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Technical paper

An integrated AHP–NLP methodology for facility layout design

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ABSTRACT

A facility layout design (FLD) problem can be generally introduced as assignment of facilities (departments) to a site such that a set of criteria are satisfied or some objectives are minimized (maximized). Hence, It can be considered as a multi-criteria problem due to presence of the qualitative criteria such as flexibility and the quantitative criteria such as total cost of handling material. This paper aims to incorporate qualitative criteria in addition to quantitative criteria for evaluating facility layout patterns (FLPs). We present a decision-making methodology based on a simple nonlinear programming model (NLP) and analytic hierarchy process (AHP). A computer-aided layout-planning tool, Spiral, is adopted to generate the FLPs, as well as their quantitative data. The AHP is then applied to determine weights of qualitative criteria. An NLP model is proposed to solve the FLD such that it considers both the quantitative and qualitative data simultaneously. Finally, the proposed integrated procedure is applied to a real example.

1. Introduction

After selecting factory location and before implementing operational schemes, the most important duty of managers, engineers and planners is suitable arrangement of equipments, departments, etc., by noting statement, goals, strategies, etc., and by evaluating the most important criteria influencing different FLPs too. Manufacturing companies spend a significant amount of time and money in FLD since the design of a facility layout has a tremendous effect on the operation of the system [1]. As stated by Tompkins et al. [2], the facility planning may include 10–30% of operational cost due to changes. Not only an inappropriate FLD causes rearrangement of existing facilities or/and material handling system, it will also undertake its resulting heavy costs. Therefore, the best work at designing process is to select an optimal FLP under different criteria or objectives, in order to obtain the maximum productivity and profitability.

During the past three decades, most of literatures as compared to solving FLD problem concerned with the procedural, algorithmic, approximated and optimization methodologies. Neither of algorithmic, procedural, approximated and optimal layout design methodologies might be suitable in practice. Procedural approach divides a FLD problem into several steps that are implemented sequentially. Unfortunately, such an approach depends heavily on designer's subjective judgments and may determine an inferior solution due to a lack of a sound scientific foundation [3]. Algorithmic approaches can efficiently generate layout designs, but the design objectives are often over-simplified [4], these approaches have over simplifying assumptions and request overwhelming computational efforts [5] and often do not consider all the design criteria (particularly, qualitative criteria) when solving the FLD. On the other hand, learning of approximated methodologies such as simulated annealing, genetic algorithm, tabu search and ant colony may be difficult for an average manager. Finally, a FLD problem can be modeled as an optimization problem. It may not determine any exact solution to the general layout problem, does not take into account qualitative criteria as objectives and results in prohibitive computation time for large problems. Thus, it is necessary to determine the most critical criteria for evaluating FLPs. In a general categorizing, two groups of criteria can affect a FLD problem. These criteria are: (1) internal criteria and (2) external criteria. The first class involves some important factors which describe characterizations within the organization's internal boundaries. External criteria include the shape and location of road related to loading and unloading the raw material and items manufactured of receive and dispatch parts in/out of the factory, respectively, water distribution and disposal system, fuel distribution system, etc. Thus, to cope with the difficulties being the cause of the above research and considering both quantitative and qualitative criteria, this paper purposes a simple integrated framework based on the NLP and AHP. A software package, Spiral, is adopted to constitute the layout alternative generation process, as well as the quantitative performance data such as distances, adjacency scores and shape ratios. The AHP is applied to collect qualitative performance data such as accessibility, maintenance and flexibility. Later, a simple weighted NLP is proposed to solve the FLD problem by

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simultaneously considering both the quantitative and qualitative performance data leading to the determination of the more robust layout design alternatives. The proposed integrated framework is successfully applied to a case study.

2. Literature review

The layout design problem is one of the best-studied fields to achieve its goal of productivity and profitability. Due to the significance of problem in manufacturing organizations, it has been as an active research area for many decades [7]. A number of formulations have been developed for this problem. When the factory site is divided into the rectangular grids (discrete) and each of facilities adopts one or some of these grids, it is often considered as Quadratic Assignment Problems (QAP). The simplest type of such problems was first introduced by Koopmans and Beckman [8], where the FLD problem includes the locating the grids cell to the facilities, by aiming the minimization of the total material handling cost. Although many heuristic and exact methods have been proposed to approximate the solutions for these problems, these problems belong to the class of NP-hard; those do not present any exact solution, particularly, when the important qualitative criteria affect FLD and also result in prohibitive computation time for large problems [5]. On the other hand, if the factory site is considered as continual [9], FLD problem is often formulated as Mixed Integer Programming (MIP). For example, Askin [10] formulated an MIP mathematical model for integrated production system planning. His economic decision model integrates product selection, capacity planning, process planning and facility layout. Also, Montreuil [11] proposed such a model, where the facility sizes and locations were variables and binary variables were introduced to impose the non-overlap constraint. In these formulations, all the facilities may be placed anywhere within the planar site [12] and must not overlap each other [11,13].

Xie and Sahinidis [14] introduced a branch-and-bound algorithm for the continuous facility layout (CFL) problem. Despite the fact that CFL admits infinitely many feasible layouts, it suffices to enumerate finitely many candidate solutions to obtain an optimal solution. Unfortunately, these approaches are not often suitable for large size problems.

The near-optimal methods can be generally classified into two classes, namely heuristics and metaheuristics. Heuristic methods are grouped into two groups the procedural and algorithmic themselves. The procedural approach such as the systematic layout planning (SLP) [15] implements the FLD in three stages the analysis, search, and selection which each of them itself includes sub-stages. Due to subjectivity of these stages and sub-stages by designer and lack of a sound scientific foundation, it has transformed into an inefficient method [3]. Also, the algorithmic approaches are divided in two classes, i.e., the constructed and improved. The constructed algorithmic approaches as ALDEP [16] and COROLAP [17] and the improved algorithmic approaches as CRAFT [18] and COFAD [19] are samples of these methods. Note that these methods have some limitations. The most significant drawback of these approaches is that they apply only one objective to FLD, such as minimization the total material handling cost or the maximization the total closeness rate. Besides, most of algorithms (e.g., CRRAFT, COFAD, and PLANET) for FLPs were developed to solve the single-floor facility layout problems in the past [20], however, the many algorithms (e.g., MULTIPLE [21]) have been recently constructed to solve the multi-floor facility layout problems (it encompasses all aspects of the single-floor facility layout problem, and in addition, it includes vertical flows and area constraints for individual floors [22]).

Many authors have used the metaheuristics approaches to obtain the near-optimal designs [23–25]. First, a large number of studies applied simulated annealing (SA) to solve a FLD problem [12,26,27]. For example, Chwif et al. [12] proposed a solution approach based on SA in the continual plane to the FLD. It addresses some practical aspects, including the facilities with different areas, shapes and orientations, any polygonal format for the border, fixed facilities and Pick-up and drop-of points. Ulutas and Islier [28] presented a clonal selection algorithm (CSA) for dynamic facility layout (DFL) problems. For simplicity, they considered machines with equal area and standardized handling equipments with identical unit costs in their study. Among the other types of these approaches can address the genetic algorithm [29–33] for solving the layout and aisle structure problems concurrently by slicing floorplan and the ant colony [34], where single row machine layout problem is first formulated as a non-linear 0-1 programming model. In this model the distance between the machines is sequence dependent. Hence, an ant colony algorithm is adopted to solve this model.

The last group of the FLD solution approaches includes multi-attribute decision-making (MADM) techniques or integration of these with other approaches such as genetic algorithm. Cambron and Evans [35], Foulds and Partovi [36], Yang et al. [37] applied the AHP to evaluate the design patterns with respect to one or some criteria. The AHP is also employed by Dweiri and Meier [38] to obtain the weights of material flow, information flow and equipment flow. A fuzzy approach is used to generate activity relationship chart, which is input of a revised CORELAP for generation of layout patterns. Then, the distances and the relationships between departments or facilities are applied to determine the score of each pattern. Yang and Kuo [3], hereafter the YK-model, introduced an integrated AHP-data envelopment analysis (DEA) methodology for ranking FLPs, where the AHP method was used for generating the performance measures of the qualitative criteria, the Spiral commercial software for determining the performance measures of the quantitative criteria, as well as the proposed FLPs and finally the DEA was applied for solving the layout performance frontiers problem by simultaneously considering both the quantitative and qualitative performance data. Whereas, the cost associated with a change incurred at the layout design stage is usually negligible, they used a Banker–Charnes–Cooper (BCC) model for solving this problem. Also, Ertay et al. [5] proposed a similar approach to rank the FLPs. Furthermore, Azadeh et al. [39] adopted an AHP/DEA methodology with computer simulation for railway system improvement and optimization. Unfortunately, in recent papers, obtaining consistent pairwise comparison matrix (PCM) is difficult, in particular, when number of the FLPs is quit big. Recently, Yang and Hung [4] presented the fuzzy technique for order preference by similarity to ideal solution (FTOPSIS) for ranking the FLPs and then the obtained results were compared with TOPSIS and YK-model. Their proposed approach depends strongly on the subjective judgments. Aiello et al. [40] proposed the genetic search algorithm and ELECTRE method to priority the FLPs in which the Pareto-optimal solutions are determined by employing a multi-objective constrained genetic algorithm.

3. The proposed model

3.1. The AHP methodology

There exist a total of 18 MADM methods, e.g., AHP, ELECTRE, TOPSIS, and outranking methods [41]. The AHP is one of the most popular MADM techniques in which problem is converted to a hierarchic structure and then the alternatives are ranked based on the decision-maker's judgments [42]. The hierarchy of a usual AHP model is as follows: the overall decision goal (the bestalternative)

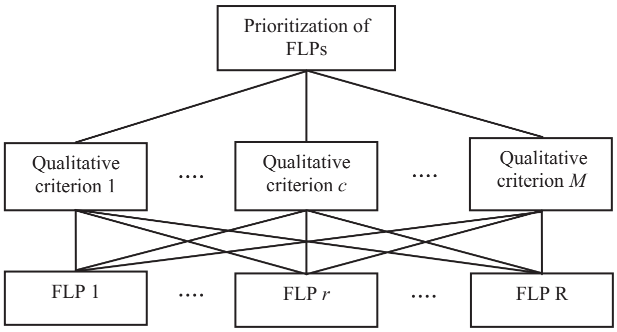

Fig. 1. A hierarchical structure of AHP for FLD.

is at the top level, criteria (if necessary, sub-criteria) lie in the middle level(s), and alternatives are at the bottom level. The reason of adopting AHP especially for the qualitative performance data is the fact that qualitative criteria are not stateable as quantitative data. Also, the decision-maker acceptability and confidence in the analysis provided by the AHP methodology is high when it is compared with other multi-attribute decision approaches [43]. The other advantages of the AHP include: providing a systematic methodology for subjective decision, applying in sensitivity analysis, presenting information about the evaluation criteria' weights, and providing better understanding and participation among the members of the decision-making group and hence a commitment to the chosen alternative [44].

In this study, the goal of the AHP usage is to obtain the weights indicating the relative importance of the FLPs (as alternatives) under each criterion. At the bottom level, the decision-maker will be asked to determine a comparison matrix by comparing pairs of the FLPs against the criteria. Analytic aspect of rating method enables decision-makers to evaluate a large number of alternatives easily. Since in this paper, the performance measures of the qualitative criteria are generated by the AHP, thus a hierarchy structure for FLD problem is proposed, as shown in Fig. 1.

In the following hierarchical structure, for example, the weights in the bottom level are determined by the PCM based on the designer's point of views. In other words, the raw data in this matrix include the designer's evaluations as compared to the importance of a FLP against the other FLPs with respect to each qualitative criterion which are selected using 1–9 scales in Table 1. Let $A_{ij}(i, j = 1, \ldots, R)$ be the comparison of ith FLP against jth FLP generated by the commercial software. By constructing the PCM for comparing R FLPs regarding to each the qualitative criterion C, $C = 1, \ldots, M$, we have:

$$A = (A_{ij})_{R\times R} = \begin{bmatrix} A_{11} & \cdots & A_{1R} \\ \vdots & \cdots & \vdots \\ A_{R1} & \cdots & A_{RR} \end{bmatrix}, \quad i, j = 1, \ldots, R, \tag{1}$$

Table 1
The 1–9 scales proposed by Saaty [42] for pairwise comparisons in the AHP.

Importance intensity	Definition
1	Equal importance
3	Moderate importance of one pattern as compared to another
5	Strong importance of one pattern as compared to another
7	Very strong importance of one pattern as compared to another
9	Extreme importance of one pattern as compared to another
2,4,6 and 8	Intermediate values
Reciprocals	Reciprocals for inverse comparison

where $A_{ij} = 1/A_{ji}$ for $i, j = 1, \ldots, R$. If in this matrix for $i, j, k = 1, \ldots, R$, $A_{ij} = A_{ik} \times A_{kj}$ hold true, then A is said to be perfectly consistent.

In matrix A, the weights can be determined by solving the following equation:

$$AW = \lambda_{\max} W \tag{2}$$

where $\lambda_{\max}$ is the maximum eigenvalue of matrix A. Obviously, it is impossible to obtain a perfectly consistent matrix with many FLPs. Hence, we can adopt an acceptable consistency limit by the following consistency ratio (CR):

$$CR = \frac{(\lambda_{\max} - n)/(n-1)}{RI} \tag{3}$$

where RI is a random inconsistency index whose value are determined according to the size of matrix A. The interested readers can refer to Saaty [42] for more detailed for determining the RI. If $CR \le 0.1$, then A is said to has acceptable consistent limit; otherwise, the pairwise comparisons should be revised.

3.2. A weighted NLP model for ranking FLPs

In this section, we propose a weighted NLP model for ranking the FLPs against the performance measures of both qualitative and quantitative criteria. Let there are R FLPs generated by commercial software. Also, let x_{rc} denotes the measurement of performance of rth FLP ($r = 1, \ldots, R$) under cth criterion ($c = 1, \ldots, M$). Then, the performance measures of criteria are transformed within a 0–1 scale using transformation $(x_{rc} - \min_{r=1,2,\ldots,R}\{x_{rc}\})/(\max_{r=1,2,\ldots,R}\{x_{rc}\} - \min_{r=1,2,\ldots,R}\{x_{rc}\})$. To facilitate the ranking, let w_c be the relative importance weight attached to the cth criterion ($c = 1, \ldots, M$). The proposed model is as follows:

$$\begin{aligned} S_r \max \sum_{c=1}^{M} w_c x_{rc} & \\ s.t. \quad \sum_{c-1}^{M} w_c^2 = 1 & \\ w_c \in \Gamma & \end{aligned} \tag{4}$$

where Γ shows the significance level of the criteria which is determined based on the designers' decisions. For example, the criteria may be ranked in a descending order such that $w_1 \ge w_2 \ge \ldots \ge w_M$.

Note that since the objective function of the proposed model is maximization, hence for cost criteria such as material handling distance, we can consider negative or reversing of performance measures.

In general, we can obtain the score of each FLP by the following stages:

1. Transform the measures x_{rc} using transformation $(x_{rc} - \min_{r=1,2,\ldots,R}\{x_{rc}\})/(\max_{r=1,2,\ldots,R}\{x_{rc}\} - \min_{r=1,2,\ldots,R}\{x_{rc}\})$ within a 0–1 scale.
2. Solve the model for each FLP by a nonlinear optimizer.
3. Sort the scores S_r values in the descending order.

4. Case study

We apply our method, to the same FLD problem as discussed in literature by Yang and Hung [4] in an IC packaging company. The interested reader can refer to Yang and Kuo [3] and Yang and Hung [4] for more details as compared to name and area of departments, the FLPs generated by commercial software Spiral and the definitions of criteria. Six criteria were taken into account in their proposed FLPs. Table 2 shows the performance measures of FLPs

Table 2
The measures of the FLPs with respect to different criteria.

Layout alternatives	Distance (m)	Adjacency score	Accessibility	Shape ratio	Maintenance	Flexibility
1	0.00537	8	0.0260	0.1207	0.0690	0.0119
2	0.00482	9	0.0260	0.2666	0.0575	0.0595
3	0.00484	8	0.0519	0.1273	0.0345	0.0714
4	0.00527	8	0.0779	0.1207	0.0460	0.0714
5	0.00472	8	0.0390	0.1290	0.0460	0.0714
6	0.00378	5	0.0519	0.4830	0.0690	0.0357
7	0.00438	8	0.0390	0.0714	0.0230	0.0476
8	0.00538	9	0.0130	0.1600	0.0575	0.0476
9	0.00538	9	0.0260	0.1273	0.0575	0.0357
10	0.00423	8	0.0779	0.1273	0.0690	0.0595
11	0.00545	8	0.1169	0.5000	0.0920	0.0952
12	0.00489	8	0.0390	0.0751	0.0575	0.0357
13	0.00443	8	0.0390	0.1228	0.0345	0.0714
14	0.00493	8	0.0779	0.1250	0.0575	0.0357
15	0.00587	9	0.1169	0.1207	0.0920	0.0952
16	0.00462	9	0.0519	0.1297	0.0690	0.0476
17	0.00556	8	0.0779	0.0970	0.0345	0.0476
18	0.00538	10	0.0519	0.0984	0.0345	0.0595
Max	0.00587	10	0.1169	0.5000	0.0920	0.0952
Min	0.00378	5	0.0130	0.0714	0.0230	0.0119

with respect to these criteria. In this table, material handling distance, adjacency score and shape ratio are the quantitative criteria, which are determined using commercial software Spiral. Besides, since material handling distance and shape ratio are loss-type criteria, i.e., they are negatively related to the importance level of a FLP, their reciprocal values are considered. The measures of the qualitative criteria (accessibility, maintenance and flexibility) have obtained by the AHP.

Table 3 displays the transformed measures within 0–1 scale using transformation $(x_{rc} - \min_{r=1,2,...,R}\{x_{rc}\})/(\max_{r=1,2,...,R}\{x_{rc}\} - \min_{r=1,2,...,R}\{x_{rc}\})$.

Now, we solve the following nonlinear model for each FLP based on data in Table 3 using Microsoft Excel Solver or the LINGO software package.

$$S_r = \max \sum_{c=1}^{6} w_c x_{rc}$$
$$s.t. \quad \sum_{c=1}^{6} w_c^2 = 1$$
$$w_1 = w_2 = w_3,$$
$$w_4 = w_5,$$
$$w_3 > w_4,$$
$$w_5 > w_6,$$

where the ranking order of criteria are stated as in Yang and Hung [4] and all weights are nonnegative. Namely material handling distance, djacency score and accessibility criteria have the equal importance and their importance is more than shape ratio and maintenance. Additionally, the importance degree of these recent two criteria is also equal and these are more than flexibility, based on designers' decisions.

By solving the proposed model for each FLP, the eighth column of Table 3 shows the score of each FLP. Also, Table 3 shows the FLPs ranking results using the proposed model, fuzzy TOPSIS [4] and YK-model. For comparison purpose, we consider the best 5 FLPs as there were 5 FLPs identified by the fuzzy TOPSIS, using the same dataset. The top 5 FLPs identified are FLPs 11, 15, 18, 4 and 17, respectively. These FLPs are the good FLPs in fuzzy TOPSIS too, due to similarity of ranking order of the criteria in the both models. Comparing the remaining FLPs shows many differences between our method and fuzzy TOPSIS, the reason is that FTOPSIS depended hardly on subjective judgments at drawing stages of membership functions and selecting the linguistic variables by designers, while in our model, these stages are obtained endogenously and by solving a weighted nonlinear optimization model and without interfering subjective judgments in scoring scheme and it is based on performance measures.

The above example has been solved by Yang and Kuo [3] as well. For comparison purpose, we consider the best 5 FLPs as there were the 5 efficient FLP identified by the YK-model in Yang and Kuo [3]. The top 5 FLPs identified are the FLPs 11, 15, 18, 2 and 16. The FLPs 11, 15 and 18 are the optimal FLPs in both YK-model and the proposed model. The FLPs 4 and 17 were not identified as the good FLPs in the YK-model. On the other hand, the FLPs 2 and 16 were identified as the good FLPs in the YK-model but were not identified by our proposed model. The reason of these differences is due to the incorporation of relative importance level of the criteria. Although, the FLPs 2 and 16 are the suitable FLPs in YK-model, the distance of these two FLPs are only 0.4975 and 0.4019, which are relatively low compared to other FLPs. When the distance is considered as a relatively important criterion, these two FLPs are eliminated. The FLPs 4 and 17 with relatively low adjacency score, 0.6 and 0.6, respectively, were rated high because of the advantage of relatively higher distances and accessibility.

5. Discussion and conclusion

The proposed approach in this paper gives an NLP model to FLD problem in the area of prioritizing the FLPs generated by Spiral tool. This model concurrently takes into account knowledge of experts with regard to weights obtained by the AHP for qualitative criteria, as well as performance measures of quantitative criteria. It is capable to consider the ranking order of criteria. The data needed for comparing the FLPs regarding to the qualitative criteria for constructing the PCM and determining the ranking order of criteria on a real case study are extracted through interviewing with design experts of a factory. It depends severely on judgments of designers for the ranking order of criteria and it might occasionally be resulted in inconsistent and contradictive knowledge. For example, although in this research, the ranking order of criteria is based on additive alliances as discussed in Section 4, it may be possible to propose different order by designers. Also, in this paper the traditional AHP was applied for comparing the FLPs with respect to each qualitative criterion in the PCM using crisp ratios (the 1–9 scales proposed by Saaty [42]). But since in world real, evaluating and comparing criteria (particularly qualitative criteria) are stated as linguistic expressions and judgments, it is better to use

Table 3
The measures of scale transformation, ranking the FLPs by our model and compared with the fuzzy TOPSIS and YK-models.

Layout alternatives	Distance (m)	Adjacency score	Accessibility	Shape ratio	Maintenance	Flexibility	Score	Fuzzy TOPSIS	YK-model
11	0.7990	0.6	1.0000	1.0000	1.0000	1.0000	2.2115	11	11
15	1.0000	0.8	1.0000	0.1150	0.0920	1.0000	1.7579	15	15
18	0.7655	1.0	0.3743	0.0629	0.1666	0.5714	1.3155	18	18
4	0.7129	0.6	0.6246	0.1150	0.3333	0.7142	1.2958	4	2
17	0.8516	0.6	0.6246	0.0597	0.1666	0.4285	1.2508	17	16
2	0.4975	0.8	0.1251	0.4554	0.5000	0.5714	1.1964	8	6
16	0.4019	0.8	0.3743	0.1360	0.6666	0.4285	1.1457	10	8
14	0.5502	0.6	0.6246	0.1250	0.5000	0.2857	1.1426	14	9
10	0.2153	0.6	0.6246	0.1304	0.6666	0.5714	1.1389	2	17
8	0.7655	0.8	0.0000	0.2067	0.5000	0.4285	1.1113	16	1
9	0.7655	0.8	0.1251	0.1304	0.5000	0.2857	1.1037	9	4
3	0.5071	0.6	0.3743	0.1304	0.1666	0.7142	1.0262	5	10
1	0.7607	0.6	0.1251	0.1150	0.6666	0.0000	1.0153	1	14
5	0.4497	0.6	0.2502	0.1343	0.3333	0.7142	0.9978	3	5
6	0.0000	0.0	0.3743	0.9603	0.6666	0.2857	0.9470	12	3
12	0.5311	0.6	0.2502	0.0086	0.5000	0.2857	0.9125	6	13
13	0.3110	0.6	0.2502	0.1199	0.1666	0.7142	0.8861	7	12
7	0.2870	0.6	0.2502	0.0000	0.0000	0.4285	0.6934	13	7

the fuzzy sets theory for comparisons. Besides, it is impossible to construct a consistent PCM with respect to each qualitative criterion when the number of the FLPs is quite big. On the other hand, the criteria under consideration in this paper according to considerations of experts participating in assessment include three quantitative criteria (distance, adjacency score and shape ratio) and three qualitative criteria (accessibility, maintenance and flexibility). However, if necessary, design experts can consider other qualitative and quantitative criteria in FLD problem, depending on nature of FLD problem, type of used commercial software or proper interpretations by experts. For example, Ertay et al. [5] consider another quantitative criterion (material handling vehicle utilization) in addition to the above criteria together with the qualitative criterion such as quality instead of accessibility and maintenance for evaluating the FLPs. Also, we can view the other criteria, e.g., construction cost of width walls due to difference in printed FLPs, speed of helping, facilitation of handling, etc., in FLD problem. But despite all these limitations, by means of the proposed robust facility layout framework, the firms can provide efficient solutions for their layout problem. Moreover, the framework presented in this paper can be easily implemented on a personal computer and offers a systematic guidance to the decision makers in planning the layout design.

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References

[1] Ramkumar AS, Ponnambalam SG, Jawahar N. A new iterated fast local search heuristic for solving QAP formulation in facility layout design. Robotics and Computer-Integrated Manufacturing 2009;25:620–9.
[2] Tompkins A, White JA, Bozer YA, Frazelle EH, Tanchoco JMA, Trevino J. Facilities planning. New York: Wiley; 1996.
[3] Yang T, Kuo C. A hierarchical AHP/DEA methodology for the facilities layout design problem. European Journal of Operational Research 2003;147:128–36.
[4] Yang T, Hung CC. Multiple-attribute decision making methods for plant layout design problem. Robotics and Computer Integrated Manufacturing 2007;23:126–37.
[5] Ertay T, Ruan D, Tuzkaya UR. Integrating data envelopment analysis and analytic hierarchy for the facility layout design in manufacturing systems. Information Sciences 2006;176:237–62.
[7] Meller RD, Gau KY. The facility layout problem: recent and emerging trends and perspectives. Journal of Manufacturing Systems 1996;15(5):351–66.
[8] Koopmans TC, Beckman M. Assignment problems and the location of economic activities. Econometrica 1957;25:53–76.
[9] Heragu SS, Kusiak A. Machine layout: an optimization and knowledge-based approach. International Journal of Production Research 1990;28:615–35.
[10] Askin RG. A formulation of the integrated facility layout, product selection and process planning problem. Journal of Manufacturing Systems 1986;5(4):267–9.
[11] Montreuil B. A modelling framework for integrating layout design and flownetwork design. In: White JA, Pence IW, editors. Progress in material handling and logistics. Springer-Verlag; 1991. p. 95–116.
[12] Chwif L, Pereira Barretto MR, Moscato LA. A solution to the facility layout problem using simulated annealing. Computers in Industry 1998;36(1–2):125–32.
[13] Das SK. A facility layout method for flexible manufacturing systems. International Journal of Production Research 1993;31(2):279–97.
[14] Xie W, Sahinidis NV. A branch-and-bound algorithm for the continuous facility layout problem. Computers and Chemical Engineering 2008;32:1016–28.
[15] Muther R. Systematic layout planning. 2nd ed. Boston, MA: Cahners Books; 1973.
[16] Seehof JM, Evans WO. Automated layout design program. The Journal of Industrial Engineering 1967;18:690–5.
[17] Lee R, Moore JM. CORELAP-computerized relationship layout planning. The Journal of Industrial Engineering 1967;18:195–200.
[18] Armour GC, Buffa ES. A heuristic algorithm and simulation approach to relative allocation of facilities. Management Science 1963;9(2):294–300.
[19] Tompkins JA, Reed JR. An applied model for the facilities design problem. International Journal of Production Research 1976;14:583–95.
[20] Lee KY, Rohb MI, Jeongb HS. An improved genetic algorithm for multi-floor facility layout problems having inner structure walls and passages. Computers & Operations Research 2005;32:879–99.
[21] Bozer YA, Meller RD, Erlebacher SJ. An improved-type layout algorithm for single and multiple-floor facilities. Management Science 1994;40(7):918–32.
[22] Meller RD, Bozer YA. Alternative approaches to solve the multi-floor facility layout problem. Journal of Manufacturing Systems 1997;16(3):192–203.
[23] Al-Araidah O, Krishnamurthy A, Malmborg CJ. A two-stage simulated annealing procedure for block layout problems. International Journal of Production Research 2006;44:4417–29.
[24] Khilwani N, Shankar R, Tiwari MK. Facility layout problem: an approach based on a group decision-making system and psychoclonal algorithm. International Journal of Production Research 2008;46:895–927.
[25] Singh SP, Singh VK. An improved heuristic approach for multi-objective facility layout problem. International Journal of Production Research 2010;48:1171–94.
[26] McKendall AR, Shang J, Kuppusamy S. Simulated annealing heuristics for the dynamic facility layout problem. Computers & Operations Research 2006;33(8):2431–44.
[27] Ariafar S, Ismail N. An improved algorithm for layout design in cellular manufacturing systems. Journal of Manufacturing Systems 2009;28:132–9.
[28] Ulutas BHA, Islier A. A clonal selection algorithm for dynamic facility layout problems. Journal of Manufacturing Systems 2009;28:123–31.
[29] Wu Y, Appleton E. The optimization of block layout and aisle structure by a genetic algorithm. Computers & Industrial Engineering 2002;41(4):371–87.
[30] Singh SP, Sharma RRK. Two-level modified simulated annealing based approach for solving facility layout problem. International Journal of Production Research 2007;46:3563–82.
[31] Diego-Mas JA, Santamarina-Siurana MC, Alcaide-Marzal J, Cloquell-Ballester VA. Solving facility layout problems with strict geometric constraints using a two-phase genetic algorithm. International Journal of Production Research 2007;47:1679–93.
[32] Raman D, Nagalingam SV, Gurd BW. A genetic algorithm and queuing theory based methodology for facilities layout problem. International Journal of Production Research 2009;47:5611–35.

[33] Sahin S, Türkbey O. A new hybrid tabu-simulated annealing heuristic for the dynamic facility layout problem. International Journal of Production Research 2009;47:6855–73.
[34] Solimanpur M, Vrat P, Shankar R. An ant algorithm for the single row layout problem in flexible manufacturing systems. Computers & Operations Research 2005;32(3):583–98.
[35] Cambron KE, Evans GW. Layout design using the analytic hierarchy process. Computers and Industrial Engineering 1991;20(2):211–29.
[36] Foulds LR, Partovi FY. Integrating the analytic hierarchy process and graph theory to model facilitates layout. Annals of Operations Research 1998;82:435–51.
[37] Yang T, Su CT, Hsu YR. Systematic layout planning: a study on semiconductor wafer fabrication facilities. International Journal of Operations and Production Management 2000;20(11):1360–72.
[38] Dweire F, Meier FA. Application of fuzzy decision making in facilities layout planning. International Journal of Production Research 1996;34:3207–25.
[39] Azadeh A, Ghaderi SF, Izadbakhsh H. Integration of DEA and AHP with computer simulation for railway system improvement and optimization. Applied Mathematics and Computation 2008;195:775–85.
[40] Aiello G, Enea M, Galante G. A multi-objective approach to facility layout problem by genetic search algorithm and Electre method. Robotics and Computer-Integrated Manufacturing 2006;22:447–55.
[41] Tolga E, Demircan ML, Kahraman C. Operating system selection using fuzzy replacement analysis and analytic hierarchy process. International Journal of Production Economics 2005;97:89–117.
[42] Saaty TL. The analytic hierarchy process: planning, priority setting. New York: McGraw Hill International Book Co.; 1980.
[43] Zakarian A, Kusiak A. Forming teams: an analytical approach. IIE Transactions 1999;31(1):85–97.
[44] Shang JS. Multicriteria facility layout problem: an integrated approach. European Journal of Operational Research 1993;66:291–304.