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A review of different approaches to the facility layout problems

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Abstract Here, an attempt is made to present a state-of-the-art review of papers on facility layout problems. This paper aims to deal with the current and future trends of research on facility layout problems based on previous research including formulations, solution methodologies and development of various software packages. New developments of various techniques provide a perspective of the future research in facility layout problems. A trend toward multi-objective approaches, developing facility layout software using meta-heuristics such as simulated annealing (SA), genetic algorithm (GA) and concurrent engineering to facility layout is observed.

Keywords Survey of facility layout problems · Combinatorial optimization · Quadratic assignment problem (QAP) · Mixed integer programming (MIP)

1 Introduction

Determining the physical organization of a production system is defined to be the facility layout problem (FLP). Where to locate facilities and the efficient design of those facilities are important and fundamental strategic issues facing any manufacturing industry. Tompkins and White [1] estimated that 8% of the United States gross national product has been spent on new facilities annually since 1955, that does not include the modification of existing facilities. Francis and White [2] claimed that from 20 to 50 percent of the total operating expenses in manufacturing are attributed to materials handling costs. Effective facilities planning could reduce these costs by 10 to 30 percent annually. For FLP, the most common objective used in mathematical models is to minimize the materials handling cost, which is a quantitative factor. Qualitative factors such as plant safety, flexibility of layout for future design changes, noise and aesthetics [2] can also be considered. They must be carefully considered in the context of the FLP. This paper gives a review of different approaches to the FLP, viz. formulations, solution methodologies and current as well as emerging trends. This paper aims to endorse readers who want to explore facility layout research and layout packages; it is an active area in which nearly 140 papers have been published on the FLP over the last 20 years. A detailed review of each and every software package is not carried out here but the references are provided.

The paper is structured as follows: In Section 2 an overview of the FLP along with the formulations is described. Solution methodology is addressed in Section 3. Current trends and further scope of work are discussed in Section 4 followed by a conclusion.

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2 Overview of facility layout problem

The FLP is a well studied combinatorial optimization problem which arises in a variety of problems such as printed circuit board design; layout design of hospitals, schools, and airports; backboard wiring problems; typewriters; warehouses; hydraulic turbine design; etc. The focus of this review work is on the facility layout of industrial (manufacturing) plants, which is concerned with finding the most efficient arrangement of '*n*' indivisible facilities in '*n*' locations. Minimizing the material handling cost is the most considered objective but Mecklenburgh [3] and Francis et al. [4] gave qualitative as well as quantitative objectives for FLP. Reduced material movement [5, 6] lowers work-in-process levels and throughput times, less product damage, simplified material control and scheduling, and less overall congestion. Hence, when minimizing material handling cost, other objectives are achieved simultaneously. The output of the FLP is a block layout that specifies the relative location of each department. Detailed layout of a department can also be obtained later by specifying aisle structure, and input/output point locations which may include flow line and machine layout problems. This paper is a survey of block layout. This section deals with the description of formulations of FLP.

In the following sub-sections, Section 2.1 describes QAP, graph theoretic approach is given in Section 2.2 and MIP formulation for FLP is provided in Section 2.3.

2.1 QAP model

FLP has been generally formulated as a QAP introduced by Koopmans and Beckman [7] which is NP-complete [8–10] and one of the frequently used formulations to resolve FLP. Consequently, even a powerful computer cannot handle a large instance of the problem. The objective can be to either minimize time, cost, traveling distance, and/or flows. Consequently, various heuristics have been proposed thus far to solve large instances of QAP and a review of these heuristic is given in Section 3.2. Equivalent linear integer formulations and heuristics have developed for solving the QAP but they are limited to particular problems [11–13]. Lawler [14] and Christofides et al. [15] demonstrated the equivalence of the QAP problem to a linear assignment problem with certain additional constraints. The following formulation is adopted from Koopmans and Beckman [7].

$$\text{MinTF} = {}^{1}\!/\!_{2} * \sum_{\substack{i=1 \\ i\neq k}}^{n} \sum_{\substack{j=1 \\ j\neq l}}^{n} \sum_{k=1}^{n} \sum_{l=1}^{n} F_{ik} * D_{jl} * X_{ij} * X_{kl} \tag{1}$$

$$\sum_{j=1}^{n} X_{ij} = 1 \quad \text{for all i} = 1 \ldots \text{n} \tag{2}$$

$$\sum_{i=1}^{n} X_{ij} = 1 \quad \text{for all } j = 1 \ldots \text{n} \tag{3}$$

X_{ij}=1 if facility "*i*" is located/assigned to location "*j*".
X_{ij}=0 if facility "*i*" is not located/assigned to location "*j*".
F_{ik} is the flow between two facilities i and k.
D_{jl} is the distance between two locations j and l.
Constraint 1 (Eq. 1) is a restriction that only one facility can be located at one location, and constraint 2 (Eq. 2) ensures that each location can only be assigned to one facility. The objective is to minimize the total flow among facilities i=1 to n and k=1 to n. As all indices are summed from 1 to n, each assignment will be counted twice; hence the need to multiply by 1/2.

2.2 Graph theory model

In the graph theoretic approaches each department or machine (ignoring the area and shape of the departments at the beginning) is defined as a node within a graph network. These rely on a predefined desirable adjacency of each pair of facilities [16, 17]. In other words, it can be said that in graph theoretic approaches, it is assumed that the desirability of locating each pair of facilities adjacent to each other is known. Like QAP approaches, unequal area problems of even small size cannot be solved optimally [18]. Various papers have been published on this subject where different models and algorithms' characteristics have been explored [19–21]. A review of the results of graph theoretic approaches can be found in Foulds [17] and Hassan and Hogg [16].

2.3 MIP model

MIP has received some attention as a way of modeling the FLP. Montreuil [22] first formulated FLP as MIP where a distance-based objective was used in a continuous layout representation that was an extension of the discrete QAP. Hegaru and Kusiak [23] developed a specialized case of this MIP. Lacksonen [24] proposed a two-step algorithm for solving the FLP while assuming variable area which can solve a general dynamic facility layout with varying departmental areas assuming that all are rectangular. Lacksonen [25] then extended the proposed model to deal with unequal areas and rearrangement costs. However, the model could only be optimally solved for small problems. Kim and Kim [26] considered the problem of locating input and output (I/O) points of each department for a given block layout with the objective of minimizing the total transportation distance. A new branch-and-bound algorithm was proposed that seems to perform efficiently even for large-size problems. However, the simultaneous solution of the block problem and the I/O points layouts has not yet been solved. Barbosa-Povoa et al. [27] proposed a mathematical programming approach for the generalized facilities detailed layout problem.

A detailed MIP for FLP can be found in Montreuil [22]. Although this MIP approach holds much promise, currently only FLP of size six or less [18] are optimally solvable. The objective is based on flow time rectilinear distance between centroid of two departments.

3 Solution methodology

In this section various solution methodologies, e.g. exact procedures, heuristics and meta-heuristics available to solve facility layout problems optimally or near to optimal, are discussed in detail. Exact procedures that can give optimal solutions to facility layout problems are discussed in Section 3.1. Section 3.2 briefly describes heuristic methods used to solve facility layout problems. Meta-heuristics available to solve facility layout problems are given is Section 3.3. Section 3.4 is devoted to artificial intelligence approaches applied to solve the facility layout problems.

3.1 Exact procedure

Branch and bound methods are used to find an optimum solution of quadratic assignment formulated FLP because QAP involves only binary variables. Only optimal solutions up to a problem size of 16 are reported in literature. Beyond n=16 it becomes intractable for a computer to solve it and, consequently, even a powerful computer cannot handle a large instance of the problem.

3.2 Heuristics

A comprehensive investigation of the FLP literature includes examining heuristics. Heuristic algorithms can be classified as *construction* type algorithms where a solution is constructed from scratch and *improvement* type algorithms where an initial solution is improved. *Construction* based methods are considered to be the simplest and oldest heuristic approaches to solve the QAP from a conceptual and implementation point of view, but the quality of solutions produced by the construction method is generally not satisfactory. *Improvement* based methods start with a feasible solution and try to improve it by interchanges of single assignments. Improvement methods can easily be combined with construction methods. CRAFT [28] is a popular improvement algorithm that uses pairwise interchange. A survey of a few well known heuristics which are popular as layout software are provided in Table 1 along with the algorithm used. These heuristics are classified as *adjacency* and *distance* based algorithms. For instance, MATCH [29] and SPIRAL [30] are *adjacency* based while CRAFT [28], SHAPE [31], LOGIC [32], MULTIPLE [33], and FLEX-BAY [34] are distance based algorithms (descriptions are not provided but interested readers can refer to the cited papers).

The difference between these two algorithms lies in the objective function. The objective function for adjacency based algorithms is given as

$$\max \sum_{i} \sum_{j} (r_{ij}) x_{ij} \tag{4}$$

where $\boldsymbol{x}_{ij}$ is 1 if department '*i*' is adjacent to department '*j*' and else 0. The basic principle behind this objective function is that the material handling cost is significantly reduced if the two departments have adjacent boundaries. The objective function of distance based algorithms is given as

$$\mathrm{Min(TC)} = \tfrac{1}{2} * \sum_{\substack{i=1 \\ i \neq k}}^{n} \sum_{\substack{j=1 \\ j \neq l}}^{n} \sum_{k=1}^{n} \sum_{l=1}^{n} C_{ik} * D_{jl} * X_{ij} * X_{kl} \tag{5}$$

The underlying philosophy behind this objective function is that the distance increases the total cost of traveling. $\boldsymbol{C}_{ik}$ can be replaced by $\boldsymbol{F}_{ik}$ depending on the objective. Equation 6 is used as an objective function when the facility layout is designed for multi-floor.

$$\min \sum_{\substack{i=1 \\ i \neq k}}^{n} \sum_{\substack{j=1 \\ j \neq l}}^{n} \sum_{k=1}^{n} \sum_{l=1}^{n} \left(C_{ikH} * D_{jlH} + C_{ikV} * D_{jlV} \right) * X_{ij} * X_{kl} \tag{6}$$

Table 1 List of facility layout packages [33, 35]

S.No	References	Name of package
1	Dr. Gordan Armour	CRAFT
2	Seehof and Evans	ALDEP
3	Dr. Moore James	CORELAP
4	Michael P. Deisenroth	PLANET
5	Teichholz Eric	COMP2
6	Kaiman Lee	COMPROPLAN COMSBUL
7	Robert C. Lee	CORELAP8
8	Robert Dhillon	DOMINO
9	Teichholz Eric	GRASP
10	Dr. Johnson T.E.	IMAGE
11	Dr. Warnecke	KONUVER
12	Dr. Warnecke	LAYADAPT
13	Raimo Matto	LAYOPT
14	John S. Gero	LAYOUT
15	Dr. Love R.F.	LOVE*
16	Dr. Warnecke	MUSTLAP2
17	Dr. Vollman Thomas	OFFICE
18	McRoberts K.	PLAN
19	Anderson David	PREP
20	Moucka Jan	RG and RR
21	Dr. Ritzman L.P.	RITZMAN*
22	Dr. Warnecke	SISTLAPM
23	Prof. Spillers	SUMI
24	Hitchings G.	Terminal Sampling Procedure
25	Johnson [36]	SPACECRAFT
26	Tompkins and Reed [37]	COFAD
27	Hassan, Hogg and Smith [31]	SHAPE
28	Banerjee et al. [38]	QLAARP
29	Tam [39]	LOGIC
30	Bozer, Meller, and Erlebacher [33]	MULTIPLE
31	Tate and Smith [34]	FLEX-BAY
32	Foulds and Robinson [40]	DA (Adjacency Based)
33	Montreuil, Ratliff and Goetschalckx [29]	MATCH (Adjacency Based)
34	Goetschalckx [30]	SPIRAL (Adjacency Based)
35	Balkrishnan et al. [41]	FACOPT

* Indicates that the names of packages are based on author's name

Where, $\boldsymbol{C}_{ikH}$ and $\boldsymbol{D}_{jlH}$ stand for horizontal material handling cost and horizontal distance, respectively. The same meanings are applicable for $\boldsymbol{C}_{ikV}$ and $\boldsymbol{D}_{jlV}$ but in vertical directions.

3.3 Meta-heuristics

Various meta-heuristics such as SA, GA, and ant colony are currently used to approximate the solution of very large FLP. The SA technique originates from the theory of statistical mechanics and is based upon the analogy between the annealing of solids and solving optimization problems. Burkard and Rendl [42] derived SA for QAP. A

Table 2 Survey of SA based FLP papers

S. No.	Reference	Year	QAP	MIP	Heuristic	
1	Kirkpatrick et al. [46]	1983	√			Simulated annealing
2	Burkard and Rendl [42]	1984	√			Simulated annealing
3	Wilhelm and Ward [47]	1987	√			Simulated annealing
4	Kaku and Thomson [48]	1986	√			Simulated annealing
5	Connolly [49]	1990	√			Simulated annealing
6	Laursen [10]	1993	√			Simulated annealing
7	Tam [32]	1992		√		Simulated annealing
8	Heragu and Alfa [50]	1992			√	Simulated annealing
9	Kouvelis et al. [51]	1992	√			Simulated annealing
10	Jajodia et al. [52]	1992			√	Simulated annealing
11	Shang [53]	1993	√			SA and AHP
12	Souilah [54]	1995		√		Simulated annealing
13	Peng et al. [55]	1996	√			Simulated annealing
14	Meller and Bozer [56]	1996			√	Simulated annealing
15	Azadivar and Wang [57]	2000	√			Simulated annealing
16	Baykasoglu and Gindy [58]	2001	√			Simulated annealing
17	Misevicius [59]	2003	√			Simulated annealing
18	Balakrishnan et al. [41]	2003	√		√	SA and GA

most recent survey of SA based facility layout papers is tabulated in Table 2.

GA gained more attention during the last decade than any other evolutionary computation algorithms; it utilizes a binary coding of individuals as fixed-length strings over the alphabet $\{0, 1\}$. GA iteratively search the global optimum, without exhausting the solution space, in a parallel process starting from a small set of feasible solutions (population) and generating the new solutions in some random fashion. Performance of GA is problem dependent because the parameter setting and representation scheme depends on the nature of the problem. Tavakkoli-Moghaddam and Shayan [43] analyzed the suitability of genetic operator for solving FLP. Table 3 provides recent papers on GA based FLP.

Tabu search (TS) is an iterative procedure designed to solve optimization problems. Helm and Hadley [44] applied TS to solve FLP. The method is still actively researched, and is continuing to evolve and improve.

Recently, a few papers have appeared where an ant colony algorithm has been attempted to solve large FLP. Talbi et al. [45] applied ant colony to solve QAP.

3.4 Other approaches

Other approaches which are also currently applied to FLP are neural network, fuzzy logic and expert system. Tsuchiya et al. [72] had proposed near-optimum parallel algorithm for solving the QAP using two-dimensional maximum neural network for an N-FLP. Knowledge based expert system has also been applied by Malakooti and Tsurushima [73], Abdou and Dutta [74], Heragu and Kusiak [75] and Sirinavakul and Thajchayapong [76] to

Table 3 Survey of GA based FLP papers

S. No.	Reference	Year	QAP	MIP	Heuristic	
1	Tam [39]	1992		√		Genetic algorithm
2	Banerjee and Zhou [60]	1995		√		Genetic search
3	Tate and Smith [34]	1995	√			GA
4	Kochhar and Heragu [61]	1998		√	√	Extension of GA
5	Islier [62]	1998				GA
6	Rajshekaran et al. [63]	1998		√	√	GA
7	Mak et al. [64]	1998		√		GA
8	Mckendall et al. [65]	1999		√	√	GA nested approach
9	Kochhar and Heragu [66]	1999			√	GA
10	Gau and Meller [67]	1999		√	√	GA
11	Azadivar and Wang [57]	2000	√			GA and simulation algorithm
12	Al-Hakim [68]	2000				GA
13	Ahuja [69]	2000	√			Genetic algorithm
14	Wu and Appleton [70]	2002		√		GA
15	Lee, Han and Roh [71]	2003		√		GA, Dijkstra algorithm
16	Balakrishnan et al. [41]	2003	√		√	GA and SA

Table 4 Survey of Papers where other approaches are applied to solve FLP

S. No.	Reference	Year	QAP	MIP	Heuristic	Techniques
1	Dutta and Sahu [78]	1982	√		√	
2	Murtagh et al. [79]	1982	√		√	
3	Foulds [80]	1983	√			Graph theory
4	Herroelen and Vangils [81]	1985				Flow dominance theory
5	Fortenberry and Fox [82]	1985			√	Pair-wise exchange
6	Hammouche and Webster [83]	1985				Graph theory (theoritical approach)
7	Foulds and Giffin [84]	1985			√	Graph theory
8	Green and Al_Hakim [85]	1985		√	√	
9	Rosenblatt [86]	1986	√			Dynamic programming
10	Kaku and Thomson [48]	1986	√			Simulated annealing
11	Hassan et al. [31]	1986		√	√	Construction
12	Foulds et al. [87]	1986	√			Graph theory
13	Grobelny [88]	1987			√	Fuzzy approach
14	Evans et al. [89]	1987	√			Fuzzy set theory
15	Urban [90]	1987	√		√	
16	Rosenblatt and Lee [91]	1987	√		√	
17	Jacobs [92]	1987	√			Graph theory
18	Montreuil et al. [29]	1987				Graph theory
19	Hassan and Hogg [16]	1987				Graph theory
20	Grobelny [93]	1988			√	Fuzzy approach
21	Kaku et al. [94]	1988	√		√	
22	Kumar et al. [77]	1988				Expert system, pattern recognition
23	Smith and Macleod [95]	1988	√			L. R. and B and B
24	Malakooti and Tsurushima [73]	1989				Expert system, rule based
25	Malakooti [96]	1989	√		√	
26	Heragu and Kusiak [97]	1988		√	√	
27	Heragu and Kusiak [75]	1990		√		Knowledge approach
28	Abdou and Dutta [74]	1990				Expert system
29	Houshyar and McGinis [98]	1990	√		√	Cut approach
30	Al-Hakim [99]	1991				Graph theory
31	Heragu and Kusiak [23]	1991		√	√	Unconstrained opt.
32	Kaku et al. [100]	1991		√	√	
33	Hassan and Hogg [101]	1991		√		Graph theory
34	Logendran [102]	1991		√	√	
35	Burkard et al. [103]	1991	√			QAP_LIB
36	Camp et al. [104]	1992		√	√	Penalty function
37	Leung [105]	1992			√	Graph theory
38	Kaku and Rachamadya [106]	1992	√		√	
39	Rosenblatt and Golany [107]	1992	√		√	
40	Goetschalckx [30]	1992	√		√	Graph theory
41	Harmonosky and Tothero [108]	1992	√		√	Pairwise, construction
42	Askin and Mitwasi [109]	1992		√	√	
43	Balakrishnan et al. [110]	1992	√		√	
44	Al-Hakim [111]	1992				Grapht theory
45	Lacksonan and Enscore [112]	1993	√			B and B, cutting plane, D.P.
46	White [113]	1993	√			Branch and bound; convex programming
47	Yaman et al. [114]	1993	√		√	
48	Das [115]	1993		√	√	
49	Raoot and Rakshit [116]	1991			√	Fuzzy based

Table 4 (continued)

S. No.	Reference	Year	QAP	MIP	Heuristic	Techniques
50	Raoot and Rakshit [117]	1994			√	Fuzzy based
51	Urban [118]	1993		√	√	
52	Montreuil et al. [119]	1993		√		Graph theory, LP
53	Bozer et al. [33]	1994			√	
54	Boswell [120]	1994			√	Graph theory based
55	Sirinaovakul [76]	1994			√	Knowledge based expert
56	Langevin et al. [121]	1994		√	√	
57	Trethway and Footle [122]	1994			√	
58	White [123]	1996	√			Lagrangian relaxation
59	Badiru and Arif [124]	1996				Fuzzy theory
60	Chiang and Kouvelis [125]	1996			√	Tabu Search
61	Watson and Giffin [21]	1997			√	Vertex splitting algo.
62	Meller [126]	1997		√	√	
63	Lacksonan [25]	1997		√	√	Branch and bound
64	Bozer and Meller [127]	1997			√	
65	Sarker et al. [13]	1998	√		√	
	Zetu et al. [128]	1998				Virtual reality(Theoritical approach)
66	Urban [129]	1998	√			Dynammic programming
67	Chan and Sha [130]	1999	√		√	
68	Smith and Helm [131]	1999				Virtual reality (Theoritical approach)
69	Dweiri [132]	1999				Fuzzy based
70	Helm and Hadley [44]	2000		√	√	Tabu-search based
71	Knowles and Corne [133]	2002	√			Multi-obj. approach
72	Kim and Kim [134]	2000		√	√	
73	Barbosa-Povoa et al. [27]	2001		√	√	
74	Al-Hakim [135]	2001				Maximally planer graph
75	Wang and Sarker [136]	2002	√		√	
76	Chan, Chan and Ip [137]	2002		√	√	
77	Diponegoro and Sarker [138]	2003	√		√	
78	Castillo and Peters [139]	2003	√		√	Extended distance based

tackle various issues related to FLP such as multi-objective, the issue of optimizing material handling equipment, etc. Kumar et al. [77] applied expert system to handle qualitative constraints via a symbolic manipulation structure. A survey of papers where these methodologies have been applied to solve FLP is given in Table 4.

4 Current trends and future scope of work

This section addresses the issues related to current trends in the area of FLP and also future research directions. Section 4.1 deals with the currents trends in facility layout followed by future scope of work.

4.1 Current trends

A summary of current trends during the last two decades is reviewed here where more than 100 papers are classified as per the facility classification scheme shown in Fig. 1. Papers in various tables are given in chronological order along with the solution methodology and formulation used

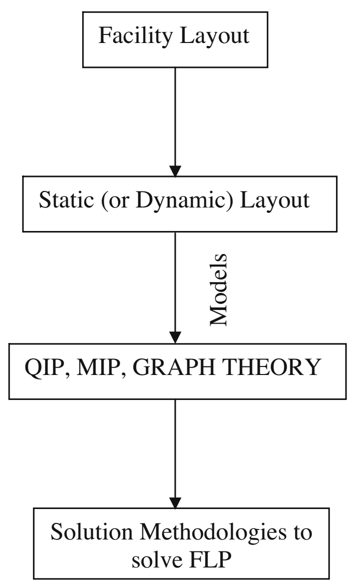

Fig. 1 Classification scheme of facility layout problems

to model FLP that helps to provide a clear understanding of various aspects of FLP.

4.2 Future scope of work

By observing all tables it has been found that research on the FLP is not converging but is somewhat diverging. Now, AI can be used apart from developing heuristic to solve large sized FLPs; and more investigation into the multi-objective function rather than single objective function is required in order to include more relevant layout criteria.

Every two years the Material Handling Institute of America [18], along with other sponsoring industries and government agencies, organizes consortium on material handling research where researchers are asked to present their research. It is found that there is a lack of application of concurrent engineering in FLP with respect to the choice of the material handling system which in turn shows that the current facility layout design is irrespective to the choice of material handling system. It has been concluded that the same facility layout design may not be appropriate for all periods since the demand can never remain the same. Hence, research should be towards a stochastic facility layout rather than a static one.

There is emerging research into applying meta-heuristic such as SA, GA and tabu search to solve large FLP. But, the final result depends on the initial solution (or population) taken. Therefore, more research is required to develop good heuristic to generate good initial feasible solutions.

5 Conclusion

The trends of facility layout research over the past two decades are presented in this paper. Recent facility layout papers are identified and summarized along with the solution methodology used. Various algorithms as well as computerized facility layout software are addressed. A further scope of work that is needed in the facility layout area is also suggested.

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