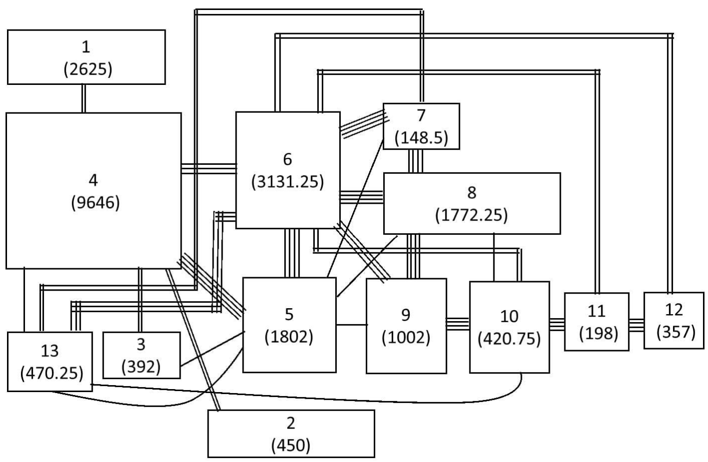

Fig. 4. Space Relationship Diagram

For designing the layout based on SLP method, the following requirements are considered.

1. Location of office, raw material store A and raw material store B are kept as it is.
2. Location of quality control and maintenance department is kept at the outer side of layout for ease of loading and unloading of semi-finished material came from vendors and gearboxes came for maintenance purpose. After applying all conditions, layout alternative is developed (Fig. 5).

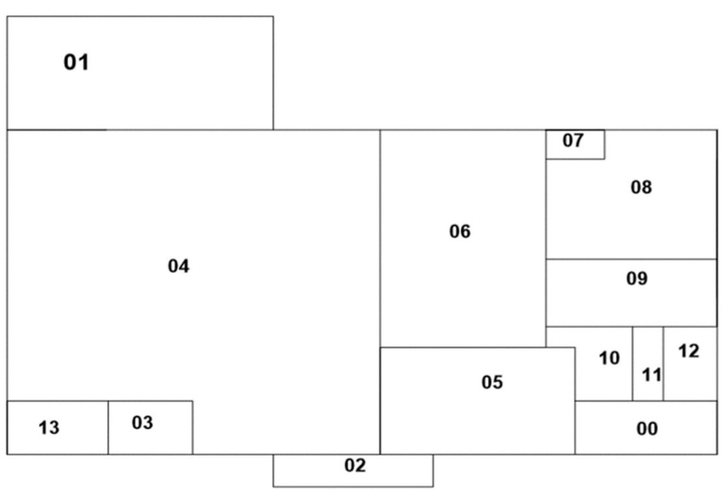

Fig. 5. Layout based on SLP method

3.2 Flow patterns

Based on the flow patterns, we generate two layout designs as S flow pattern (Fig. 6) and U flow pattern (Fig. 7). In these designs, the arrangement of departments is made as per the operations sequence and production tasks.

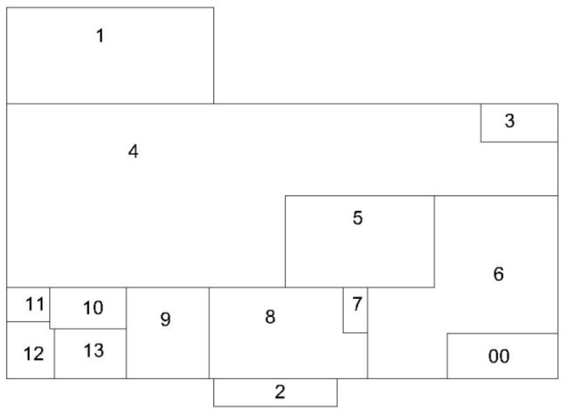

Fig. 6. Layout based on "S" shaped flow pattern

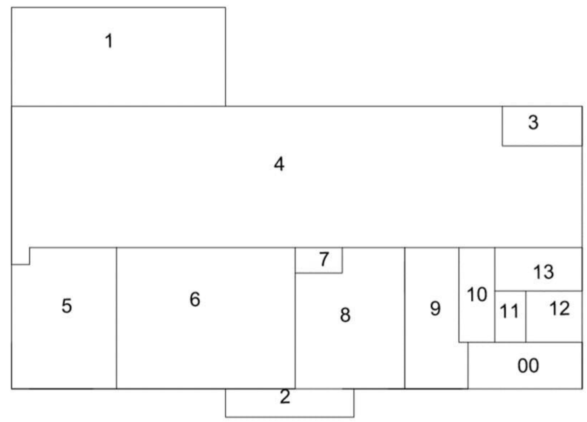

Fig. 7. Layout based on "U" shaped flow pattern

3.3 ALDEP algorithm

This approach constructs the design by putting the departments in the layout successively. A layout score is calculated after putting all the departments. Table 5 shows the symbols and values mentioned by Panneerselvam (2017) to indicate the degree of closeness between departments.

Table 5
Symbols and values of Closeness

Closeness	Notations	Value
Absolutely necessary	A	64
Especially important	E	16
Important	I	4
Ordinary closeness Okay	O	1
Unimportant	U	0
Not Desirable	X	-1064

In the layout matrix, placement of department is from upper left corner to lower right corner whereas sweep width is user defined. In the present study, considering sweep width 5, minimum department preference is A, E and I, layout matrix size is 55 × 40 and 1 Cell equals to 9.09 Square Feet. Table 6 indicates the number of the squares for all the departments.

Table 6
Department and number of squares

Department No.	0	1	2	3	4	5	6	7	8	9	10	11	12	13
No. of Square	73	289	50	43	1061	198	345	16	195	110	46	22	39	52

In the first design, layout generation starts from a random selection of departments (department No.3). Department No. 4 has an "A" relationship with department No. 3, therefore its placement is next to department 3. Similarly, departments 5,6,7,8,9,10,11 and 12 has "A" relationship with departments 4,5,6,7,8,9,10 and 11, respectively, so they are placed next to previously placed departments. In the placement sequence, only department 13 is left which is placed at last and accordingly layout is generated as shown in Fig. 8. Applying the same procedure, ten alternative layouts are generated. After the generation of alternative layout designs, layout score is computed. Table 7 displays the closeness rating between the departments and the layout score of the first alternative. Similarly, for the remaining ten layout designs, the computed score is listed in Table 8.

Table 7
Closeness of department and layout score

Department	3-4	4-5	4-6	5-6	6-10	6-7	6-8	7-8	7-9	8-9	9-10	9-11	9-12	9-13	10-11	11-12	12-13	6-9	Layout score
Closeness	I	A	E	A	I	A	A	A	U	A	A	U	U	U	A	A	U	E	

Value	4	64	16	64	4	64	64	64	0	64	64	0	0	0	64	64	0	16	**616**

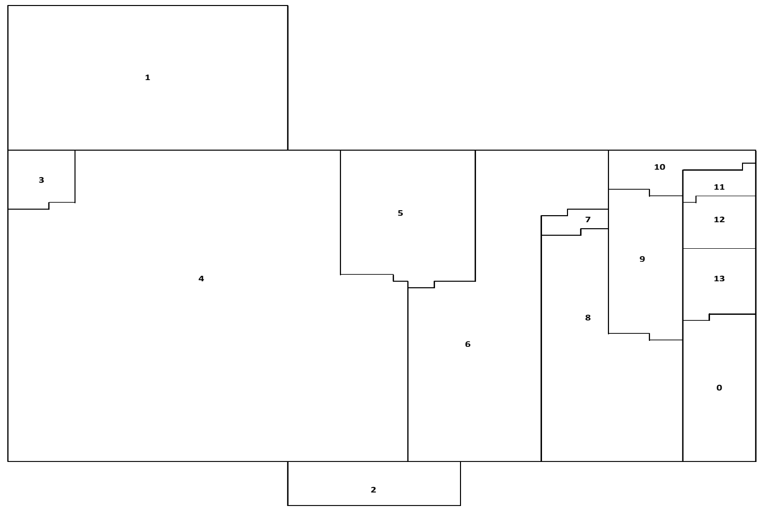

Fig. 8. Layout generated by ALDEP

Table 8
Alternative layout score and respective rank

Alternative Layout	Sequence	Score	Rank
1	3-4-5-6-7-8-9-10-11-12-13	616	1
2	4-5-6-7-8-9-10-11-12-13-3	594	3
3	5-4-6-7-8-9-10-11-12-13-3	530	8
4	6-5-4-3-7-8-9-10-11-12-13	468	9
5	7-8-9-10-11-12-6-5-4-3-13	562	4
6	8-6-7-13-9-10-11-12-5-4-3	438	10
7	9-10-11-12-6-7-8-5-4-3-13	546	6
8	10-11-12-6-7-8-9-5-4-3-13	547	5
9	11-12-6-5-4-3-13-7-8-9-10	418	11
10	12-11-10-9-8-7-6-5-4-3-13	616	2
11	13-6-7-8-9-10-11-12-5-4-3	535	7

The alternative of having a maximum score is to be considered as the solution. Table 7 shows the maximum score as 616, but it is for two alternatives 1 and 10. To resolve this tie for selection of the first rank, total flow distance and practical limitations are considered and based on that alternative is ranked as 1.

3.4 CRAFT algorithm

The first alternative (Fig. 8) developed from ALDEP is considered as the existing layout (starting point). Possible pairwise interchanges of the departments are taken into account. For all these pairs, assuming 1 trip per hour and ₹1 per trip, layout cost is calculated using Eq. (1) given by Deshpande et al. (2016).

$$\min z = \sum_{i=1}^{m} \sum_{j=1}^{m} f_{ij} c_{ij} d_{ij} \tag{1}$$

where,

z is layout cost per hour
m is number of the department
f_{ij} is the number of trips between departments i and j
c_{ij} is the cost to make one trip between departments i and j
d_{ij} is the distance from department i to j

After carrying pairwise interchange for possible departments, the interchange of departments 6 and 7 gives the minimum cost of ₹ 739.07. This cost is less than the cost ₹ 960.11 of the existing layout. This change is accepted and accordingly the interchange of the selected pair of the departments is done. In the second iteration, possible interchanges are identified and the computed costs for each interchange are summarized in Table 9.

Table 9
Pairwise interchange and respective cost

Pair No.	Pairwise interchange	Cost per hour	Pair No.	Pairwise interchange	Cost per hour	Pair No.	Pairwise interchange	Cost per hour
1	3-4	749.26	7	7-6	739.07	13	9-11	883.16
2	4-5	855.44	8	6-10	1024.28	14	9-12	875.06
3	4-7	1113.15	9	6-9	940.30	15	9-13	1024.92
4	4-6	930.21	10	6-8	858.96	16	10-11	802.99
5	5-6	845.95	11	8-9	770.19	17	11-12	797.97
6	5-7	768.83	12	9-10	871.19			

From Table 9 it is clear that the costs pair-wise interchange is least for pair No.7 and therefore, this is considered as stopping criteria for the algorithm. The solution in term of layout from the CRAFT algorithm is shown in Fig. 9.

Fig. 9. Layout generated by CRAFT

3.5 CORELAP method

Using the relationship chart, Total Closeness Rating (TCR) is computed for all the departments. Relationship between departments in the existing layout is shown in Table 10 while TCR and rank of each department are shown in Table 11.

Table 10
Relationship of department

Department	3	4	5	6	7	8	9	10	11	12	13
3.Fabrication shop	-	I/1	O/2,4	U/4	U	U	U	U	U	U	U
4.Machine shop	I/1	-	A/1,2,4	E/1,4	U	U/4	U	U	U	U	O/4
5.Quality control	O/2,4	A/1,2,4	-	A/1,4	O/4	O/4	O/2,4	U/2	U/2	U/4	O/4
6.Store	U/4	E/1,4	A/1,4	-	A/1,4	A/1,4	E/1,4	I/1,4	I/1,4	I/1,4	E/1,4
7.Cleaning and lapping	U	U	O/4	A/1,4	-	A/1,4	U/4	U	U	U	I/1,4
8.Assembly shop	U	U/4	O/4	A/1,4	A/1,4	-	A/1,4	O/1	U	U	U
9.Test Running	U	U	O/2,4	E/1,4	U/4	A/1,4	-	A/1	U	U	U
10.Painting shop	U	U	U/2	I/1	U	O/1	A/1	-	A/1,3	U/3	O/1,4
11.Packing shop	U	U	U/2	I/1	U	U	U	A/1,3	-	A/1,3	U
12.Dispatch	U	U	U/4	I/1	U	U	U	U/3	A/1,3	-	U
13.Maintenance	U	O/4	O/4	E/1,4	I/1,4	U	U	O/1,4	U	U	-

Table 11
TCR values and placement sequence

Department	3	4	5	6	7	8	9	10	11	12	13	TCR	Placement Sequence
3.Fabrication shop	0	4	3	2	2	2	2	2	2	2	2	23	11
4.Machine shop	4	0	6	5	2	2	2	2	2	2	3	30	7
5.Quality control	3	6	0	6	3	3	3	2	2	2	3	33	3
6.Store	2	5	6	0	6	6	5	4	4	4	5	47	1
7.Cleaning and lapping	2	2	3	6	0	6	2	2	2	2	4	31	6
8.Assembly shop	2	2	3	6	6	0	6	3	2	2	2	34	2
9.Test Running	2	2	3	5	2	6	0	6	2	2	2	32	4
10.Painting shop	2	2	2	4	2	3	6	0	6	2	3	32	5
11.Packing shop	2	2	2	4	2	2	2	6	0	6	2	30	8
12.Dispatch	2	2	2	4	2	2	2	2	6	0	2	26	10
13.Maintenance	2	3	3	5	4	2	2	3	2	2	0	28	9

As an illustration, the department No.6 (store) has the largest TCR, so it is selected at first place in placement order. In second place, the department No.5 having the strongest relationship with the department No.6 is placed. This is repeated for placing the remaining departments in placement sequence and accordingly placement order is generated as 6-5-8-7-4-9-13-10-11-12-3. As per placement rule of CORELAP, department No.6 (first in the sequence) is placed at the center of layout. The department No.5 (second in the sequence) is kept adjacent to department No.6. For placing department No.8 which is at third place in sequence, three combinations are possible. Therefore, based on maximum Placement Rating (PR) the position of department No. 8 in the sequence is decided. PR is expressed in terms of the sum of the weighted closeness rating and their values are mentioned in Table 12 as taken from Panneerselvam (2017).

Table 12
Weighted closeness rating values

Closeness relationship	Pre-assigned	A	E	I	O	U	X
Weighted Rating	729	243	81	27	9	1	-729

PR calculation in the present study is illustrated as follows. In the first arrangement, department No. 8 is placed adjacent to department No. 6 then the closeness relationship between them is "A" having weighted rating 243. Similarly, in the second arrangement department No. 8 is placed adjacent to departments No. 6 and department No. 5, hence, the close relationship between them is "A" and "O" while weighted rating is 243 and 9 which gives PR equal to 243 + 9 = 252. As per the third arrangement, department No. 8 can be placed adjacent to department No. 5, then the closeness relationship between them is "O" whereas weighted rating is 9. Based on maximum PR the second arrangement is considered. These steps of identifying the closeness and calculating the placement rating are repeated for the placement of remaining departments and accordingly a new layout as shown in the Fig. 10 is generated.

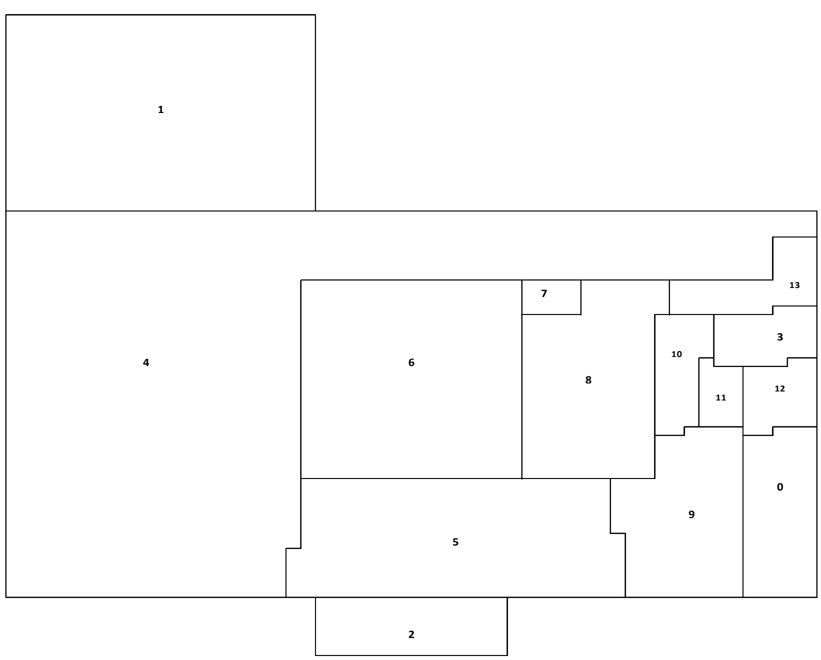

Fig. 10. Layout generated by CORELAP

4. Performance measures and AHP method

To evaluate the performance of the generated layouts, various metrics such as flow distance, adjacency score, aspect ratio, production volume, cost of the manufactured component, flexibility, accessibility, maintenance, human issue, information flow, machine reconfigurability, and quality factors are available in the literature (Abdul-Hamid et al., 1999; Agarwal & Singholi, 2018; Aiello et al., 2012; Goyal et al., 2012). Based on expert advice from the industry and based on literature study, the qualitative performance measures selected are flexibility, accessibility, maintenance, and human issue and quantitative performance measures considered are flow distance and adjacency score. The objectives are to minimize flow distance and to maximize remaining five performance measures. For finding the value of the qualitative measures, AHP method which has certain advantages as mentioned by Ertay et al. (2006) is applied. The decision hierarchy of AHP in this case is shown in Fig. 11. The terms A1, A2, A3, A4, A5, and A6 are used for layout generated by SLP, "S" type flow, "U" type flow, ALDEP, CRAFT and CORELAP, respectively.

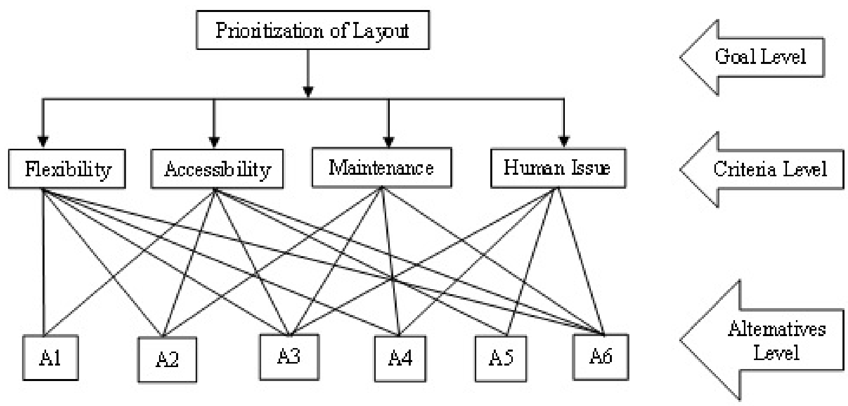

Fig. 11. Decision hierarchy for qualitative criteria in the layout selection

In the layout design problem, all the performance measures will not have the same importance. Therefore, a pairwise comparison is applied in the second step to determine the comparative significance of the performance and alternatives (layouts) according to their influences. Construction of a comparative matrix by a pairwise comparison based on designer preference can be done using a numerical scale shown in Table 13 as mentioned in Yang & Kuo, (2003).

Table 13
Nine-point intensity of importance scale

Intensity of Importance	Definition
1	Equal Importance
3	Moderate Importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values between the two adjacent judgments

The comparison matrices for all the four criteria are generated using numerical scale values. The matrix for flexibility criteria is shown in Table 14 as an example.

Table 14
Pairwise comparison matrix of flexibility

Alternative	A1	A2	A3	A4	A5	A6
A1	1	3	3	7	7	7
A2	1/3	1	3	5	5	5
A3	1/3	1/3	1	5	5	3
A4	1/7	1/5	1/5	1	1/3	1/3
A5	1/7	1/5	1/5	3	1	2
A6	1/7	1/5	1/3	3	1/2	1

After developing the comparison matrix, normalization is done. For example, in the case of alternative 1, the normalised value is calculated as 1/ (1+ 0.33 + 0.33 + 0.14 + 0.14 + 0.14) = 0.477. Subsequently arithmetic mean is computed that gives criteria weight. For alternative 1 criteria weight equal to (0.477 + 0.608 + 0.388 + 0.292 + 0.372 + 0.382) / 6 = 0.420. Table 15 displays a normalized matrix and criteria weight for flexibility criteria.

Table 15
Normalised matrix and criteria weight

Alternative	A1	A2	A3	A4	A5	A6	Criteria weight
A1	0.477	0.608	0.388	0.292	0.372	0.382	0.420
A2	0.159	0.203	0.388	0.208	0.265	0.273	0.249
A3	0.159	0.068	0.129	0.208	0.265	0.164	0.166
A4	0.068	0.041	0.026	0.042	0.018	0.018	0.035
A5	0.068	0.041	0.026	0.125	0.053	0.109	0.070
A6	0.068	0.041	0.043	0.125	0.027	0.055	0.060

Then, weighted sum is the sum of product of each value in a pairwise comparison matrix to criteria weight of the corresponding alternative. For example, in case of alternative 1, the weighted sum equals (0.420 ×1) + (0.249 ×3) + (0.166 × 3) + (0.035 ×7) + (0.070 ×7) + (0.060 ×7) = 2.82. This weighted sum is divided by criteria weight for computation of weighted priority. In case of flexibility criteria, weighted priority of alternative 1 equal to (2.82 / 0.420) = 6.722. In the same manner, weighted priority is calculated for all criteria and alternatives. Subsequently, averaging the results of each row is done which gives the maximum eigenvalue (λ max). For flexibility, λ max is calculated as (6.722 + 6.867 + 6.618 + 6.269 + 6.240 + 6.134) / 6 = 6.475. Similarly, λ max for the remaining three qualitative measures are computed and listed in Table 16.

Table 16
Criteria and respective eigenvalues (λ max)

Criteria	Flexibility	Accessibility	Maintenance	Human Issue
λ max	6.475	6.383	6.354	6.465

The Consistency Index (CI) is expressed by Eq. (2).

$$(\mathrm{CI}) = \frac{(\lambda_{\mathrm{Max}} - \mathrm{n})}{(\mathrm{n} - 1)} \tag{2}$$

where n is the number of compared alternatives. In case of flexibility, λmax is 6.475 and n is 6. Using Equation 2, CI equals to (6.475 - 6) / (6 - 1) = 0.095. Similarly, for remaining criteria, CI are computed (Table 17).

Table 17
Criteria and respective CI values

Criteria	Flexibility	Accessibility	Maintenance	Human Issue
CI	0.095	0.077	0.071	0.093

Consistency Ratio (CR) is computed by

$$(\mathrm{CR}) = \frac{(\mathrm{CI})}{(\mathrm{RI})} \tag{3}$$

Random index (RI) for different attributes (n) are listed in Table 18. When CR is greater than 0.1, this procedure is repeated to improve consistency (Hadi-vencheh & Mohamadghasemi, 2013).

Table 18
Random Index values for different values of n

n	3	4	5	6	7	8	9	10
RI	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

For example, CR for flexibility is equal to 0.095/1.24 = 0.077 and thus the CR values for all the criteria are computed and are listed in Table 19.

Table 19
Criteria and CR values

Criteria	Flexibility	Accessibility	Maintenance	Human Issue
CR	0.077	0.062	0.057	0.075

Since all CR values are not greater than 0.1, the findings are acceptable and show the goodness of the decisions. The values of quantitative performance measures are measured from layout designs discussed in previous section 3. The values of quantitative and qualitative measures under consideration are reported in Table 20.

Table 20
Performance measures values for layout alternatives

Layout Alternative	Quantitative Performance		Qualitative Performance			
	Flow Distance	Adjacency Score	Flexibility	Accessibility	Maintenance	Human Issue
A1	816.76	616	0.224	0.106	0.026	0.056
A2	834.17	599	0.133	0.074	0.018	0.039
A3	875.81	598	0.088	0.040	0.010	0.021
A4	777.69	616	0.019	0.015	0.002	0.006
A5	739.07	553	0.038	0.009	0.005	0.005
A6	900.88	597	0.032	0.019	0.004	0.010

5. Optimum layout design

For the selection of optimum layout design, MCDM methods namely TOPSIS and WASPAS are applied this case for determining the best solution amongst these six alternatives.

5.1 TOPSIS method coupled with Entropy method

For finding out the positive ideal solution and the negative ideal solution in the TOPSIS method the procedure mentioned by Behzadian et al. (2012) is adopted. After forming an initial decision matrix (Table 20), each element is normalized by Eq. (4).

$$r_{ij} = \frac{x_{ij}}{\sqrt{\Sigma x_{ij}^2}} \qquad \text{For } i = 1, \dots\dots, m;\ j = 1, \dots\dots, n \tag{4}$$

where x_{ij} and r_{ij} are the original and normalized values. For example, the normalised value of flow distance for alternative No.1 is calculated as,

$$r_{ij} = \frac{816.76}{\sqrt{816.76^2 + 834.17^2 + 875.81^2 + 777.69^2 + 739.07^2 + 900.88^2}} = 0.4037330$$

For remaining alternatives and criteria, normalized values are computed and reported in Table 21.

Table 21
Normalized decision matrix for TOPSIS

Alternative	Flow Distance	Adjacency Score	Flexibility	Accessibility	Maintenance	Human Issue
A1	0.4037330	0.4213320	0.8000000	0.7681159	0.7647059	0.7671233
A2	0.4123390	0.4097043	0.4750000	0.5362319	0.5294118	0.5342466
A3	0.4329221	0.4090203	0.3142857	0.2898551	0.2941176	0.2876712
A4	0.3844203	0.4213320	0.0678571	0.1086957	0.0588235	0.0821918
A5	0.3653301	0.3782412	0.1357143	0.0652174	0.1470588	0.0684932
A6	0.4453144	0.4083364	0.1142857	0.1376812	0.1176471	0.1369863

The weighted normalized decision matrix (v_{ij}) is given by Eq. (5).

$$v_{ij} = w_j r_{ij} \tag{5}$$

Weights of individual criteria are found by Entropy method (applied by Chen et al., 2014 for food industry). Normalizing decision matrix (Table 21) is again normalized by using Eq. (6).

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m}(x_{ij})} \tag{6}$$

where x_{ij} and r_{ij} are the initial and normalized values. For example for cell (1,1) the value by entropy method is equal to (0.4037330) / (0.4037330 + 0.4123390 + 0.4329221 + 0.3844203 + 0.3653301 + 0.4453144) = 0.1651896. In this way the other values mentioned in the Table 22 are calculated.

Table 22
Normalized decision matrix for Entropy method

Alternative	Flow Distance	Adjacency Score	Flexibility	Accessibility	Maintenance	Human Issue
A1	0.1651896	0.1721151	0.4194757	0.4030418	0.4000000	0.4087591
A2	0.1687107	0.1673652	0.2490637	0.2813688	0.2769231	0.2846715
A3	0.1771324	0.1670858	0.1647940	0.1520913	0.1538462	0.1532847
A4	0.1572877	0.1721151	0.0355805	0.0570342	0.0307692	0.0437956
A5	0.1494768	0.1545124	0.0711610	0.0342205	0.0769231	0.0364964
A6	0.1822028	0.1668064	0.0599251	0.0722433	0.0615385	0.0729927

After normalization, next step is to calculate entropy value (e_j) which is calculated using Eq. (7).

$$e_j = -h\sum_{i=1}^{m} r_{ij}\ln r_{ij} \quad (7)$$

where, h = 1/ln (m) and m is number of criteria. Here m is 6, therefore h = 1/ln (6) = 0.5581. Using Eq. (7), entropy value of flow distance equal to -0.5581 × [(0.1651896 + ln 0.1651896) + (0.1687107 + ln 0.1687107) + (0.1771324 + ln 0.1771324 + (0.1572877 + ln 0.1572877) + (0.1494768 + ln 0.1494768) + (0.1822028+ ln 0.1822028)] = 0.9987357 and similarly other entropy values are computed and are summarized in Table 23.

Table 23
Entropy values

Criteria	Flow Distance	Adjacency Score	Flexibility	Accessibility	Maintenance	Human Issue
e_j	0.9987357	0.9996279	0.8277693	0.8249606	0.8293663	0.8146639

Weight factor (w_j) for each criteria is determined by Eq. (8).

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{n}(1 - e_j)} \quad (8)$$

According to Table 23, entropy value (e_j) of flow distance is 0.9987357. Using Eq. (8), weight of flow distance is equal to (1 - 0.9987357) / (1 - 0.9987357) + (1 - 0.9996279) + (1- 0.8277693) + (1- 0.8249606) + (1- 0.8293663) + (1- 0.8146639) = 0.0017936 and similarly weight factors as reported in Table 24 are calculated.

Table 24
Weight factors

Criteria	Flow Distance	Adjacency Score	Flexibility	Accessibility	Maintenance	Human Issue
w_j	0.0017936	0.0005279	0.2443418	0.2483265	0.2420762	0.2629343

By considering these weighted factors, the weighted normalized decision matrix along with positive and negative ideal solutions A* and A' (calculated by using Equations 9 and 10) are summarized in Table 25.

$$A^* = \{v_1^*, \dots, v_n^*\}, \text{Where}, v_j^* = \{\max(v_{ij}) \text{ if } j \in J; \min(v_{ij}) \text{ if } j \in J'\} \quad (9)$$
$$A' = \{v_1', \dots, v_n'\} \quad \text{Where}, v' = \{\min(v_{ij}) \text{ if } j \in J; \max(v_{ij}) \text{ if } j \in J'\} \quad (10)$$

Table 25
Weighted normalized decision matrix with positive and negative ideal solution

Alternative	Flow Distance	Adjacency Score	Flexibility	Accessibility	Maintenance	Human Issue
A1	0.0007241	0.0002224	0.1954734	0.1907435	0.1851171	0.2017030
A2	0.0007422	0.0002163	0.1160624	0.1331606	0.1281580	0.1404717
A3	0.0007793	0.0002159	0.0767931	0.0719787	0.0711989	0.0756386
A4	0.0006920	0.0002224	0.0165803	0.0269920	0.0142398	0.0216110
A5	0.0006576	0.0001997	0.0331607	0.0161952	0.0355994	0.0180092
A6	0.0008016	0.0002156	0.0279248	0.0341899	0.0284796	0.0360184
A*	0.0006576	0.0002224	0.1954734	0.1907435	0.1851171	0.2017030
A'	0.0008016	0.0001997	0.0165803	0.0161952	0.0142398	0.0180092

The separation from the positive ideal alternative is given by

$$S_i^* = [\Sigma(v_j^* - v_{ij})^2]^{\frac{1}{2}} \;\; i = 1, \dots, m \quad (11)$$

The separation from the negative ideal alternative is given by

$$S_i' = [\Sigma(v_j' - v_{ij})^2]^{\frac{1}{2}} \;\; i = 1, \dots., m \quad (12)$$

For alternative No.1, separation of positive ideal solution is equal to [(0.0007241 - 0.0006576) ^2 + (0.0002224 - 0.0002224) ^2 + (0.1954737- 1954734) ^2 + (0.1907435 - 0.1907435) ^2 + (0.1851171 - 0.1851171) ^2 + (0.2017030 - 0.2017030) ^2] ^0.5 = 0.0000844 and the entire results are shown in Table 26. Also, the relative closeness coefficient of each alternative is calculated by using Eq. (13).

$$C_i^* = S_i' \Big/ (S_i^* + S_i'), \quad 0 < C_i^* < 1 \tag{13}$$

For alternative No.1, (C_i^*) is equal to 0.3541389 / (0.0000844 + 0.3541389) = 0.9997618 and these results are also shown in Table 26.

Table 26
Separation measures of positive and negative ideal solutions, relative closeness and rank

Alternative	Separation measure of positive ideal solution (S_i^*)	Separation measure of negative ideal solution (S_i')	Relative closeness (C_i^*)	Rank
A1	0.0000844	0.3541389	0.9997618	1
A2	0.1288671	0.2270534	0.6379329	2
A3	0.2388398	0.1153409	0.3256555	3
A4	0.3470268	0.0113847	0.0317644	6
A5	0.3359901	0.0270407	0.0744859	5
A6	0.3233384	0.0313014	0.0882626	4

Larger relative closeness (C_i^*) value shows the optimum alternative for all the performance measures under consideration. So from Table 26, it is clear that alternative 1 is having maximum relative closeness value and hence is the optimum solution of TOPSIS coupled with entropy method.

5.2 WASPAS method coupled with Entropy method

WASPAS method is a unique combination Weighted Sum Method (WSM) and Weighted Product Method (WPM) and is useful to improve ranking accuracy. The application of WASPAS method (illustrated by Chakraborty & Zavadskas, 2014 for manufacturing decision making) is applied in this case as follows. For the initial decision matrix (Table 20), normalization of beneficial and non-beneficial criteria are done. For beneficial criteria,

$$r_{ij} = \frac{x_{ij}}{\max_i x_{ij}} \quad i = 1,2,\dots,m \text{ and } j = 1,2,\dots,n \tag{14}$$

For non-beneficial criteria,

$$r_{ij} = \frac{\min_i x_{ij}}{x_{ij}} \quad = 1,2,\dots,m \text{ and } j = 1,2,\dots,n \tag{15}$$

where x_{ij} and r_{ij} are the original and normalized values. Flow distance is non beneficial criteria and its minimum value is 739.07 which is for alternative No. 5. For example, the normalized value of alternative No. 1 is equal to 739.07/816.76 = 0.9048803. Similarly, normalized values for remaining performance measures and alternative are computed and listed in Table 27.

Table 27
Normalised decision matrix for WASPAS method

Alternative	Flow Distance	Adjacency Score	Flexibility	Accessibility	Maintenance	Human Issue
A1	0.9048803	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000
A2	0.8859945	0.9724026	0.5937500	0.6981132	0.6923077	0.6964286
A3	0.8438702	0.9707792	0.3928571	0.3773585	0.3846154	0.3750000
A4	0.9503401	1.0000000	0.0848214	0.1415094	0.0769231	0.1071429
A5	1.0000 000	0.8977273	0.1696429	0.0849057	0.1923077	0.0892857
A6	0.8203867	0.9691558	0.1428571	0.1792453	0.1538462	0.1785714

The total relative importance of the i_{th} alternative based on WSM is calculated using Eq. (16).

$$Q_i^{(1)} = \sum_{j=1}^{n} r_{ij} w_j \tag{16}$$

where, w_j is weight of j_{th} criteria. As reported earlier, criteria weight (w_j) obtained by Entropy method is employed. By considering the weights calculated for entropy method (Table 24), normalised value of flow distance for alternative No.1 is 0.9048803 × 0.0017936 = 0.0016230 and performance score ($Q_i^{(1)}$) is equal to (0.0016230 + 0.0005279 + 0.2443418 +

0.2483265 + 0.2420762 + 0.2629343) = 0.9998297. Similarly for remaining alternatives weighted normalised decision matrix and performance scores are computed (Table 28).

Table 28
Weighted normalised decision matrix and performance score of WSM

Alternative	Flow Distance	Adjacency Score	Flexibility	Accessibility	Maintenance	Human Issue	$Q_i^{(1)}$
A1	0.0016230	0.0005279	0.2443418	0.2483265	0.2420762	0.2629343	0.9998297
A2	0.0015891	0.0005133	0.1450779	0.1733600	0.1675912	0.1831150	0.6712466
A3	0.0015136	0.0005125	0.0959914	0.0937081	0.0931062	0.0986004	0.3834322
A4	0.0017045	0.0005279	0.0207254	0.0351405	0.0186212	0.0281715	0.1048912
A5	0.0017936	0.0004739	0.0414508	0.0210843	0.0465531	0.0234763	0.1348321
A6	0.0014714	0.0005116	0.0349060	0.0445114	0.0372425	0.0469526	0.1655954

The total relative importance of the i_{th} alternative based on WPM is calculated by using Eq. (17).

$$Q_i^{(2)} = \prod_{j=1}^{n} (r_{ij})^{w_j} \tag{17}$$

The weighted normalised value of flow distance for alternative No.1 is 0.9048803 ^ 0.0017936 = 0.9998207 and performance score ($Q_i^{(2)}$) is equal to (0.9998207 × 1.000000 × 1.000000 × 1.000000 × 1.000000 × 1.000000) = 0.9998207. Accordingly weighted normalised decision matrix values and performance scores are shown in Table 29.

Table 29
Weighted normalized decision matrix and Performance score of WPM

Alternative	Flow Distance	Adjacency Score	Flexibility	Accessibility	Maintenance	Human Issue	$Q_i^{(2)}$
A1	0.9998207	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	0.9998207
A2	0.9997829	0.9999852	0.8804038	0.9146241	0.9148296	0.9092574	0.6696547
A3	0.9996956	0.9999843	0.7958928	0.7850491	0.7934962	0.7726774	0.3829618
A4	0.9999086	1.0000000	0.5472542	0.6153433	0.5374534	0.5558327	0.1005893
A5	1.0000000	0.9999430	0.6482512	0.5420341	0.6709229	0.5298154	0.1248942
A6	0.9996450	0.9999835	0.6215946	0.6525462	0.6356426	0.6357344	0.1638498

A joint generalized equation for determining the total relative importance of criteria (Qi) is displayed in Eq. (18).

$$Q_i = 0.5Q_i^{(1)} + 0.5\,Q_i^{(2)} \tag{18}$$

For Alternative No.1, Q_i = (0.5 × 0.9998297) + (0.5 × 0.9998207) = 0.9998252. Table 30 summarizes values of total relative importance for all the alternatives.

Table 30
Total relative importance

Alternative	$Q_i^{(1)}$	$Q_i^{(2)}$	Q_i	Rank
A1	0.9998297	0.9998207	0.9998252	1
A2	0.6712466	0.6696547	0.6704507	2
A3	0.3834322	0.3829618	0.3831970	3
A4	0.1048912	0.1005893	0.1027402	6
A5	0.1348321	0.1248942	0.1298632	5
A6	0.1655954	0.1638498	0.1647226	4

According to Table 30, alternative 1 has the highest rank, so it gives the best multiple performance characteristics and is taken as optimum solution of WASPAS method. To increase ranking accuracy and effectiveness more generalized Eq. (19) is used. Total relative importance of i_{th} alternative is found by,

$$Q_i = \lambda Q_i^{(1)} + (1-\lambda)Q_i^{(2)} \tag{19}$$

where, λ = 0, 0.1……1. For example λ = 0.9, total relative importance (Qi) of alternative No.1 is equal to (0.9 × 0.9998297) + ((1 - 0.9) × 0.9998207) = 0.9998288. Similarly for remaining alternatives total relative importance for different values of λ is as shown in Table 31.

Table 31
Ranking of alternatives for different λ values

Alternative	λ = 0	λ = 0.1	λ = 0.2	λ = 0.3	λ = 0.4	λ = 0.5	λ = 0.6	λ = 0.7	λ = 0.8	λ = 0.9	λ = 1
A1	0.9998207	0.9998216	0.9998225	0.9998234	0.9998243	0.9998252	0.9998261	0.9998270	0.9998279	0.9998288	0.9998297
A2	0.6696547	0.6698139	0.6699731	0.6701323	0.6702915	0.6704507	0.6706098	0.6707690	0.6709282	0.6710874	0.6712466
A3	0.3829618	0.3830088	0.3830558	0.3831029	0.3831499	0.3831970	0.3832440	0.3832910	0.3833381	0.3833851	0.3834322
A4	0.1005893	0.1010195	0.1014497	0.1018799	0.1023101	0.1027402	0.1031704	0.1036006	0.1040308	0.1044610	0.1048912
A5	0.1248942	0.1258880	0.1268818	0.1278756	0.1288694	0.1298632	0.1308569	0.1318507	0.1328445	0.1338383	0.1348321
A6	0.1638498	0.1640243	0.1641989	0.1643735	0.1645480	0.1647226	0.1648972	0.1650717	0.1652463	0.1654209	0.1655954

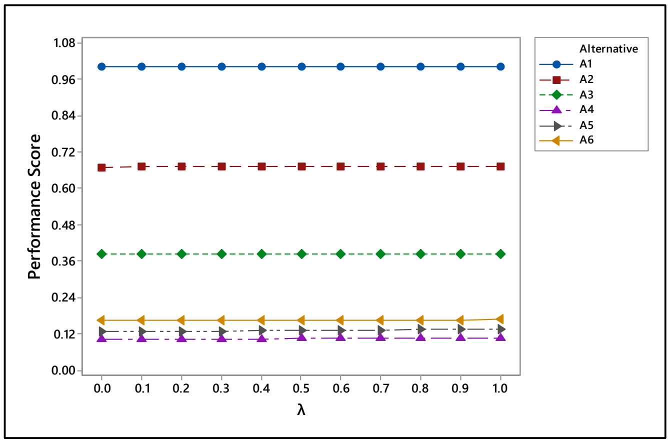

Fig. 12. Variation of performance scores for different λ values

Fig. 12 highlights the effect of the varying values of λ on the performance scores and ranking in WASPAS method. It is interesting to note that the ranking of all alternatives remains constant over the considered range of λ values.

6. Rank Reversal study

The objective of this section is to study the rank reversal in TOPSIS by numerical analysis. The effect of addition of an alternative on the ranking order is checked. There are six alternatives, each of which has six attributes. The initial and combination values for the alternatives and the ranking results are reported in Table 32. It is clear that, when alternative 4 i.e. layout having a lower rank is eliminated, then the ranking of the five old alternatives becomes A5 > A1 > A2 > A3 > A6. When the new alternative A7 is added to the previous six alternatives, the first rank does not change but remaining ranks get changed and it becomes A1 > A2 > A7 > A3 > A6 > A5 >A4. In the above two combinations, different rankings are obtained as compared to the original one. So vector normalization affects the independence between alternatives which disturbs the initial ranking. To overcome this, it is necessary to apply normalization method which maintain independence between alternatives by keeping the ideal solution constant. Considering the above condition, the Max-Min normalization method is used and the results are reported in Table 33.

Table 32
Initial and combination values by considering Vector normalization method

	Layout	Flow Distance /Cost-1	Adjacency Score	Flexibility	Accessibility	Maintenance	Human Issue	Rank
Initial layout	A1-SLP	816.76	616	0.224	0.106	0.026	0.056	1*
	A2-S	834.17	599	0.133	0.074	0.018	0.039	2
	A3-U	875.81	598	0.088	0.04	0.01	0.021	3
	A4-ALDEP	777.69	616	0.019	0.015	0.002	0.006	6
	A5-CRAFT	739.07	553	0.038	0.009	0.005	0.005	5
	A6-CORELAP	900.88	597	0.032	0.019	0.004	0.010	4
Delete Layout 4	A1-SLP	816.76	616	0.224	0.106	0.026	0.056	2
	A2-S	834.17	599	0.133	0.074	0.018	0.039	3
	A3-U	875.81	598	0.088	0.04	0.01	0.021	4
	A5-CRAFT	739.07	553	0.038	0.009	0.005	0.005	1*
	A6-CORELAP	900.88	597	0.032	0.019	0.004	0.010	5
Addition of Layout 7	A1-SLP	816.76	616	0.224	0.106	0.026	0.056	1*
	A2-S	834.17	599	0.133	0.074	0.018	0.039	2
	A3-U	875.81	598	0.088	0.04	0.01	0.021	4
	A4-ALDEP	777.69	616	0.019	0.015	0.002	0.006	7
	A5-CRAFT	739.07	553	0.038	0.009	0.005	0.005	6
	A6-CORELAP	900.88	597	0.032	0.019	0.004	0.010	5
	A7	824.06	596.50	0.089	0.044	0.011	0.023	3

Table 33
Initial and other combination values by considering Max-Min normalization method

	Layout	Flow Distance /Cost-1	Adjacency Score	Flexibility	Accessibility	Maintenance	Human Issue	Rank
Initial layout	A1-SLP	816.76	616	0.224	0.106	0.026	0.056	1*
	A2-S	834.17	599	0.133	0.074	0.018	0.039	2
	A3-U	875.81	598	0.088	0.04	0.01	0.021	3
	A4-ALDEP	777.69	616	0.019	0.015	0.002	0.006	6
	A5-CRAFT	739.07	553	0.038	0.009	0.005	0.005	5
	A6-CORELAP	900.88	597	0.032	0.019	0.004	0.010	4
Delete Layout 4	A1-SLP	816.76	616	0.224	0.106	0.026	0.056	1*
	A2-S	834.17	599	0.133	0.074	0.018	0.039	2
	A3-U	875.81	598	0.088	0.04	0.01	0.021	3
	A5-CRAFT	739.07	553	0.038	0.009	0.005	0.005	5
	A6-CORELAP	900.88	597	0.032	0.019	0.004	0.010	4
Addition of Layout 7	A1-SLP	816.76	616	0.224	0.106	0.026	0.056	1*
	A2-S	834.17	599	0.133	0.074	0.018	0.039	2
	A3-U	875.81	598	0.088	0.04	0.01	0.021	4
	A4-ALDEP	777.69	616	0.019	0.015	0.002	0.006	7
	A5-CRAFT	739.07	553	0.038	0.009	0.005	0.005	6
	A6-CORELAP	900.88	597	0.032	0.019	0.004	0.010	5
	A7	824.06	596.50	0.089	0.044	0.011	0.023	3

From Table 33, it is observed that the first rank remains unchanged for all cases which ensures good agreement in the decision results.

7. Conclusion

This paper addresses the real-life problem of the gearbox manufacturing industry. Six alternative layout designs are developed by using SLP, S flow pattern, U flow pattern, ALDEP, CRAFT, and CORELAP methods. For choosing the optimum configuration, we considered quantitative and qualitative performance measures. Quantitative performance is directly measured from layout design whereas AHP method is applied for getting the qualitative performance data. For layout designs, all the criteria do not have equal impact, therefore it is not possible to assign equal weights to these performance measures. For this purpose, for calculating the weights, the Entropy method is used. Subsequently, two MCDM approaches TOPSIS and WASPAS both coupled with the entropy method are considered for selection and comparison of the optimum layout design. The ranks of all the alternatives obtained by the TOPSIS method are the same as those obtained by the WASPAS method. Both MCDM approaches give SLP layout as optimum solution. In the case of the WASPAS method, the ranking of all alternatives remains unaffected for λ values which confirms the optimum solution developed by SLP. Also, rank reversal phenomenon is applied to TOPSIS and the causes of occurrence are reported. It has been observed that the Max-Min normalization method is stable and robust compared to the vector normalization method.

Acknowledgment

The authors are grateful to the Managers of Kavitsu Transmissions Pvt. Ltd. to support this study and to provide all the necessary facilities to obtain the necessary data.

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