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ORIGINAL ARTICLE

Classification of facility layout problems: a review study

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Abstract Facility layout problem (FLP) is defined as the placement of facilities in a plant area, with the aim of determining the most effective arrangement in accordance with some criteria or objectives under certain constraints, such as shape, size, orientation, and pick-up/drop-off point of the facilities. It has been over six decades since Koopmans and Beckmann published their seminal paper on modeling the FLP. Since then, there have been improvements to these researchers' original quadratic assignment problem. However, research on many aspects of the FLP is still in its initial stage; hence, the issue is an interesting field to work on. Here, a review of literature is made by referring to numerous papers about FLPs. The study is mainly motivated by the current and prospective trends of research on such points as layout evolution, workshop characteristics, problem formulation, and solution methodologies. It points to gaps in the literature and suggests promising directions for future research on FLP.

Keywords Facilities planning and design · Material handling cost · Dynamic facility layout problem · Survey

1 Introduction

To operate production and service systems efficiently, companies should not only be operated with optimal planning and operational policies but also have a facility layout that is well-designed [1]. Facility layout problem (FLP) is defined as finding the most efficient arrangement of elements on the factory floor subject to different constraints in order to meet one or more objectives [2, 3]. An effective facility layout design increases throughput, overall productivity, and efficiency [4]. In return, a poor facility layout results in increased work-in process and manufacturing lead time [1].

The most significant indicator of the efficiency of a layout is the material handling cost (MHC) [5]. Since 20–50% of the total operating costs of a manufacturing company and 15–70% of the total cost of manufacturing of a product are attributed to MHC [6], companies can reduce these costs by at least 10–30% [1] and improve their productivity if their facilities are arranged effectively. Conversely, an ineffective layout can add as much as 36% to MHC [2]. Additionally, research shows that more than 35% of system efficiency is likely to be lost by applying incorrect layouts and location designs [7]. Hence, FLP is one of the most important problems in the literature of production management and industrial engineering, attracting the attention of many researchers in the field of static and dynamic layouts.

When the flow of materials between facilities does not change over time, the problem is known as the static facility layout problem (SFLP), and, in the simplest form, it can be formulated as a quadratic assignment problem (QAP) [5]. In the QAP formulation, all facilities have the same area, and the layout is divided into N equal-sized locations, where each facility is assigned to exactly one location and vice versa [8]. Therefore, SFLP is mapping from facilities to locations along with minimizing of the sum of MHC between each pair of facilities [9]. It is very unlikely that material flows between facilities remain unchanged during a long planning horizon. As noted by Gupta and Seifoddini, one third of US companies undergo major reorganization of their production facilities

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every 2 years, and, on average, 40% of a company's sales come from new products [10]. According to Shore and Tompkins, some of the factors that lead to a change in the flow of materials between facilities are as follows [11]:

1. Shorter product life cycles
2. Changes in the design of an existing product
3. Addition or deletion of products
4. Changes in production quantities and the associated production schedules
5. Replacement of existing production equipment

Based on the factors listed above, when material flows between facilities change during the planning horizon, the SFLP becomes a dynamic facility layout problem (DFLP) [11]. It is assumed that the data of flow for each period are predicted and remain constant throughout the period [12]. Generally, DFLP includes the selection of a static layout for each period and making decisions on whether the layout will be changed to another layout in the next period or not [13]. Therefore, the layout plan is determined in a planning horizon in such a way that the sum of the MHC and the cost of rearranging facilities in consecutive periods is minimized [11].

FLP is one of the most important classical problems of production management and industrial engineering that has attracted the attention of many researchers during recent decades. Interestingly, research on many aspects of this problem is still in its initial stage; hence, FLP is a problem worth working on. This paper reviews the classification of FLP through a comprehensive and extensive investigation and analysis of extant literature, which includes 186 publications in the last 30 years. The literature review is a valid approach and necessary step in exploring new research directions, which helps to scrutinize the conceptual aspects and guides the research towards new theoretical development [14]. There are several reviews in FLP, but they are not new (for example [15–21]) or are restricted to certain specific aspects of FLPs (e.g., [22, 23]). The literature analysis given here is recent and not limited to specific considerations about layout design. In order to provide a general overview of the research conducted for FLPs, the essential features with which to characterize layout problems are categorized in Fig. 1 as a tree representation. This tree is composed of four main branches (i.e., layout evolution, workshop characteristics, problem formulation, and resolution approaches). Consequently, the rest of this study is organized in accordance with this representation and with the most important features identified. The main motivation for this article is to study the current and future trends based on existing researches. Further potential research issues and opportunities of FLP are also identified in this research. Tables 1 and 2 summarize the characteristics of the literature review based on the classification of Fig. 1. The publication years of the manuscripts are from 1987 to 2016. Furthermore, see Fig. 2 for publication distribution by journal. The top four journals contribute 53% of the whole publications.

The present paper is structured as follows. Section 2 overviews the workshop characteristics. Section 3 considers how FLPs can be formulated. Different methods used to solve the problem are addressed in Sect. 4. Section 5 highlights the layout evolution. Section 6 points to the gaps in the literature and suggests promising directions for future research on FLP. Finally, the paper ends with a conclusion in Sect. 7.

2 Overview of workshop characteristics

Several factors and design issues are addressed in the literature, particularly the production variety and volume, the facility shapes and dimension, the material handling system chosen, and different possible flows allowed for parts. These factors are detailed below.

2.1 Manufacturing systems

Facility layouts are directly influenced by the specifications of production systems, such as product variety and production volumes. In a classic classification, manufacturing systems can be divided into four categories, namely, product layout, process layout, fixed-position layout, and cellular layout. In a product layout, the machines and equipment are arranged in one line depending upon the sequence of operations required for the product. The materials move from one workstation to another sequentially without any backtracking or deviation. Product layouts are used for systems with a high production capacity and a low variety of products. In a process layout, the machines of a similar type are arranged together in one place. For example, machines performing drilling operations are arranged in the drilling department, and machines performing painting operations are grouped in the painting department. Process layout is often reported to be suited when the operation system must handle a wide variety of products on a relatively small scale. In a fixed-position layout, the major product being produced is fixed in one location, and machines, equipment, labor, and components are taken there. This particular type of layout is relevant for industries that manufacture heavy and large-scale products, such as locomotives, wagons, ships, and airplanes. In a cellular layout, operations required to produce a particular class of parts are arranged in a certain sequence. Cellular layouts are used when the operation system must handle an average variety of products in moderate volumes. This type of layout combines the aspects of both product and process layouts.

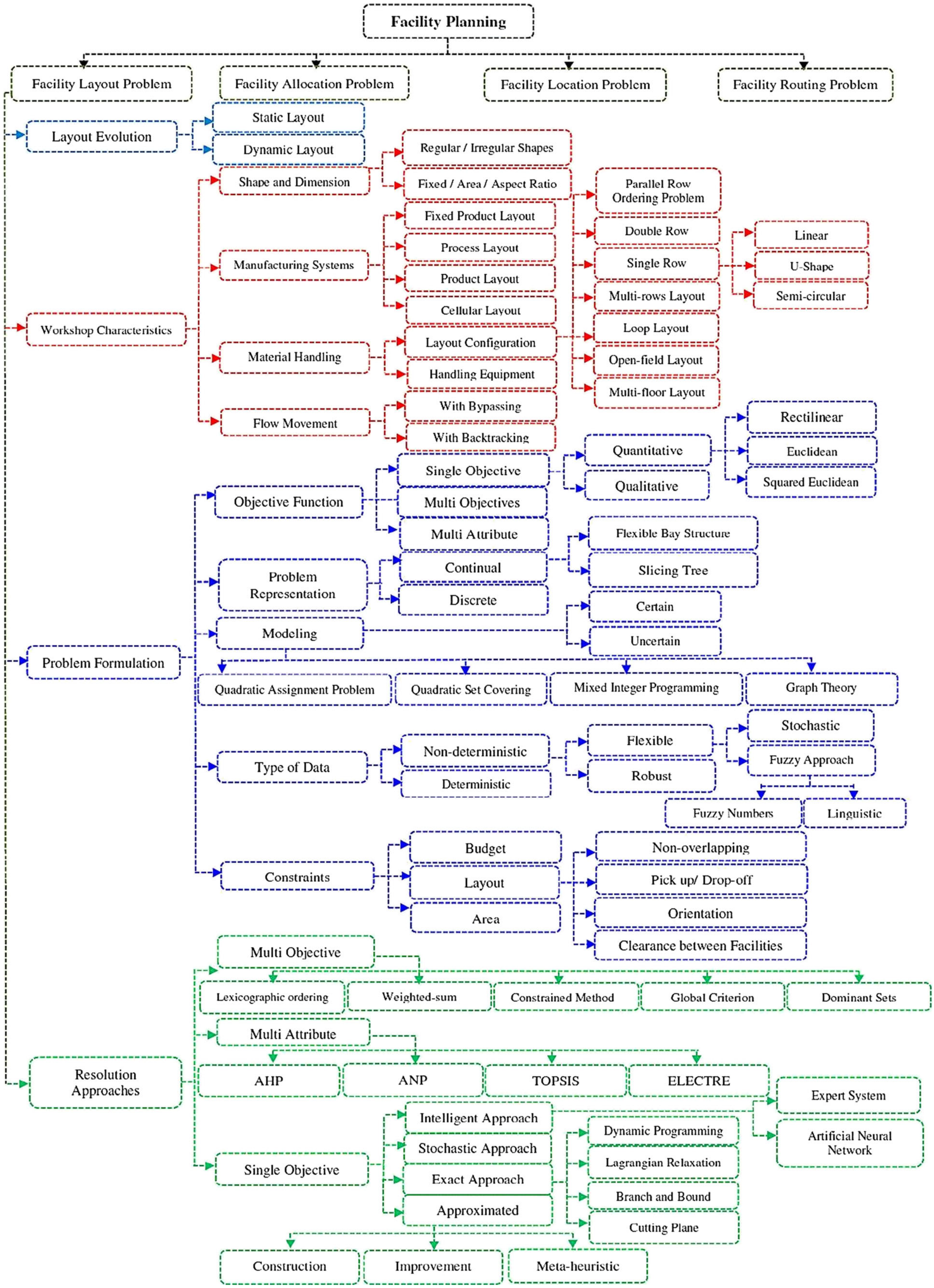

Fig. 1 Classification of the layout problems

Table 1 Summary of SFLP papers

Reference	Workshop characteristics												Problem formulation																Resolution approaches			
	Sh. & Dim.				MHS								OF		Rep		TOD				MD		CONST									
	Regular	Irregular	Fixed	Area / Aspect Ratio	Single Row Layout	Multi Row Layout	Double Row Layout	Parallel Row Ordering	Loop Layout	Open-field Layout	Multi Floor Layout	Handling Equipment	Single-criterion	Multi-criterion	Continual	Discrete	Deterministic	Robust	Fuzzy	Stochastic	Certain	Uncertain	Budget	Area	Non-overlapping	Pick-up / Drop-off	Orientation	Clearance	**Exact**	**Stochastic**	**Approximated**	**Intelligent**
[24]	☑		☑							☑		☑		☑	☑		☑				☑			☑	☑				☑			
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Sh. & Dim.: Shape and dimension, **MHS:** Material handling systems, **OF:** Objective function, **Rep:** Representation, **TOD:** Type of data, **MD:** Model, **CONST:** Constraints

2.2 Facility shapes and dimensions

Based on studies in the literature, there are two different facility shapes to identify [17] including regular shapes, i.e., rectangular, and irregular shapes, i.e., generally polygons, each with an angle sum of at least 270°. A facility can be defined by a fixed length and a fixed width. In this case, the facility is called fixed or rigid block [42]. According to [196], a facility may be also represented by its area, or its aspect ratio. The aspect ratio of facility *i* is defined as

$$\alpha_i = \frac{\text{Length of facility } i}{\text{Width of facility } i} = \frac{L_i}{W_i} \tag{1}$$

where α_i is between an upper bound α_{iu} and a lower bound α_{il} ($\alpha_i \in [\alpha_{il}, \alpha_{iu}]$). If $\alpha_i = \alpha_{il} = \alpha_{iu}$, it corresponds to the case of fixed-shape blocks [196]. Figure 3 shows the distribution of publications, categorized by the shapes and dimensions of facilities.

2.3 Material-handling system

Material-handling system (MHS) is defined as the selection and arrangement of a handling device along a material-handling path in order to reduce the MHC. MHS can be evaluated on the basis of the following two aspects:

1. Material-handling equipment: It may include conveyors, cranes, elevators, auxiliary equipment, industrial trucks, automated guided vehicles (AGVs), robots, etc.

Table 1 (continued)

Reference	Workshop characteristics												Problem formulation																Resolution approaches			
	Sh. & Dim.				MHS								OF		Rep		TOD				MD		CONST									
	Regular	Irregular	Fixed	Area / Aspect Ratio	Single Row Layout	Multi Row Layout	Double Row Layout	Parallel Row Ordering	Loop Layout	Open-field Layout	Multi Floor Layout	Handling Equipment	Single-criterion	Multi-criterion	Continual	Discrete	Deterministic	Robust	Fuzzy	Stochastic	Certain	Uncertain	Budget	Area	Non-overlapping	Pick-up / Drop-off	Orientation	Clearance	**Exact**	**Stochastic**	**Approximated**	**Intelligent**
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Table 1 (continued)

Reference	Workshop characteristics												Problem formulation																Resolution approaches			
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[107]	✓		✓			✓								✓		✓	✓				✓			✓							✓	
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[8]	✓			✓		✓							✓		✓		✓				✓			✓	✓				✓			
[131]	✓		✓			✓								✓		✓	✓				✓			✓							✓	
[132]	✓			✓						✓			✓		✓		✓				✓			✓	✓				✓			
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[136]	✓		✓							✓				✓	✓		✓		✓		✓			✓	✓	✓					✓	✓
[137]	✓			✓							✓			✓	✓		✓				✓			✓	✓						✓	
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[151]	✓	✓		✓						✓				✓		✓	✓				✓			✓							✓	
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[161]	✓		✓			✓							✓			✓	✓	✓			✓			✓							✓	

Sh. & Dim.: Shape and dimension, **MHS:** Material handling systems, **OF:** Objective function, **Rep:** Representation, **TOD:** Type of data, **MD:** Model, **CONST:** Constraints

Table 2 Summary of DFLP papers

Reference	Workshop characteristics												Problem formulation																Resolution approaches			
	Sh. & Dim.				MHS								OF		Rep		TOD				MD		CONST									
	Regular	Irregular	Fixed	Area / Aspect Ratio	Single Row Layout	Multi Row Layout	Double Row Layout	Parallel Row Ordering	Loop Layout	Open-field Layout	Multi Floor Layout	Handling Equipment	Single-criterion	Multi-criterion	Continual	Discrete	Deterministic	Robust	Fuzzy	Stochastic	Certain	Uncertain	Budget	Area	Non-overlapping	Pick-up / Drop-off	Orientation	Clearance	**Exact**	**Stochastic**	**Approximated**	**Intelligent**
[162]	✓		✓		✓	✓								✓		✓	✓				✓			✓					✓		✓	
[4]	✓		✓			✓							✓		✓		✓			✓	✓			✓	✓			✓			✓	
[163]	✓		✓			✓								✓		✓	✓				✓			✓							✓	
[164]	✓		✓							✓				✓	✓		✓		✓	✓	✓			✓	✓						✓	
[165]	✓		✓			✓							✓			✓	✓				✓			✓							✓	
[166]	✓		✓				✓						✓		✓		✓				✓			✓	✓			✓			✓	
[38]	✓		✓							✓			✓		✓		✓				✓			✓	✓						✓	
[167]	✓			✓						✓			✓		✓		✓				✓			✓	✓						✓	
[168]	✓			✓						✓			✓		✓		✓				✓			✓	✓						✓	
[169]	✓		✓		✓									✓		✓	✓				✓			✓							✓	
[170]	✓		✓			✓							✓			✓	✓		✓		✓			✓							✓	
[171]	✓		✓			✓							✓			✓	✓				✓			✓							✓	
[172]	✓		✓			✓							✓			✓	✓				✓			✓							✓	
[10]	✓		✓			✓							✓			✓	✓		✓		✓			✓							✓	
[173]	✓			✓		✓							✓		✓		✓				✓			✓	✓						✓	
[174]	✓		✓			✓							✓			✓	✓				✓			✓							✓	
[175]	✓		✓			✓							✓			✓	✓				✓			✓							✓	
[176]	✓		✓			✓							✓			✓	✓				✓			✓						✓	✓	
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[177]	✓		✓			✓								✓		✓	✓		✓		✓			✓							✓	
[178]	✓		✓			✓							✓			✓	✓				✓		✓	✓						✓		
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[180]	✓		✓		✓								✓			✓	✓			✓	✓			✓							✓	
[1]	✓		✓			✓							✓			✓	✓	✓			✓			✓							✓	
[181]	✓		✓			✓							✓			✓	✓				✓			✓							✓	
[182]	✓		✓			✓								✓		✓	✓			✓	✓			✓							✓	
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[189]	✓		✓			✓							✓			✓	✓				✓		✓	✓							✓	
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[190]	✓		✓			✓							✓			✓	✓				✓			✓							✓	
[191]	✓		✓							✓			✓		✓		✓				✓			✓	✓	✓	✓		✓		✓	
[192]	✓		✓			✓							✓			✓	✓				✓			✓					✓		✓	
[193]	✓		✓							✓			✓		✓		✓	✓			✓			✓	✓		✓				✓	
[194]	✓		✓			✓							✓			✓	✓				✓		✓	✓							✓	
[195]	✓		✓			✓							✓			✓	✓				✓		✓	✓					✓		✓	

Sh. & Dim.: Shape and dimension, **MHS:** Material handling systems, **OF:** Objective function, **Rep:** Representation, **TOD:** Type of data, **MD:** Model, **CONST:** Constraints

As aforementioned, MHC plays a very important role in manufacturing systems.

2. Layout configuration: FLPs are classified into seven well-known categories, namely, single-row, multi-row, double-row, parallel-row, loop, open-field, and multi-floor layouts as illustrated in Fig. 4. These categories, which are described below, are distinguished by the shape of their material-handling path.

 a. *Single-row layout problem* (*SRLP*): This problem is concerned with the arrangement of a given number of

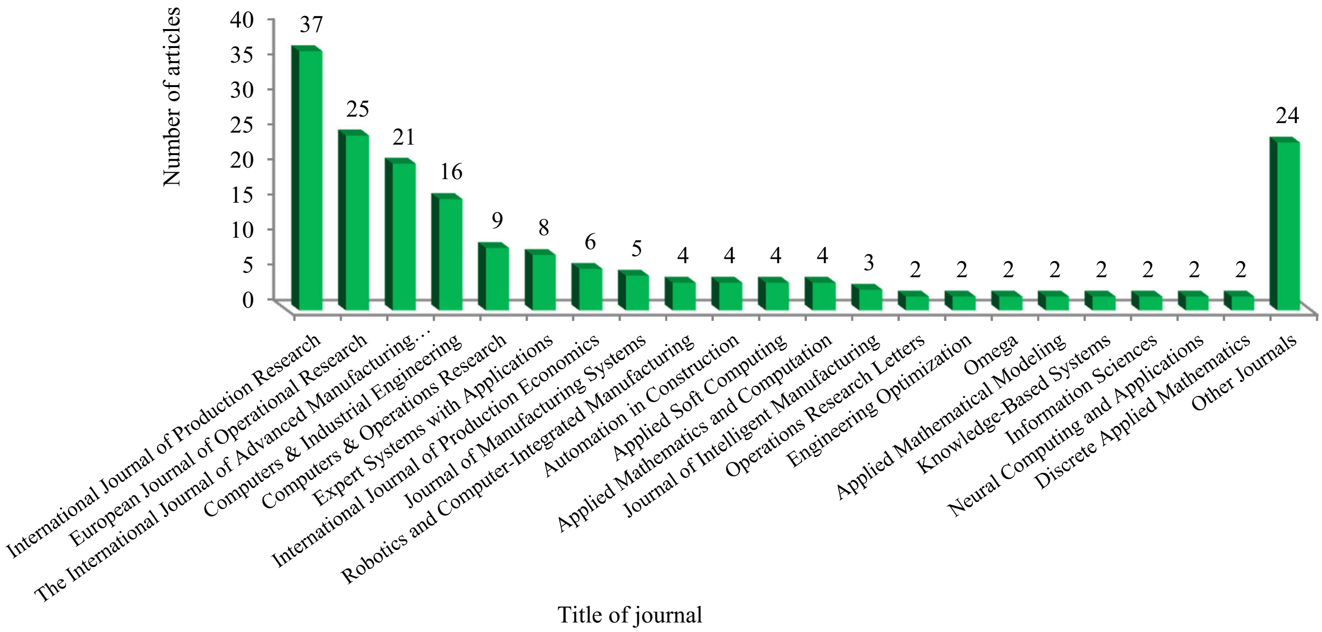


Fig. 2 Publication distribution by journal

rectangular facilities next together along a line so as to minimize the total arrangement cost, which is the sum of the products of the flows and center-to-center distances between all pairs of facilities [36, 102]. Several shapes may be detected from SRLP, such as straight line, semicircular, or *U* shape [17]. Simmons was the first to study SRFLP, proposing a branch and bound (B&B) algorithm [64].

b. *Multi-row layout problem* (*MRLP*): MRLP places a set of rectangular facilities on a given number of rows in a two-dimensional space, so that the total weighted sum of the center-to-center distances between all pairs of facilities is minimized. In this type of configuration, each facility can be assigned to any of the given rows. These rows all have the same height, and the distances between adjacent rows are all equal [49].

c. *Double-row layout problem* (*DRLP*): DRLP involves arranging a number of rectangular facilities of varying widths on both sides of a straight-line corridor to minimize the total cost of material handling between facilities [66]. An AGV system operates along the aisle to move the materials from one facility to another. Chung and Tanchoco [104] first proposed DRLP and formulated it as a mixed integer programming (MIP) model.

d. *Parallel-row ordering problem* (*PROP*): In a PROP, parts of facilities with some common characteristics are arranged along one row, with the remaining facilities left to be arranged on a parallel row [68, 166]. DRLP and PROP are different because PROP assumes that the arrangements in both rows start from a common point and that no space is allowed between two adjacent facilities, while DRLP does not make such an assumption. Moreover, DRLP assumes that the distance between two parallel rows is zero, while PROP does not [68].

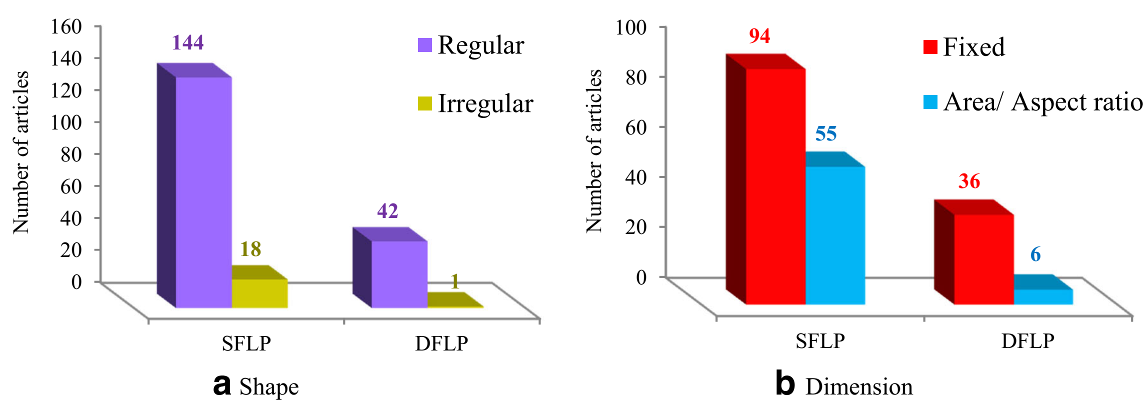


Fig. 3 Publications: shape and dimension

e. *Loop layout problem* (*LLP*): This type of layout aims to find an assignment of n facilities to n predetermined candidate locations in a closed ring network, such that the total handling cost is minimized [55]. A loop layout incorporates a load/unload station, i.e., a location from which a part enters and leaves the loop. This station is unique, and it is assumed to be located between position n and 1 [17].
f. *Open-field layout problem* (*OFLP*): Open-field layouts correspond to situations where facilities can be placed without the restrictions induced by such arrangements as single-row, double-row, parallel-row, multi-row, or loop layouts [17]. The most prominent limitation of designing an open-field layout is the non-overlapping constraints of the model that force the facilities to lie on the ground without any overlapping [197].
g. *Multi-floor layout problem* (*MFLP*): Insufficient space in cities and the exorbitant costs of providing living space, particularly in metropolitans, make designers and engineers consider multi-floor layouts instead of single-floor ones [56]. Also, in rural areas where land can be supplied cheaper than in urban areas, multi-floor factories are preferable to save land for future extension [150]. Figure 4g shows that parts can move not only horizontally on a given floor (i.e., in a horizontal flow direction) but also from one floor to another located at a different level (i.e., in a vertical flow direction) [17]. Moseley was the first researcher who concentrated on MFLP in 1963 [56]. He presented a model in which facilities were allowed to be arranged in the predetermined locations of a multi-floor building. Figure 5 presents the number of publications related to layout configurations.

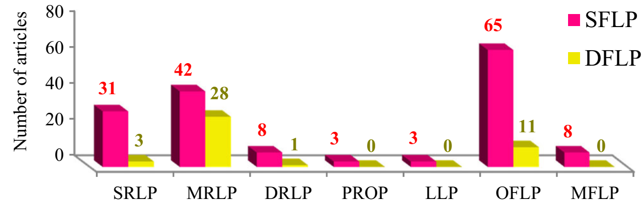


Fig. 5 Publication classification according to their layout configuration

2.4 Flow movement

There are two types of movements associated with flow-line layouts, which affects the flow of products. The movements include backtracking and bypassing. Backtracking, as shown in Fig. 6, is the movement of a part from one facility to another preceding it in the sequence of facilities in the flow-line arrangement. Bypassing occurs when a part skips some facilities during its moving towards the flow line arrangement [17].

3 Problem formulation

3.1 Problem representation

Discrete and continual layout is one of the other significant factors on the layout design (see Fig. 7). A discrete layout divides a plant site into rectangular blocks with the same area and shape, and each block is assigned to a

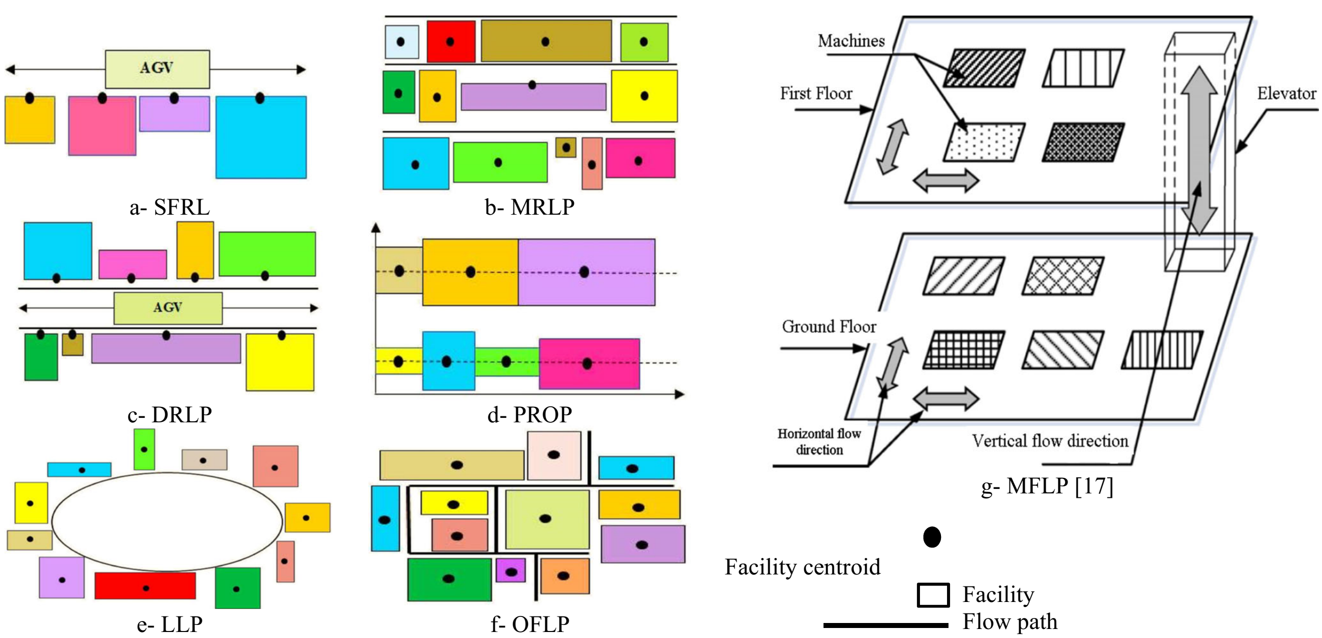


Fig. 4 Layout of facilities with respect to material handling systems [17]

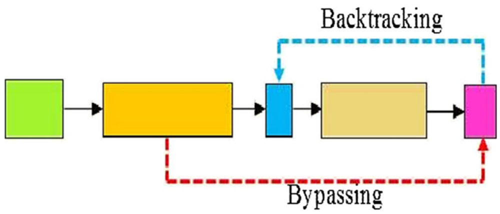


Fig. 6 Backtracking and bypassing

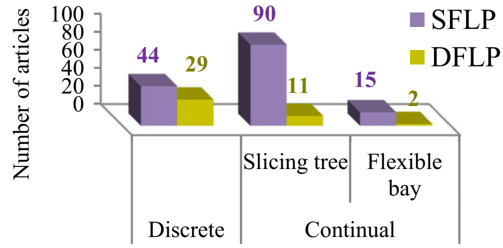


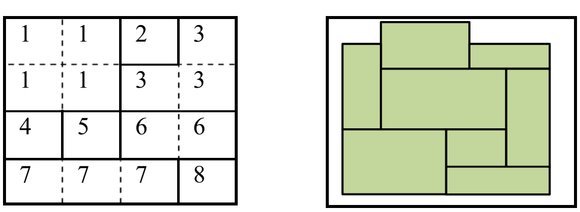
Fig. 8 Publications: problem representation

facility [17]. Koopmans and Beckman were the first to model the discrete layout as a QAP [16]. According to [133], if facilities have unequal areas, the space required for each facility can be provided by two or more blocks with equal units. Armor and Buffa [198] were the first to state the unequal area FLP and proposed a QAP formulation by breaking the facilities into small grids with equal areas. In fact, the problem is the assignment of facilities to their locations so that the total cost of material handling can be minimized.

If the dynamic nature of a facility layout is concerned, the QAP model is not efficient and the formulation must be modified. Rosenblatt [199] was the first to fully address the DFLP. He took into account equal-area facilities and used the discrete representation of the layout [11]. He developed heuristic procedures based on dynamic programming to solve the DFLP optimally.

Discrete layouts are not suited to represent the exact position of facilities in the plant floor and cannot model specific appropriate constraints as the orientation of facilities, pick-up and drop-off points, or clearance between facilities [17]. In such cases, a continuous representation is found to be more relevant. In this type of layout, facilities are located on a continuous surface with various sizes under the following assumptions [98, 99]:

1. All facilities must be located within a given fixed rectangular region, or plant floor.
2. The number of facilities, the area of each facility, the cost, and the flow values associated with each pair of facilities are known beforehand.
3. Facilities do not overlap each other and are within the boundaries of the plant floor.



a- Discrete representation b- Continual representation (slicing tree)

Fig. 7 Problem representations [17]

4. The layout must pose maximum-ratio constraints (or minimum-value restrictions) for the dimensions of facilities (length and width of each facility).

FLP on a continuous surface can be formulated as an MIP problem [73]. The first MIP formulation for solving continual layout problems was introduced by Montreuil in 1990 [35]. In the proposed model, binary variables are used to specify the relative location of each facility pair and to ensure that they do not overlap. Moreover, a set of linear constraints are used to approximate the facility areas with the aid of bounds placed on each facility's length, width, and perimeter [84]. In 1991, Montreuil and Venkatadri presented the first formulation for DFLP with unequal-area and various-shape facilities [11, 13]. In the proposed model, the relative position of facilities is fixed, and their shapes and sizes in the next period can be changed. Since the situation of facilities cannot be changed in comparison with each other, rearrangement cost is not included in the model [13]. For this reason, the formulation was expanded in subsequent years, and an MIP model was introduced in reference [11]. The number of publications based on problem representation is presented in Fig. 8.

According to the arrangement method of facilities, continuous FLPs can be classified into two major categories including a flexible bay structure (FBS) and a slicing tree. FBS was first proposed by Tong [86]. In the layout based on FBS, the plant floor is divided into parallel horizontal or vertical bays in which the width of each bay is flexible and dependent on the total area of the facilities that are located in that bay [173]. In this type of representation, facilities are restricted to be located only in one bay, and they are not allowed to expand over multiple bays [88]. As stated in Kulturel-Konak et al. [200], there is no limit on the number, width, and content of bays; that is why this representation is called flexible bay. A sample FBS layout is given in Fig. 9. The facilities are located from left to right and from top to bottom. As illustrated in Fig. 9a, facilities 8, 6, 10, 12, and 2 are in the first bay; 1, 11, and 7 are in the second; 4, 3, and 9 are in the third; and 13 and 5 are in the fourth.

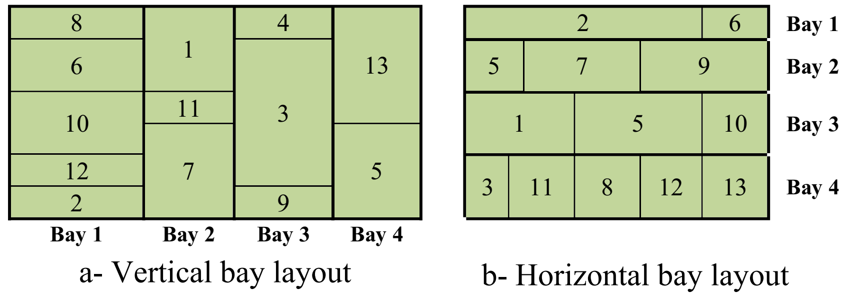


Fig. 9 A sample FBS layout

3.2 Objective function

Approaches to evaluate FLPs pursue either of the two sets of objectives: quantitative or qualitative objectives. Quantitative objectives aim at minimizing the sum of material flow between facilities based on the distance function [2]. Qualitative objectives aim to place facilities that utilize common materials, personnel, or utilities adjacent to each another, while separating the facilities for the reasons of safety, noise, or cleanliness [2]. For qualitative objectives, a relationship chart is used (by values A = absolutely, E = especially, I = important, O = ordinary, U = unimportant, and X = undesirable) to maximize the closeness of various facilities.

3.3 Type of data

To solve an FLP, several types of data such as those about dimensions of facilities, transportation costs, and material flows between facilities are required. In most pieces of research, it has been assumed that these data are deterministic and precisely known in advance. Although this assumption can be true in some applications, it is not realistic in many others; since the study design of a workshop is obviously done much before it is operating, so data related to customer demands, for example, are generally not known with enough precision [10]. Thus, the use of methods that are able to model the uncertainty of data is necessary. In practice, the flexibility and robustness of FLP are the two major issues that have been the center of attention in recent studies [52].

In the literature, the consistency of a layout with uncertainty is defined as its flexibility [52]. The approaches that are used for solving this problem can be classified into two general groups of stochastic and fuzzy formulations [10]. Fuzzy models for FLPs include two main classes, approaches that define parameters by using linguistic variables and methods that consider information as fuzzy numbers [170]. Shore and Tompkins were the first who developed the concept of plant layout flexibility [161].

The robustness of an alternative can be measured by the number of times that its solution lies within a pre-specified percentage of an optimal solution for different sets of scenarios [161]. This approach generates a series of solutions that are progressively less sensitive to realizations of input data from a set of scenarios [201]. Using this method, the decision-maker will select the alternative that has the highest frequency of being closest to the optimal solution [161]. In robust optimization, unlike probability models, there will be no need to determine the distribution and the exact value of parameters. Rosenblatt and Lee [161] were the first to demonstrate the effectiveness of the robustness approach to the layout problem by a numerical example. In their study, there were stochastic product demands for SFLP and the problem was modeled as QAP [52]. Kouvelis et al. [202] presented a new method to find a robust layout under demand uncertainty in DFLP and proposed a QAP model and a B&B algorithm to solve. Figure 10 shows the distribution of publications categorized by the type of data.

3.4 Modeling

Various mathematical models have been developed for FLP during the past six decades. They can be divided into seven classes as follows:

1. Quadratic assignment problem (QAP): As mentioned before, an FLP with a discrete representation and equal-sized facilities may be formulated by QAP. The name was decided to be so because the objective function is a second-degree function of the variables [16].
2. Quadratic set covering problem (QSP): An FLP with unequal-sized facilities and a discrete representation can be formulated as QSP [19]. Bazaraa [203] was the first to state and study QSPs. In his proposed model, the total area occupied by all the facilities is divided into a number of blocks [16], where each facility is assigned to exactly

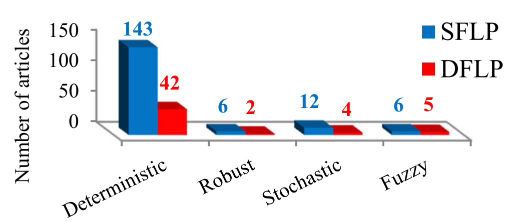


Fig. 10 Publications: type of data

one location and each block is occupied by at most one facility [204]. The goal is to minimize the total material handling cost, which is a function of the distance and the amount of material flow between facilities.

3. Linear programming (LP): LP is a technique for optimizing a linear objective function, which is subject to linear constraints.
4. Integer programming (IP): An IP model is a mathematical optimization in which all of the variables must be integers. Lawler was the first to formulate an FLP as a linear IP [16].
5. Mixed integer programming problem (MIP): As noted previously, MIP is an appropriate model to formulate FLP with a continuous representation and unequal-sized facilities. An MIP model consists of the objective function of a mixture of integer and non-integer decision variables subject to a number of equality and inequality constraints [19]. In 1978, Kaufman and Broeckx developed an MIP formulation based on QAP [204].
6. Nonlinear programming (NLP): The problem is called an NLP if the objective function is non-linear and/or the feasible region is determined by nonlinear constraints.
7. Graph theoretic problem (GT): In this approach, the adjacency of each pair of facilities can be represented by a graph, in which nodes denote facilities and edges demonstrate the existence of flows or relationships between facilities [154]. In a GT model, assume that the desirability of locating each pair of facilities adjacent to each other is known [96]. For more details, please refer to [16]. Distribution of the papers based on mathematical models is provided in Fig. 11.

From another viewpoint, an FLP can be modeled based on two categories as follows:

1. Certain layout problems: If all the input data are already known, operations research models can be used effectively. In this case, objective functions and constraints are fixed, and optimization can be done in certain conditions.
2. Uncertain layout problems: In most models, it is supposed that transportation costs, flow of materials, and the distances between facilities are determined independently and no interaction exists between them. However, these assumptions are far from real, and the material flow between facilities is defined based on the product demand whose value is not predictable regardless of the behavior of rivals. There are not only the effects of rivals but also the influence of MHS designing exerted on FLP. Both MHS designers and facility layout designers need to calculate MHC, but this cost depends on the flow of materials between facilities. This parameter is unknown and depends on the demand [82]. To determine the demand, it is necessary to know the price of the product. The price of the product depends on all the costs of producing the product, and one of the major costs is MHC [82]. Therefore, the traveled distance, MHC, and the flow of materials are dependent on one another. A facility layout is, thus, done in uncertain conditions where in addition to external competitors, some internal system problems such as MHS designs affect layout designs. In these circumstances, the game theory can be an effective tool for modeling FLPs. Figure 12 shows the distribution of publications, categorized by the certain and uncertain layout problems.

3.5 Constraints

Generally, constraints of FLPs consist of items such as area, clearance between facilities, orientation, non-overlapping, pick-up/drop-off points, and budget. Distribution of the papers written on constraints is provided in Fig. 13.

4 Resolution approach

Facility layout problems are widely classified as single-criterion FLPs and multi-criterion FLPs. In single-criterion FLPs, only one objective, either qualitative or quantitative, is taken into account. Objectives such as minimization of the total MHC, rearrangement cost, backtracking and bypassing, and shape irregularities are quantitative while maximization of the closeness between facilities is qualitative. Various methods and procedures have been developed to solve single-criterion FLPs, which can be divided into four categories including

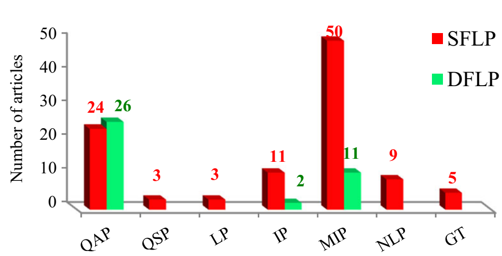


Fig. 11 Publications: mathematical models

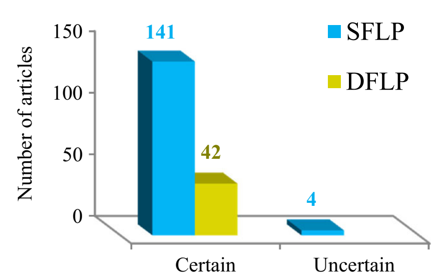
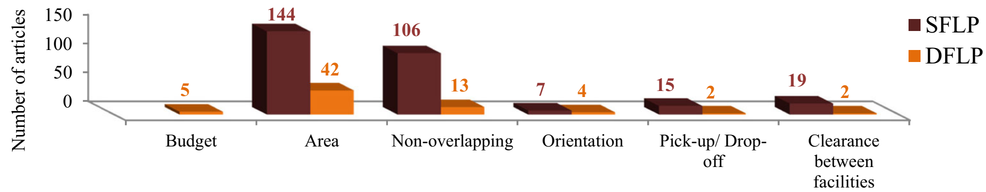


Fig. 12 Publications: modeling

Fig. 13 Publications: constraints



exact, stochastic, approximated, and artificial intelligent approaches. Distribution of the articles based on resolution approaches is given in Fig. 14. The approaches are defined as follows:

1. Exact approaches: During the early 1960s, a considerable amount of research was done to develop optimal algorithms for QAP [16]. Exact methods are useful approaches to find optimal solutions for small-sized FLPs. Dynamic programming, branch and bound method, cutting plane algorithm, and semidefinite programming are examples of exact approaches. Figure 15 referred to distribution of publications made by these methods.

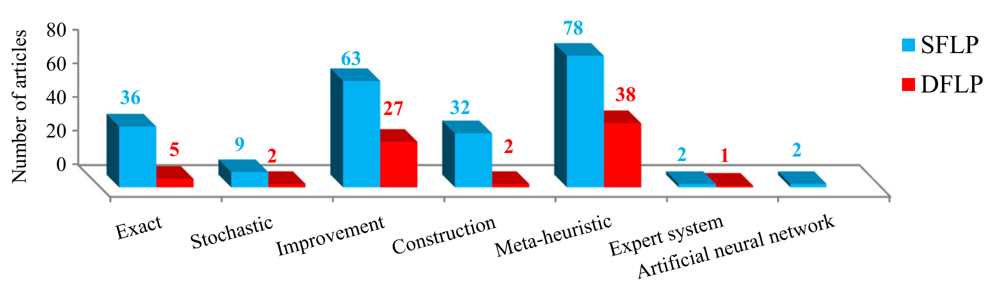
2. Stochastic approaches: They are algorithms that produce near-optimal solutions with high probability. Discrete event simulation approach is an example of stochastic approaches.
3. Approximated approaches: Sahni and Gonzalez showed that QAP is NP-complete [16] and that optimization methods are not capable of solving problems with 15 or more facilities within a reasonable amount of time [1]. Therefore, there is a need for approximated algorithms that can provide good suboptimal solutions. These approaches are widely classified as

a. *Improvement algorithms*: Improvement methods start with an initial solution and attempt to improve it by swapping the locations of facilities [205]. The swap that produces the best solution is retained, and the procedure continues until the solution cannot be improved any further [16]. Hence, the solution quality of improvement procedures is very sensitive to initial layouts [154]. Examples of these methods are pair-wise exchange, insertion neighborhood, Lin–Kernighan neighborhood, computerized relative allocation of facilities technique (CRAFT), computerized facility aided design (COFAD), etc.
b. *Construction algorithms*: Construction procedures build a layout from scratch by successively selecting and placing facilities until a completed layout is obtained [205]. These methods have one drawback in common; that is, the final solution may be far from optimal because the methods generate only one layout [154]. Well-known examples of construction algorithms are computerized relationship layout planning (CORELAP), automated layout design program (ALDEP), and programming layout analysis and evaluation technique (PLANET).
c. *Meta-heuristic algorithms*: Different meta-heuristics methods are presented to solve FLPs. The best known of these techniques are genetic algorithm, tabu search, simulated annealing, and ant colony optimization. Figure 16 shows the distribution of references by these approaches.

4. Artificial intelligence approaches: These methods belong to a branch of computer science that simulates intelligent human behavior by machines. Expert systems and artificial neural networks are the most important subdivisions of artificial intelligence algorithms.

In the real world, FLPs must take both qualitative and quantitative criteria into consideration [47]. Rosenblatt first formulated a multi-objective FLP [47] and proposed an improvement heuristic approach for solving layout problems associated with two conflicting objectives, viz. minimization of total flow costs and maximization of total closeness rates. There are various approaches for solving multi-criterion FLPs, such as weighted sum method, global criterion method, fuzzy multi-objective programming, analytic hierarchy process, and analytic network process. Figure 17 shows the distribution of publications by these methods. Furthermore, the

Fig. 14 Publications: resolution approach



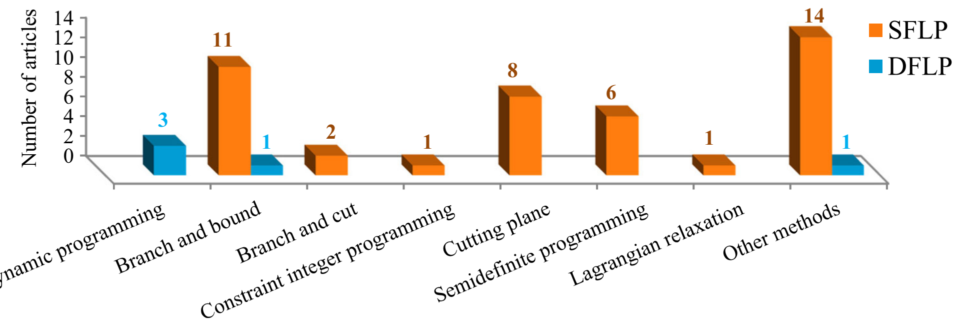


Fig. 15 Publications: exact approaches

distribution of the articles concerning objective functions is provided in Fig. 18.

5 Layout evolution

Based on the length of the planning horizon, plant layout problems can be classified into two categories, SFLP and DFLP. As mentioned previously, when the flow of materials between facilities does not change during the planning horizon, SFLP occurs, and, in the simplest form it can be formulated as a QAP model. However, it is very unlikely for the material flow between facilities to remain unchanged during a long planning horizon. Nowadays, severe global competition, rapid changes in technology, and shortening life cycle of products make companies evaluate and modify their facility layouts periodically fashion [195]. Hence, the idea of dynamic layouts comes into focus in addition to static layouts [42]. Figure 19 shows the number of publications based on static and dynamic FLPs. Also, Fig. 20 presents a summary of the layout evolution during the last 30 years.

6 Current trends and future scope of work

This section addresses the issues related to the current trends and future research directions in the area of FLPs. In this paper, we have presented a review of SFLPs and DFLPs along with their workshop characteristics, mathematical models, and solution approaches with the following conclusions:

1. In today's manufacturing environments, facility layouts need to be adaptable to changes. In other words, focusing on dynamic layouts is now more important than ever because of rapid scientific developments and product changes [179]. As suggested in Fig. 19, most researchers have studied SFLPs. Hence, research should be directed towards DFLPs rather than SFLPs.
2. The most common objective followed in mathematical models is to minimize MHC, which is a quantitative factor. Most of the relevant research in the literature is focused on this criterion as a factor for deciding the suitability of a layout, but it neglects other important factors. Hence, qualitative factors such as closeness rating between facilities, plant safety, and flexibility of layouts for future design changes must also be considered carefully in the context of FLPs. According to Fig. 18, of the 186 articles reviewed, only 57 fall in the field of multi-criterion FLPs. Therefore, it is obvious that, in FLPs, different criteria simultaneously are ignored in order to provide appropriate layouts.
3. In most researches, it has been assumed that the values of input data are deterministic and precisely known in advance. Although this assumption can be true in some applications, it is not realistic in many other. In real-world applications, exact approximation of certain parameters

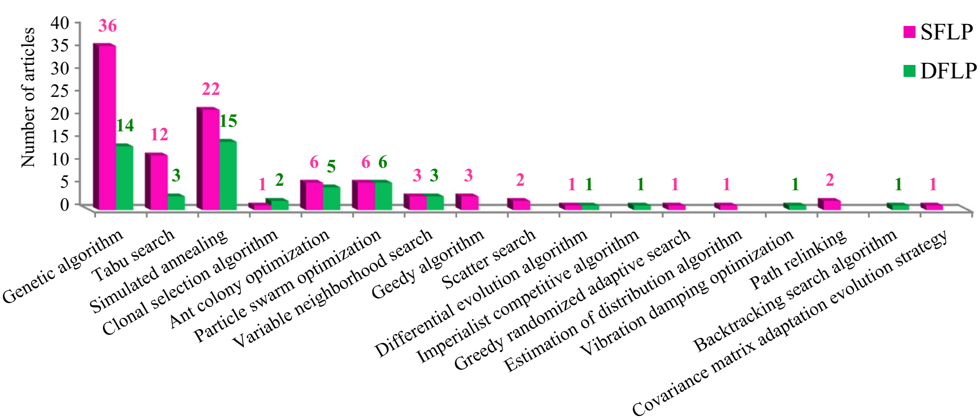


Fig. 16 Publications: meta-heuristics algorithms

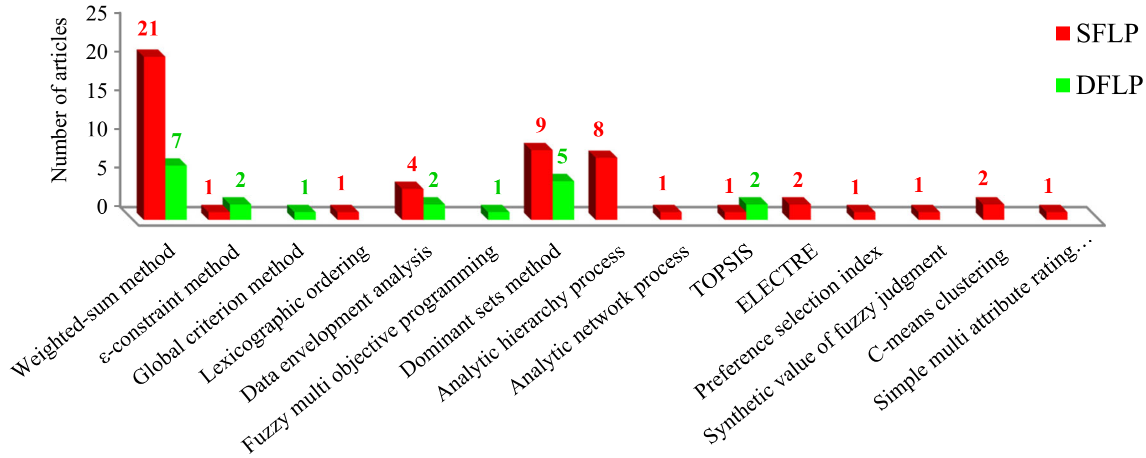


Fig. 17 Publications: methodology for solving multi-criterion FLPs

(e.g., product demand, transportation costs, and dimension of facility) is difficult and, in some cases, impossible for such reasons as measurement errors and forecasting methods. Thus, it is necessary to use methods that are capable of modeling the uncertainty of data. In practice, the flexibility and robustness of FLPs are the two major issues that have been a center of attention in recent studies.

4. In DFLPs, rearrangements are costly activities. It is natural for a company to have a limited budget in this regard and to have to operate within the limits of that given budget. Therefore, to be realistic, one has to consider the budget constraints when solving a DFLP [184]. It should be noticed that most previous researches did not consider the company budget for rearrangement of departments. To the best of our knowledge, there are only five studies on DFLP with budget constraints (see Fig. 13). Interested readers can find the details in [178, 184, 189, 194, 195].
5. Existing studies have primarily dealt with minimizing the MHC but failed to recognize the probabilistic aspects that significantly affect system performance. The static nature of the available models has reduced the quality of the estimates of performance and led to no achievement of an optimal layout. Simulation and queuing theory can be used to overcome this drawback [109]. Of the 186 articles surveyed, only three papers (i.e., [33, 108, 109]) have considered the probabilistic aspects of SFLPs. Hence, research should be directed towards finding stochastic facility layouts rather than static ones.
6. In most models, it is supposed that the transportation costs, the flow of materials, and the distances between facilities are determined independently and no interaction exists among them. However, in real-world scenarios, material flows between facilities are defined based on product demand, whose value is not predictable regardless of the behavior of rivals. In addition to the effects of competitors, FLP is influenced by MHS designing. Both the MHS designer and the FL designer need to calculate MHC, but this cost depends on the flow of materials between facilities. Also, as a parameter, it is unknown and depends on the demand [82]. To determine the demand, it is necessary to know the price of the product. In turn, the price of the product depends on all the costs spent on production of the product, and one of the major costs is MHC [82]. Therefore, the traveled distance, MHC, and the flow of materials are dependent on one another. A facility layout is, thus, done in uncertain conditions where, in addition to external competitors, some internal system problems such as MHS design affect the layout design. Of the 186 articles reviewed, only one paper (see

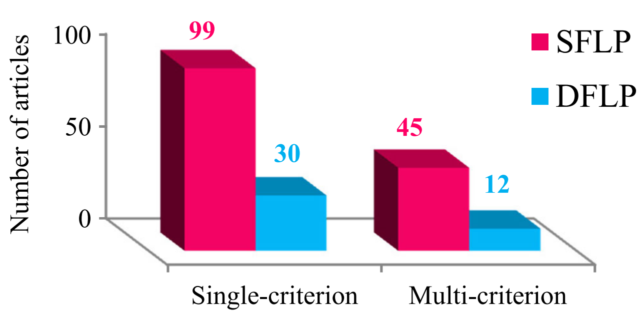


Fig. 18 Publications: objective function

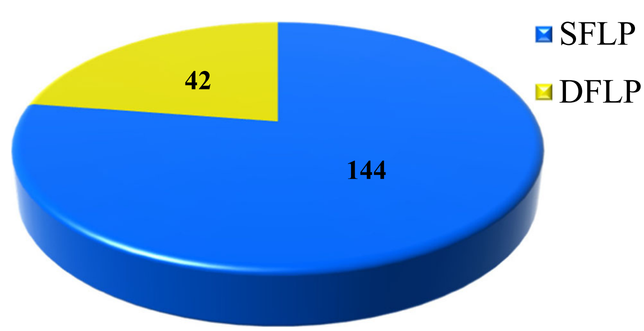


Fig. 19 Number of papers published about layout evolution

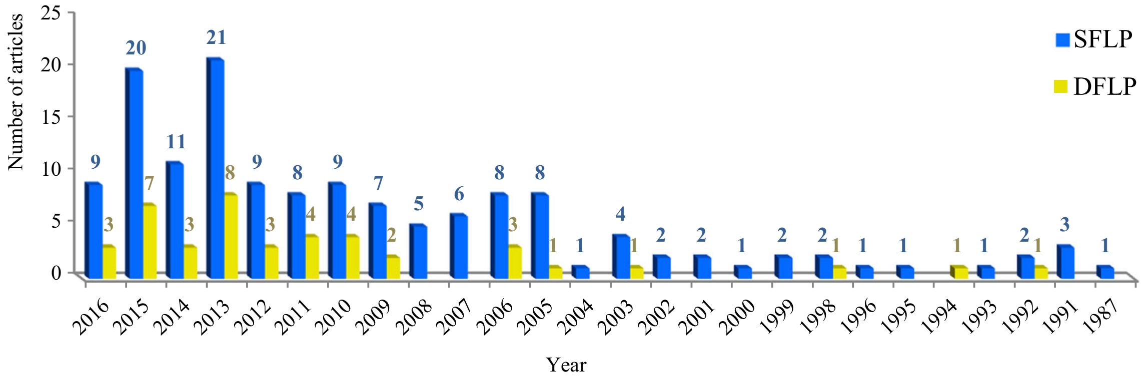


Fig. 20 Number of papers published during the last 30 years

[82]) investigates this issue. In this paper, an FLP is modeled with conflicting objectives under a duopoly Bertrand competition as a game.

7. FLPs are NP-complete, and optimization methods are useful tools to find an optimal solution to small-sized problems. In other words, the computational time required to solve a problem increases exponentially with the problem size [4]. Therefore, there is a need for approximated algorithms that provide good suboptimal solutions. The algorithms can be classified as constructive, improvement, and meta-heuristic methods. During the last 20 years, meta-heuristic techniques have been broadly applied to solve FLPs. Furthermore, comparing metaheuristics together, one finds the procedures based on genetic algorithms and simulated annealing the most popular (see Fig. 16).
8. Most solution techniques reported in the literature for DFLP use a discrete representation of the layout (see Fig. 8). However, in most applications, equality of facility areas is a very poor assumption [2]. Hence, the idea of continuous representation layout should be considered in addition to the discrete representation.

7 Conclusion

FLP is one of the most important classical problems of production management and industrial engineering that has attracted the attention of many researchers in the literature during the recent decades. In spite of this significance, research on many aspects of the problem is still in its initial stage; hence, it seems both interesting and promising to work on FLPs. In this study, an attempt was made to present a comprehensive and extensive review of various papers about FLPs based on numerous literature references, which can help to understand the current research status in this area and enrich the knowledge base of this interdisciplinary study. Readers could identify their interested issues referring to the results of this literature review. Among the many references listed at the end of this paper, we found over 180 published since 1987 that are considered from different aspects (i.e., layout evolution, workshop characteristics, problem formulation, and resolution approaches). From this analysis, it appears that articles related to layout designs continue to be regularly published in major academic journals and that FLPs remain an open research issue.

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