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Selection of multi-criteria plant layout design by combining AHP and DEA methodologies

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Abstract. This paper deals with the problem of finding the optimal plant layout design. Decision-making methodologies based on analytic hierarchy process (AHP) and data envelopment analysis (DEA) approach are applied in the selection of the best plant layout. New layouts are developed, in an efficient manner, based on the systematic layout planning (SLP). By using the multiple criteria, AHP is applied to weigh the qualitative performance measures. DEA is then used to determine the suitable layout design by measuring layouts' efficiency, using the information of AHP and combining with the quantitative data. The utilization of the proposed procedure is applied to a real data set of a machining precision parts manufacturing company.

1 Introduction

Plant layout is one of the most important components that significantly has an impact on productivity, profitability, and performance of any manufacturing industries, regardless of the size of plant or the type of operation. The necessity of designing a plant layout arises not only when a new plant is about to be elected but also during production process due to various reasons. The selection of an appropriate layout design is a multi-criteria decision making (MCDM) which requires joint consideration of multiple alternatives, which are various designed layouts and several conflicting evaluation criteria that influence the layout decision. Moreover, in the evaluation process, both of the qualitative and quantitative criteria are necessary to be taken into consideration. Consequently, it is challenging and time consuming for layout generation and evaluation.

This paper explores the problem of finding the optimal plant layout design by applying a decision-making methodologies based on an integration of analytic hierarchy process (AHP) and data envelopment analysis (DEA). Empirical illustration from a practical case study of a machining precision parts manufacturing company illustrates the effectiveness of the proposed methodology. Firstly, an existing plant layout is improved by adopting systematic layout planning (SLP) methodology in order to generate new layouts as well as to collect quantitative performance data of each alternative, namely distance and cost. In the next step, an expert judgment is applied to perform the individual pairwise comparisons of the qualitative performance data related to flexibility, safety, and space utilization in AHP. Finally, DEA is used to solve the problem of layout design selection by simultaneously considering both quantitative and qualitative performance criteria which leads to the identification of the more optimal plant layout design alternative.

2 Literature review

One of the effective and frequently used methods for layout design or redesign is SLP. The method presents layout planning step that can be easily used in developing a new layout or improving an existing layout [1]. It is also a proven tool in providing layout design guidelines and it is widely used in the manufacturing industry for facility layout planning [2].

Pitil and Kuber [3] improved productivity of Auto Ancillary company by using SLP. Hossain et al. [4] developed plant layout of jute industry based on SLP pattern theory. The new plant layout showed that the distance and overall cost of material flow from stores to dispatch area were significantly decreased. Sutari and Rao [5] applied SLP to design plant layout of a nacelle production. The new plant layout could significantly decrease the distance of material and work flow travel and resulted in increasing the productivity. Ojaghi et al. [6] minimized travel distance, material handling and losses of company producing meatball and soup paste by using SLP to generate new layouts. Chen et al. [7] adopted SLP approach to enhance the performance on optimizing the layout design of a large auto parts manufacturing enterprise. In this study, AHP was adopted to evaluate optimal layout.

AHP has been accepted as one of robust and flexible multi-criteria decision making tools for dealing with complex problems [8,9]. The method requires the decision maker to provide judgements about the relative importance of each criterion which is then used in specifying a preference for each decision alternative. The

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output of AHP is in a form of weights of each alternative based on the overall preferences evaluated by the decision maker [10-13]. The methodology of AHP has been applied to support decision of facility layout design selection in various cases.

Yang and Deuse [14] made use of Matlab-based to generate three new layout designs. Afterwards, the weights for each of six decision criteria was obtained by AHP calculation. Each layout alternative was then evaluated using PROMETHEE to get final ranking. Yang et al. [15] generated ten new layout alternatives of a paint department by a Pareto-based multi-objective optimization approach. Rough set theory was integrated with AHP to determine the weights for each of five criterion of alternatives. The final alternative facility layout design was obtained by using TOPSIS method. Hadi-Vencheh and Mohamadghasemi [16] adopted a computer-aided layout planning tool, Spiral, to generate the facility layout patterns. Six criteria were taken into account. AHP was applied to determine weights of qualitative criteria and nonlinear programming model was then used to solve the problem of selecting one out of 18 alternatives by considering both quantitative and qualitative data. Shokri et al. [17] tackled the same facility layout design problem as Hadi-Vencheh and Mohamadghasemi, by employing AHP to weigh the qualitative performance measures. VIKOR was then applied to find a compromise priority ranking of alternatives according to the selected criteria. Bacudio et al. [18] generated three layout alternatives of a metal manufacturing company by applying SLP. Considering four criteria, AHP was applied to determine the priority weights and the best layout.

DEA is one of the most popular tools in management analysis. The technique is applied to evaluate performance or efficiency of a homogeneous set of entities which is referred as decision making units (DMUs) by considering multiple input and multiple output factors [19]. The DMUs could represent any businesses, operations, or entities under an evaluation that convert multiple inputs into multiple outputs. The maximum ratio of weighted sum of outputs to weighted sum of inputs is defined as the efficiency, which is calculated for each DMU. Then the efficiency of observed DMU is evaluated relatively by other DMUs [20]. The goal of DEA is to determine the productive efficiency of DMUs by comparing how well the DMU converts inputs into outputs [21].

Liu [22] applied fuzzy DEA with an assurance region approach for selecting a flexible manufacturing system. Twelve alternatives were compared using two inputs and four outputs performance measures. Yand and Kuo [23] used commercial software called Spiral for generation of 17 layouts of IC packaging company. Qualitative measures were weighted by AHP. The DEA was adopted to select the final design. Ertay et al. [24] utilized VisFactory, which is a computer-aided layout-planning tool, to create 18 layout alternatives of a plastic production company. The performance measures on qualitative criteria were developed using AHP. Ranking of the alternatives was later obtained by considering six criteria using DEA.

3 Methodology

The proposed framework used in solving the layout design problem is illustrated in Fig.1.

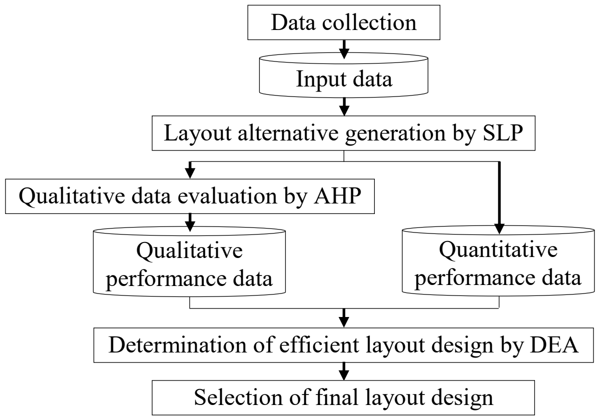

Fig. 1. Framework for plant layout selection.

3.1 Data collection

An important data of the existing plant including flow of materials, procedures and activities, space available and requirements have to be collected in order to assure the validity of input data at the layout design stage. Information related to quantitative and qualitative criteria also have to be assembled.

3.2 SLP for layout alternative generation

SLP is a procedural layout design approach which its process is relatively straightforward but yet is proven a powerful tool in providing the layout design guideline [25]. A step-by-step planning procedure of SLP uses to determine a reasonable production system layout scheme and develop a new plant layout with an improved process flow and an effective utilization of space. A workplace in a plant is arranged by locating two areas that contain high frequency and logical relationships close to each other. Readers are suggested reference [25] for detailed discussion and explanation of the SLP technique.

3.3 AHP for qualitative data evaluation

Since qualitative data which is part of criteria to be evaluated is usually complicated and conflict, AHP are applied in order to provide the weights that indicate the relative importance of the layout alternatives for each criterion. The management are asked to determine a comparison matrix by comparing any pairs of qualitative criteria one at a time. Scale of importance according to Saaty 1-9 scale for the pairwise comparison is used in the comparison process. In order to avoid potential comparative inconsistency between any pairs of criteria in pairwise comparison matrix, a consistency ratio (CR), which is an index for consistency, is then calculated to assure the appropriateness of the comparisons. For the details of AHP methodology and CR development, readers are referred to look further at Saaty [26].

3.4 DEA for optimal layout design determination

DEA uses the linear programming to assess efficiencies of DMUs with the goal to determine the productive efficiency of DMUs by comparing how well the DMU converts inputs into outputs [21]. Assume that there are n DMUs to be evaluated, where each DMU consumes varying amounts of inputs to produce different amounts of outputs. x_{ij} and y_{rj} are respectively amounts of input ith and output rth of DMU_j, which are positive number. v_i and u_r are decision variables and are respectively called input and output multipliers or input and output weights. The efficiency score, h_0, of a particular DMU being evaluated, DMU_0, is obtained by solving the following model:

$$\max h_0(u,v) = \frac{\sum_r u_r y_{r0}}{\sum_i v_i x_{i0}} \tag{1}$$

$$\text{s.t.:} \quad \frac{\sum_r u_r y_{rj}}{\sum_i v_i x_{ij}} \le 1 \quad \forall j \tag{2}$$

$$u_r, v_i \ge 0 \quad \forall r,i \tag{3}$$

The objective function is to maximize the ratio of weighted outputs to weighted inputs or efficiency value for a particular DMU, subject to the constraints that the ratio of weighted outputs to weighted inputs is less than or equal to one. The model can be converted to a linear programming model, which is called CCR model as following:

$$\max h_0 = \sum_{r=1}^{s} u_r y_{r0} \tag{4}$$

$$\text{s.t.:} \quad \sum_{i=1}^{m} v_i x_{io} = 1 \tag{5}$$

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \le 0 \quad \forall j \tag{6}$$

$$u_r, v_i \ge 0 \quad \forall r,i \tag{7}$$

The model is run n times to identify the efficiency scores of all DMUs. DEA will identify the DMU(s) that produces the largest amounts of outputs by consuming the least amounts of inputs and then allocate efficiency score equal to one to the DMU(s). Other inefficient DMUs will be given efficiency scores relatively to the efficient DMU(s) which is less than one.

4 Performance evaluation for selection of plant layout design

A manufacturing company considered in this study focuses on manufacturing and design of high precision and high complexity mechanical components, including design, test, production, distribution and return/repair services. The company located in Thailand offers its products worldwide, especially in Europe and the USA. Due to a business expansion plan, the company has to double its machines in order to be able to handle the plastics precision line of product separately. Therefore, to ensure the effectiveness of the production line, the new plant layout needs to be function on supporting the production's upcoming activities.

4.1 Data collection

Fundamental data of the company such as product data, manufacturing process data, flow of process, plant layout pattern, and manufacturing facilities are collected. The current facility layout and the size of each area are shown in Fig. 2 and Table 1. The criteria (or the performance measures) for the selection of this plant layout design are determined by reviewing literatures as general layout guidelines and by discussing with the company's management. As a result, those criteria are: distance, cost, flexibility, safety, and utilization.

The *distance* is an average transit distance of any materials that are carried into and out of four department areas throughout the production process—turning, milling, quality control, and washing. The *cost* involves an investment cost in a renovation of the plant for the new layout design. The *flexibility* involves accessibility, maintenance, and ability to perform a variety of tacks for the future expansion. The *safety* involves both of personal and working environment that is safe from danger or harm in manufacturing workplace. The *utilization* is a proper utilization of the floor space.

4.2 Generation of plant layout alternatives

In order to support the expansion of the company's production line, the management decides to move several working areas from the current layout to the building nearby. The office area which includes meeting

Table 1. Size of facility's areas.

Available floor space = 18 m (Width) × 45 m (Length)

No.	Area	W×L	Size (m²)
1	Turning	14×15	210
2	Milling	14×21	294
3	Finish goods storage	9×14	126
4	Quality control (QC room)	4×6	24
5	Washing room	4×6	24
6	Office	4×25	100
7	WC (East)	4×3	12
8	WC (West)	4×5	20

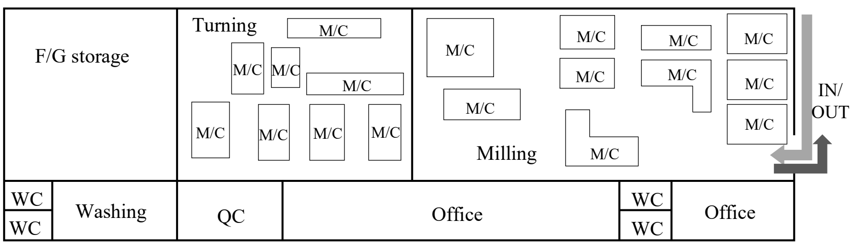

Fig. 2. Current facility layout.

room, CAD/CAM and planning rooms, and finish good storage area will be moved. The washing and quality control process, these working areas previously set separately but next to each other, are required during the manufacturing of turning and milling process. Since both processes are linked, the new layout will group them together for gaining advantage of the area extension.

By applying SLP technique, the relationships between departments in each process from material storage area to final product storeroom is collected. Accordingly, a relationship chart is drawn. As shown in Fig. 3, the closeness values are defined as following: A as absolutely necessary, E as an especially important, I as an important, O as ordinary closeness, and U as unimportant. Furthermore, the indicator of this relationship are defined as following: 1 as continuous operation, 2 as convenience, 3 as noise, 4 as lighting, 5 as shared workers, and 6 as vibration.

Three alternative plant layouts are developed based on modifying of the current layout. Since the management is deciding if the restrooms are staying in the new layout or not, six more choices of alternative layouts are generated, including three layouts with two WCs and other three layouts without any. All nine alternative plant layouts are displayed in Fig. 4 for further evaluation. The quantitative performance data related with each alternative layout, which will be used as the parameters of the DMU for DEA methodology, are shown in Table 2.

4.3 Evaluation of qualitative data

The qualitative performance data are obtained by AHP methodology and solved by a spreadsheet. The eigenvector or relative weight of each three qualitative criteria namely flexibility, safety, and utilization are 0.293, 0.078, and 0.629 respectively. The CR value is 0 (zero). Since CR is smaller than the commonly critical value of 0.1, there is no evidence of inconsistency.

The resulting relative weights of each criterion for each of nine alternatives are shown in Table 3. These weights then become parameters for the DMUs in DEA calculation. The resulting CR values for the comparison of alternatives are shown in Table 4. The pairwise comparison is considered to be consistent enough since all values are smaller than 0.1.

4.4 Determination of optimal layout design

The inputs and outputs of DMUs are necessary information for the computation of the DEA model. The criteria that are to be minimized are considered as inputs whereas the criteria to be maximized are viewed as outputs. For this case study of the plant layout designs, all output variables—flexibility, safety, and utilization—of DEA are from AHP analysis, and all inputs—distance and cost—are from layout design.

The DEA equations (4) to (7) are applied to the data set of the nine facility layout alternatives. Table 5 shows the efficiency scores obtained by using DEA. The results show that alternatives 1 and 7 are relatively efficient. They are equally viable candidates for the final layout design.

5 Conclusions

This paper addresses the evaluation of the facility layout design by developing framework based on AHP and DEA methodologies. SLP is adopted to develop the layout alternatives as well as to gather the quantitative performance data. The qualitative performance data are obtained by applying AHP to assess weights expressing

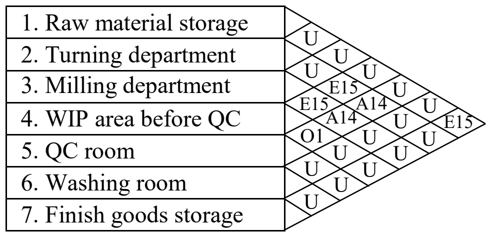

Fig. 3. Relationship chart.

Table 2. Quantitative measures for layout alternatives.

DMU no.	Distance (m)	Cost (thousand THB)
1	117.75	10
2	103.00	10
3	112.00	10
4	117.75	15
5	120.00	15
6	93.50	15
7	115.50	20
8	128.50	20
9	112.00	20

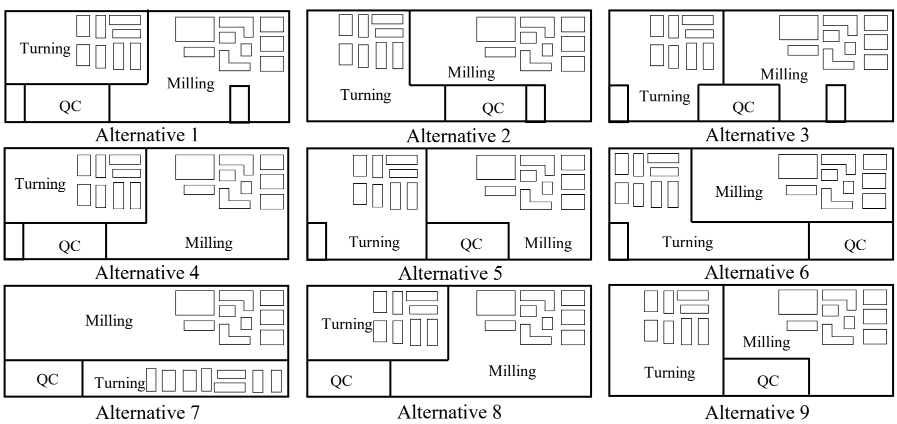

Fig. 4. Layout alternatives.

Table 3. Qualitative measures for layout alternatives.

DMU no.	Flexibility	Safety	Utilization
1	0.0739	0.0197	0.0552
2	0.0276	0.0067	0.0369
3	0.0215	0.0058	0.0323
4	0.0522	0.0141	0.0287
5	0.0232	0.0046	0.0244
6	0.0134	0.0039	0.0202
7	0.0429	0.0117	0.1672
8	0.0276	0.0074	0.1414
9	0.0107	0.0041	0.1227

Table 4. CR values.

Criteria	Flexibility	Safety	Utilization
CR	0.0652	0.0642	0.0656

Table 5. Final efficiency scores.

DMU no.	Efficiency score
1	1.0000
2	0.5436
3	0.4619
4	0.7143
5	0.3282
6	0.2807
7	1.0000
8	0.8457
9	0.7567

the relative importance of the layout alternatives for each criterion. DEA model is then applied to identify the efficiency scores by considering both the quantitative and qualitative performance data. The result indicates that DEA model is useful for finding global priorities among the layout designs. The proposed decision support framework offers a systematic guideline for the decision makers in planning the facility layout which could contribute to a successful final decision.

The framework is applied to a real data set of the manufacturing company which consists of both the quantitative and qualitative data for evaluating nine alternative layouts. Since the optimize outcome turns out to be more than one option, the final decision still needs to be made on which layout to be selected. However, this case study has successfully illustrated the effectiveness of this proposed framework, as a result. Moreover, the framework presented in this paper can easily be implemented without the need of using any software tools.

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