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REVIEW

Facility layout planning. An extended literature review

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ABSTRACT
Facility layout planning (FLP) involves a set of design problems related to the arrangement of the elements that shape industrial production systems in a physical space. The fact that they are considered one of the most important design decisions as part of business operation strategies, and their proven repercussion on production systems' operation costs, efficiency and productivity, mean that this theme has been widely addressed in science. In this context, the present article offers a scientific literature review about FLP from the operations management perspective. The 232 reviewed articles were classified as a large taxonomy based on type of problem, approach and planning stage and characteristics of production facilities by configuring the material handling system and methods to generate and assess layout alternatives. We stress that the generation of layout alternatives was done mainly using mathematical optimisation models, specifically discrete quadratic programming models for similar sized departments, or continuous linear and non-linear mixed integer programming models for different sized departments. Other approaches followed to generate layout alternatives were expert's knowledge and specialised software packages. Generally speaking, the most frequent solution algorithms were metaheuristics.

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KEYWORDS
Facility design; facility layout; facility planning; materials handling; modelling

1. Introduction

Facility layout planning (FLP) involves the process of physically arranging all the production factors that make up the production system so it can suitably and efficiently comply with the organisation's strategic objectives. As part of business operational strategies, FLP is considered one of the most important design decisions (Ghassemi Tari and Neghabi 2015; Kheirkhah, Navidi, and Bidgoli 2015; Sun et al. 2018). It also significantly affects the efficiency of production systems and their productivity level (Altuntas and Selim 2012; Navidi, Bashiri, and Messi Bidgoli 2012; Ku, Hu, and Wang 2011). Figure 1 depicts a general framework of FLP, which can also be used by the reader as a guiding thread throughout this article.

Efficient FLP must ensure that production schedules are met in the short, mid and long terms and at a lower cost, while adequately using space and guaranteeing, in turn, a certain degree of flexibility for future re-layouts and minimum health/security risks at work. Conversely, inefficient layouts can simultaneously lead to bottlenecks, congestion and poorly used space, and too much work underway can accumulate, while job posts can become idle or overloaded. All this can entail anxiety and ill ease for workers, accidents at work, and make the control of operations and personnel management difficult (Pérez-Gosende 2016). Moreover, if a good closeness level is lacking among the organisation's working centres, the working day in transport activities cannot be put to the best use, which contributes no value. This is one of the main reasons why production times increase and work productivity levels lower.

Despite its importance, FLP is no easy problem to solve. The most convenient generation and selection of facility layouts for an organisation involve a complex and iterative process that depends on rating the elements shaping the goods/services production system. According to the computational complexity theory, FLP is considered an NP-hard (non-polynomial hard problem) optimisation problem because no solution algorithms exist that provide an optimum solution in a reasonable polynomial time (Grobelny and Michalski 2017). Despite their high degree of complexity, several authors have dealt with these problems by contributing acceptable solutions in realistic calculation times.

It is stressed that when FLP is planned by assuming demand remains constant throughout the planning

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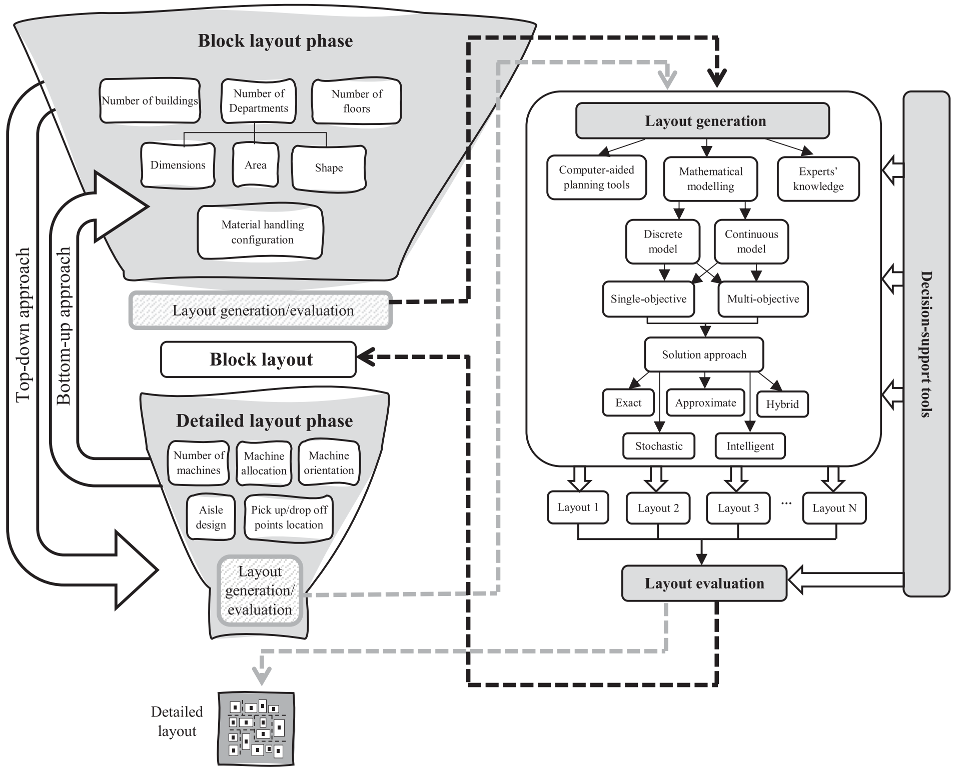

Figure 1. FLP general framework.

horizon, this problem is known as static or single-period FLP (SFLP). In many production systems however, considering a single design may not be practical because the material flow is not likely to remain invariable with time. Conversely, when demand is seasonal or vastly varies, it might be more worthwhile considering a different FLP for each time period, in which case the planning approach is either dynamic or multiperiod (DFLP) (Turanoğlu and Akkaya 2018; Al Hawarneh, Bendak, and Ghanim 2019; Pournaderi, Ghezavati, and Mozafari 2019). In line with this, Hosseini-Nasab et al. (2018) identify that DFLP has less repercussion in the scientific literature than the SFLP approach.

Since the second half of the twentieth century, FLP has been a broadly discussed scientific subject because it has been considered one of the most important classic operations management and industrial engineering problems. Some literature reviews have dealt with it in more or less depth. Most have centred on specific dimensions of the problem (Anjos and Vieira 2017; Ahmadi, Pishvaee, and Jokar 2017; Saraswat, Venkatadri, and Castillo 2015; Keller and Buscher 2015; Renzi et al. 2014; Saravanan and Ganesh Kumar 2013; Moslemipour, Lee, and Rilling 2012; Maganha, Silva, and Ferreira 2019; Pérez-Gosende, Mula, and Díaz-Madroñero 2020), but others have covered them more generally (Hosseini-Nasab et al. 2018; Drira, Pierreval, and Hajri-Gabouj 2007; Singh and Sharma 2006; Meller and Gau 1996). Despite such wide scientific coverage, research into many FLP aspects is still in its early days (Hosseini-Nasab et al. 2018). This is because physical layout requirements in industry constantly change to adapt to the technolocial changes related to the fourth industrial revolution, the proliferation of cyberphysical systems, increasingly more demanding market requirements, a shift to more flexible manufacturing styles that permit large product nomenclatures in increasingly smaller lots, and the development of health and safety guidelines in the workplace, which are all motivations to keep contributing to its understanding. This article presents a literature review of 232 articles published in science journals of known prestige in their category. Previously, Hosseini-Nasab et al. (2018) proposed an FLP classification system based on the review of 186 bibliographic sources published between 1987 and 2016. According to these authors, FLP decisions depend on the layout evolution, characteristics of workshops, formulating the problem and its resolution approaches. Here we produced a new taxonomy to extend this proposed classification by including new classification criteria based on the most recent literature review in the FLP context; namely: problem type, approach and planning phase, characteristics of production facilities, materials handling system configuration, approaches employed to generate FLP alternatives and assessment approaches. The taxonomy also deals with characteristics of FLP mathematical modelling approaches as regards model type, objective function type, data type, certain or uncertain demand, distance metrics and considered solution approach. Consequently, the main contribution of this article was detailed, accurate and structured FLP conceptualisation, contextualisation and description, which ensures the difference regarding the review study by Hosseini-Nasab et al. (2018).

The rest of the article is arranged as follows. Section 2 describes the employed review methodology. Section 3 presents an FLP taxonomy. Section 4 deals with the current trends in mathematical modelling of FLP and Section 5 addresses its solution approaches. Approaches for layout evaluation are introduced in Section 6. Section 7 discusses the decision-support tools used to tackle the FLP. Section 8 deals with real-world applications. Section 9 points out the gaps in the reviewed scientific literature and proposes guidelines for future research works. Finally, Section 10 summarises the conclusions drawn in this work.

2. Review methodology

The literature search about FLP was performed by considering scientific articles in the journals indexed in the *Science Citation Index Expanded* (SCIE) of *Web of Science* (WoS) for the 2010–2019 time window. The employed key words were: *facility(ies) layout problem; facility(ies) layout design; facility(ies) layout planning; facility(ies) layout; plant(s) layout design; plant(s) layout; layout design; facility(ies) design; facility(ies) planning.* Initially the search focused on fields: title, abstract, authors' key words and *KeyWords Plus®* through the TS field label, which gave 2,083 articles. This led the authors to restrict the key words search to only the title field of each record by the TI field label, which gave 496 articles. These publications were filtered according to the authors' critical judgment by ruling out those contributions that did not deal with the problem from the operations management viewpoint. As a result of filtering, 232 articles were selected. The employed advanced search strategy is detailed in Table 1.

Figure 2 shows, in frequency order, the scientific journals in which the 232 selected articles were published. It is worth stressing that eight journals published more than 50% of the articles that have dealt with FLP in the last decade.

3. FLP taxonomy

Hosseini-Nasab et al. (2018) proposed an FLP classification system based on layout evolution, characteristics of workshops, and formulating the problem and its solution approaches. This research proposes the inclusion of the following classification criteria: problem type, approach and planning phase, characteristics of production facilities, materials handling system configuration, and methods to generate and assess layout alternatives. These criteria are set out below:

(1) Problem type. It refers to FLP decision making in completely new facilities or for those already operating.
   (a) *Greenfield design.* This refers to designing the layout of planned facilities
   (b) *Re-layout.* When making adjustments to the layout of already existing facilities
(2) Planning approach. Depending on the variability of the material flow during the planning horizon, the problem may be considered static or dynamic.
   (a) *Static.* When the material flow between departments remains constant throughout the planning horizon
   (b) *Dynamic.* When the planning horizon is divided into several discrete time periods ($t = 1, \ldots, T$) with a different material flow intensity
   b.1 *Flexible layout.* A layout is designed for each time period t
   b.2 *Cyclic layout.* A layout is designed for each time period t. When the planning horizon during time period T ends, the material flow between departments returns to its initial state in $t = 1$

Table 1. References collection methodology.

Field labels, keywords, and boolean operators	(TI = ('facilit* *layout problem') OR TI = ('facilit* *layout design') OR TI = ('facilit* *layout planning') OR TI = ('facilit* *layout') OR TI = ('plant* *layout design') OR TI = ('plant* *layout') OR TI = ('layout design') OR TI = ('facilit* design') OR TI = ('facilit* planning'))
Database	Web of Science (WoS)
Index	Science Citation Index Expanded (SCIE)
Document type	Research articles
Time window	2010–2019
Language	English
Initial number of articles	496
Removed based on title and abstract	240
Removed based on content	24
Final number of articles	232

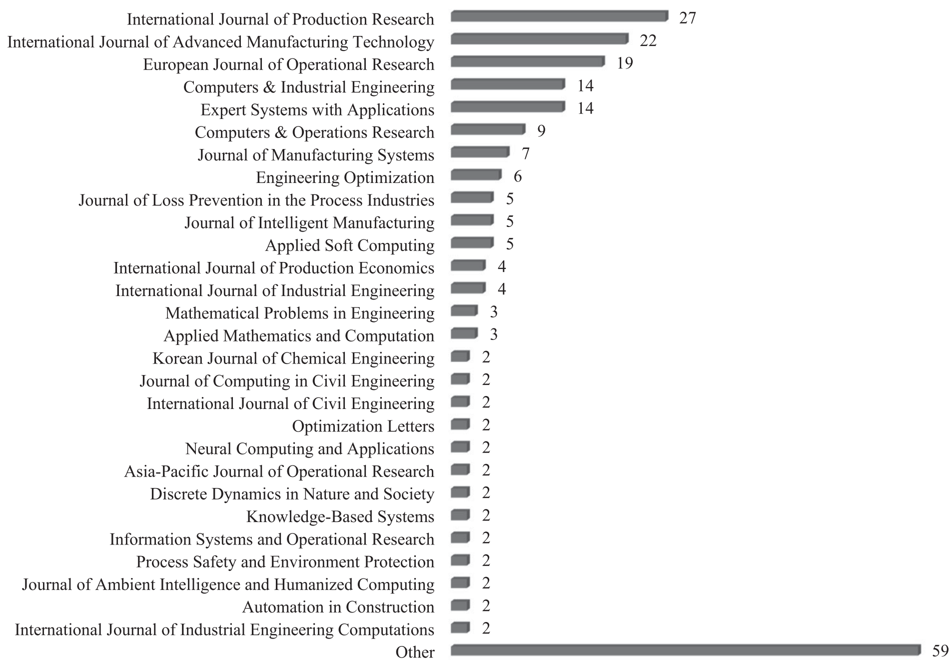

Figure 2. Distribution of publications per scientific journal.

b.3 *Robust layout.* A single layout is designed and is used throughout the planning horizon

(3) Planning phase. It includes the layout as a whole (block) and the detailed layout.

(a) *Block layout.* It is the phase when departments are arranged in buildings by considering if one relevant objective is met, or some

(b) *Detailed layout.* The phase in which the elements making up the production system in the physical space inside each department are arranged

(4) Characteristics of facilities. They include analysing the number of buildings and floors required in facilities to perform industrial operations normally, as well as the space, shape, area and sizes of departments.

(a) *Number of facilities.* This refers to the number of buildings required for the company to perform its operations

a.1 *Single facility.* Layout is designed by considering a single building

a.2 *Multi-facility.* More than one building is considered

(b) *Number of floors.* This refers to the number of floors inside a building required for the company to operate

b.1 *Single floor.* Only one level or floor is employed

b.2 *Multi-floor.* Two floors or more are estimated

(c) *Considering space.* This refers to considering the space inside the building in two or three dimensions

c.1 *Bidimensional.* Only the land area is considered

c.2 *Tridimensional.* The whole cubic space is considered

(d) *Shape of departments.* This refers to the regular or irregular shape of the departments on the plan

d.1 *Regular.* Departments are considered rectangular

d.2 *Irregular.* Departments are not considered rectangular

(e) *Area of departments.* This refers to whether departments have equal areas or unequal areas

e.1 *Equal.* All the departments have the same area

e.2 *Unequal.* Departments do not necessarily have the same area

(f) *Dimensions.* This refers to the flexibility level of departments' length and width when arranged in physical spaces

f.1 *Fixed.* The width and length of departments must remain intact

f.2 *Flexible.* Departments can adopt a variable width and length within the preset interval

f.3 *Mixed.* The width and length of departments are treated indistinctly as fixed or variable depending on the area constraints

(5) Materials handling system configuration. This refers to the way that the departments on a building's floor are arranged to facilitate the material flow.
   (a) *Single-row configuration.* Departments are arranged one next to another so that the material flow follows one line
   (b) *Double-row configuration.* Departments are arranged in two parallel rows on both sides of a corridor in a straight line through which the material flow generally circulates via a self-guided vehicle
   (c) *Parallel-row configuration.* Departments are arranged in two parallel rows, and the material flow of each row flows linearly and independently
   (d) *Multiple-row configuration.* Departments are arranged in more than two rows, and the material flow takes place linearly and independently inside each row
   (e) *Loop configuration.* Departments are arranged in such a way that the material flow circulates like a closed loop
   (f) *Open-field configuration.* Departments are located freely in space so that the material flow follows no specific pattern
(6) Approaches for layout generation. This deals with the methods followed to generate alternative layouts.
   (a) *Mathematical modelling.* It refers to using mathematical optimisation models
   (b) *Experts' knowledge.* A trial-and-error approach in which alternatives are produced based on a group of experts' experience
   (c) *Software packages.* Alternatives are generated by using specialised software
(7) Approaches for layout evaluation. This refers to the methods employed to assess the level of suitability of a finite group of layout alternatives for relevant objective and/or subjective criteria to select the most suitable alternative for a given production system.
   (a) *Multicriteria decision methods.*They are based on the hierarchisation of a set of alternatives according to the assessment of a series of decision criteria
   (b) *Data envelopment analysis.* This is a technique based on linear programming to compare the relative efficiency of a set of layout alternatives that produce similar outputs with a series of common inputs
   (c) *Simulation.* It implies the simulation of certain layout performance indicators that depend on the layout outline identified for each alternative
   (d) *Non-linear programming.* It refers to non-linear mathematical optimisation models
   (e) *Fuzzy constraint theory.* A technique that allows the assessment of different layout diagrams based on an objective function and several constraints under uncertainty conditions
   (f) *Simple criteria comparison.* Each alternative is compared according to how one quantitative performance criterion behaves, or several

The above taxonomy is shown as a diagram in Figure 3. According to these criteria, 232 contributions to FLP have been classified. This classification is presented in Table 2 for those articles that deal with FLP from a static point of view, and those that deal with it from a dynamic viewpoint, which are offered in Table 3. In both cases, the codes defined for each classification category in Figure 3 were used.

3.1. Planning phase

Like most design engineering problems, FLP must be based on a hierarchical approach. In the first phase, departments are assigned specific locations in the facilities' physical space, which is often known as block layout (Saraswat, Venkatadri, and Castillo 2015; Asef-Vaziri and Kazemi 2018). Next the detail phase takes place, when the elements making up the production system inside each department are organised (Bukchin and Tzur 2014). These phases should be dealt with consecutively in what Meller, Kirkizoglu, and Chen (2010) called a top-down approach. Nonetheless, most research works available in the FLP context have dealt with both phases separately. In the present study, 86% of the works dealt with the first phase, 10% covered the second phase, and only about 4% (9 articles) worked with both phases as part of the same problem.

3.2. Planning approach

According to the planning approach, FLP can be classified as static or dynamic. When the layout is planned by assuming that the materials flow among departments is constant throughout the planning horizon, the problem is known as SFLP. This approach is recommended for the case of production systems with low-cost facility relayouts (Moslemipour, Lee, and Loong 2017). Nonetheless, considering a single design might prove impractical in most industrial sectors because the materials flow is not likely to remain invariable with time.

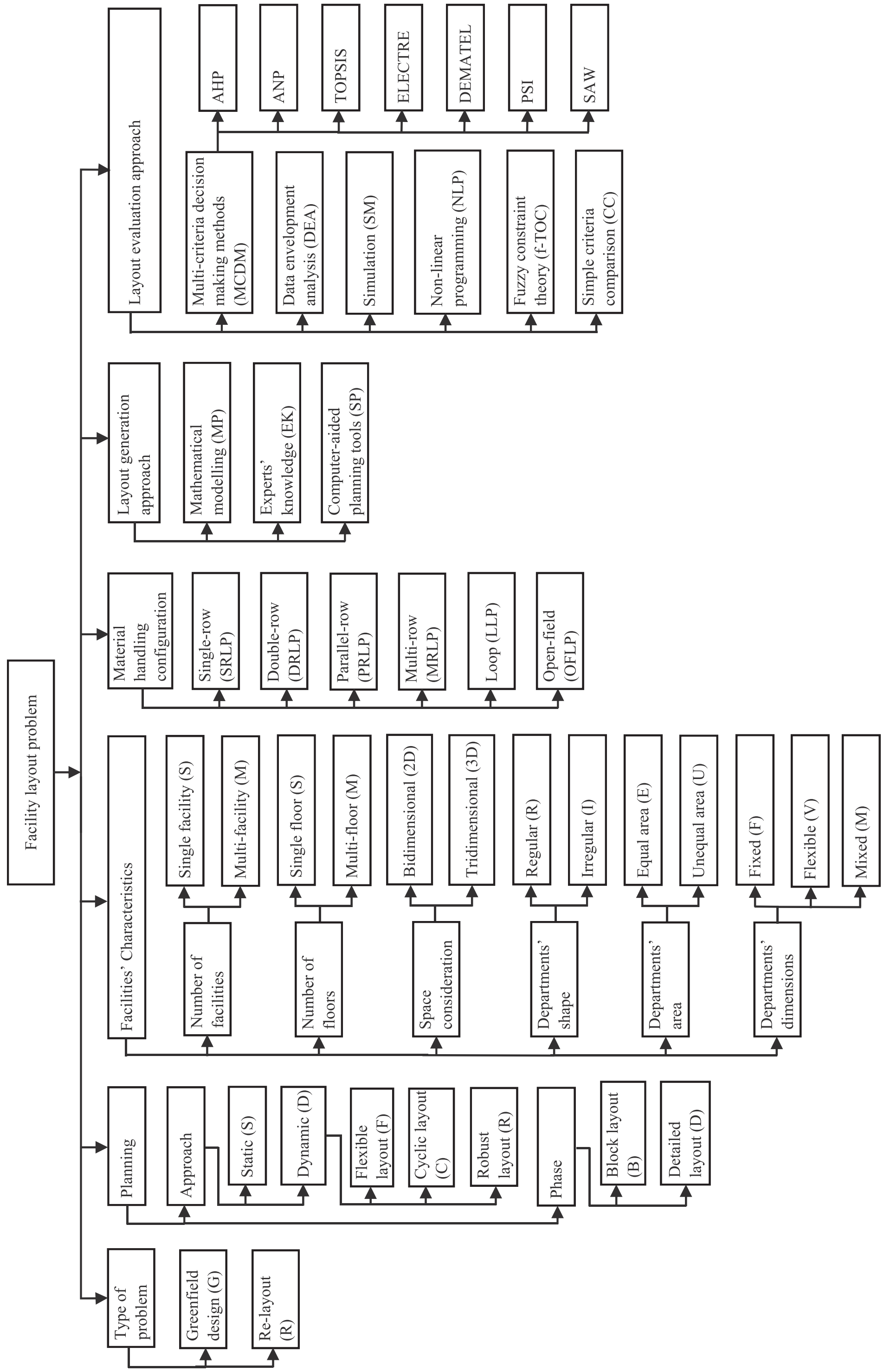

Figure 3. Classification of the literature on FLP.

Companies need to constantly adapt to changing market requirements. To do so, they increase or reduce their production capacity, partly or totally change technology, create new products/services, and improve and set up new processes. So having to make sufficiently flexible layouts in this context is understandable (Emami and Nookabadi 2013).

Based on the so-called dynamic planning (DFLP) approach, an optimum layout is designed for each time period in such a way that the total costs of transporting materials and those related to re-layouts in facilities are minimised (Turanoğlu and Akkaya 2018; Al Hawarneh, Bendak, and Ghanim 2019; Pournaderi, Ghezavati, and Mozafari 2019).

Table 2. An overview of the FLP considering a static planning approach.

References	Problem type	Planning phase	Number of facilities	Number of floors	Space consideration	Department shape	Department dimensions	Department area	Material handling configuration	Layout generation approach	Decision-support tools[1]
Samarghandi, Taabayan, and Jahantigh (2010)	G	B	S	S	2D	R	F	U	SRLP	MP	3.b
Chung and Tanchoco (2010)	G	D	S	S	2D	I	F	E	OFLP	-	3.a, 4.e
Díaz-Ovalle, Vázquez-Román, and Sam Mannan (2010)	R	B	S	S	2D	R	F	U	OFLP	MP	2.d, 2.j
Drezner (2010)	G	B	S	S	2D	R	F	U	OFLP	MP	
Hernández Gress et al. (2011)	G	B	S	S	2D	R	V	U	OFLP	MP	2.a
Jithavech and Krishnan (2010)	G	B	S	S	2D	R	F	E	MRLP	MP	4.b
Jung et al. (2010)	G	B	S	S	2D	R	F	U	OFLP	MP	2.a, 2.i, 2.j
Komarudin and Wong (2010)	G	B	S	S	2D	R	V	U	OFLP	MP	
Meller, Kirkizoglu, and Chen (2010)	G	B,D	S	S	2D	R	V	U	OFLP	MP	2.a
Samarghandi and Eshghi (2010)	G	B	S	S	2D	R	F	U	SRLP	MP	
Sanjeevi and Kianfar (2010)	G	B	S	S	2D	R	F	E	SRLP	MP	
Scholz, Jaehn, and Junker (2010)	G	B	S	S	2D	R	M	U	OFLP	MP	
Singh and Singh (2010)	G	B	S	S	2D	R	F	E	MRLP	MP	2.b
Yew Wong and Chiak See (2010)	G	B	S	S	2D	R	F	E	MRLP	MP	3.f
Kulturel-Konak and Konak (2011a)	G	B	S	S	2D	R	V	U	MRLP	MP	
Alsyouf et al. (2012)	R	B	S	S	2D	R	V	U	OFLP	EK	
Datta, Amaral, and Figueira (2011)	G	B	S	S	2D	R	F	U	SRLP	MP	
Eben-Chaime, Bechar, and Baron (2011)	G	B	S	S	2D	R	F	E	MRLP	EK	
González-Cruz and Gómez-Senent Martínez (2011)	G	B	S	S	2D	R,I	V	U	OFLP	MP	1.a
Jankovits et al. (2011)	G	B	S	S	2D	R	V	U	OFLP	MP	
Ku, Hu, and Wang (2011)	G	B	S	S	2D	R	V	U	OFLP	MP	3.a
Kulturel-Konak and Konak (2011b)	G	B	S	S	2D	R	V	U	MRLP	MP	
Kumar et al. (2011)	G	D	S	S	2D	R	F	E	SRLP	MP	
Maniya and Bhatt (2011)	G	B	S	S	2D	R	-	E,U	all	-	
Park et al. (2011)	G	D	S	M	2D	R	V	U	OFLP	MP	2.a
Şahin (2011)	G	B	S	S	2D	R	F	E	MRLP	MP	3.j
Singh and Singh (2011)	G	B	S	S	2D	R	F	E	MRLP	MP	2.b

(*continued*)

Table 2. Continued.

References	Problem type	Planning phase	Number of facilities	Number of floors	Space consideration	Department shape	Department dimensions	Department area	Material handling configuration	Layout generation approach	Decision-support tools[1]
Taghavi and Murat (2011)	G	D	S	S	2D	R	V	U	SRLP	MP	2.a
Tuzkaya et al. (2013)	G	B	S	S	2D	R	F	E	MRLP	MP	
Vasudevan and Son (2011)	R	B	S	S	2D	R	F	U	OFLP	EK	
Yang, Chang, and Yang (2012)	G	B	S	S	2D	R	F	E	MRLP	EK	
Cheng and Lien (2012a)	G	B	S	M	2D	R	F	E	MRLP	MP	
Lee and Tseng (2012)	R	B	S	S	2D	R	V	E,U	OFLP	MP	4.a
Aiello, La Scalia, and Enea (2012)	G	B	S	S	2D	R	V	U	OFLP	MP	
Altuntas and Selim (2012)	G	D	S	S	2D	R	F	E	MRLP	MP	4.f
Amaral and Letchford (2013)	G	B	S	S	2D	R	F	E	SRLP	MP	3.d
Bernardi and Anjos (2013)	G	B	S	M	2D	R	V	U	OFLP	MP	2.a, 2.i
Bozer and Wang (2012)	G	B	S	S	2D	R	V	U	OFLP	MP	2.a
Cheng and Lien (2012b)	G	B	S	S,M	2D	R	F	E	MRLP	MP	
Ulutas and Kulturel-Konak (2012)	G	B	S	S	2D	R	V	U	MRLP	MP	3.i
Hale, Huq, and Hipkin (2012)	G	B	S	S	2D	R	F	E	MRLP	MP	
Hungerländer and Rendl (2013)	G	B	S	S	2D	R	F	U	SRLP	MP	
Kaveh, Shakouri, and Zolfaghari (2012)	G	B	S,M	S,M	2D	R	F	E	MRLP	MP	
Krishnan et al. (2012)	G	B,D	S	S	2D	R	F	E	MRLP	MP	
Kulturel-Konak (2012)	G	B	S	S	2D	R	V	U	MRLP	MP	
Lee (2012)	R	B	S	S	2D	R	F	E,U	OFLP	MP	4.a
Liu and Sun (2012)	G	B	S	S	2D	R	V	U	OFLP	MP	
McDowell and Huang (2012)	R	D	S	S	2D	R	F	E,U	OFLP	EK	
Mohamadghasemi and Hadi-Vencheh (2012)	G	B	S	S	2D	R,I	V	U	OFLP	SP	1.a
Navidi, Bashiri, and Messi Bidgoli (2012)	G	B	S	S	2D	R	F	E	MRLP	MP	3.a
Palubeckis (2012)	G	B	S	S	2D	R	F	E	SRLP	MP	
Yang, Deuse, and Jiang (2013a)	G	B	S	S	2D	R	F	U	MRLP	MP	
Garcia-Hernandez et al. (2013a)	G	B	S	S	2D	R	F	U	MRLP	MP	
Kothari and Ghosh (2013a)	G	B	S	S	2D	R	F	E,U	SRLP	MP	3.d
Matai, Singh, and Mittal (2013a)	G	B	S	S	2D	R	F	E	MRLP	MP	

(*continued*)

Table 2. Continued.

References	Problem type	Planning phase	Number of facilities	Number of floors	Space consideration	Department shape	Department dimensions	Department area	Material handling configuration	Layout generation approach	Decision-support tools[1]
Aiello, La Scalia, and Enea (2013)	G	B	S	S	2D	R	V	U	OFLP	MP	
Amaral (2013)	G	B	S	S	2D	R	F	E,U	PRLP	MP	2.a
Kothari and Ghosh (2014a)	G	B	S	S	2D	R	F	U	SRLP	MP	
Kothari and Ghosh (2014b)	G	B	S	S	2D	R	F	E,U	SRLP	MP	
Chang and Ku (2013)	G	B	S	S	2D	R	V	U	OFLP	MP	
Garcia-Hernandez et al. (2015)	G	B	S	S	2D	R	V	U	MRLP	MP	
Garcia-Hernandez et al. (2013b)	G	B	S	S	2D	R	V	U	MRLP	MP	3.e
Hadi-Vencheh and Mohamadghasemi (2013)	G	B	S	S	2D	R	V	E,U	OFLP	SP	1.c
Hathhorn, Sisikoglu, and Sir (2013)	G	B	S	M	2D	R	V	E,U	OFLP	MP	2.c
Jabal-Ameli and Moshref-Javadi (2014)	G	B,D	S	S	2D	R	F	E,U	OFLP	MP	
Jahanshahloo et al. (2013)	G	B	S	S	2D	R	V	E,U	MRLP	-	
Javadi et al. (2013)	G	B,D	S	S	2D	R	V	U	OFLP	MP	2.a
Leno et al. (2012)	G	B	S	S	2D	R	F	U	OFLP	MP	
Jia et al. (2013)	R	D	S	S	2D	R	F	U	SRLP,MRLP	MP	3.b
Jiang and Nee (2013)	R	D	S	S	2D	R	F	E,U	OFLP	MP	1.e
Khaksar-Haghani et al. (2013)	G	B	S	M	2D	R	F	E	MRLP	MP	2.b, 3.a
Kothari and Ghosh (2013b)	G	B	S	S	2D	R	F	U	SRLP	MP	3.d
Kulturel-Konak and Konak (2013)	G	B	S	S	2D	R	V	U	OFLP	MP	
Lenin et al. (2013)	G	D	S	S	2D	R	F	E	SRLP	MP	
Lin et al. (2015)	G	B	S	S	2D	R	F	E,U	OFLP	EK	
Matai, Singh, and Mittal (2013b)	G	B	S	S	2D	R	F	E	MRLP	MP	2.b
Ou-Yang and Utamima (2013)	G	B	S	S	2D	R	F	U	SRLP	MP	
Ripon et al. (2013)	G	B	S	S	2D	R	F	U	OFLP	MP	
Ulutas and Kulturel-Konak (2013)	G	B	S	S	2D	R	V	U	MRLP	MP	
Xiao, Seo, and Seo (2013)	G	B	S	S	2D	R	F	U	OFLP	MP	1.b, 2.a, 3.d
Yang, Deuse, and Jiang (2013b)	R	B	S	S	2D	R	-	E,U	MRLP	-	
Azadeh and Moradi (2014)	G	D	S	S	2D	R	F	E,U	OFLP	SP	1.b

(*continued*)

Table 2. Continued.

References	Problem type	Planning phase	Number of facilities	Number of floors	Space consideration	Department shape	Department dimensions	Department area	Material handling configuration	Layout generation approach	Decision-support tools[1]
Moatari-Kazerouni, Chinniah, and Agard (2015a)	G,R	B	S	S,M	2D	R	F	E,U	all	MP	
Al-Hawari, Mumani, and Momani (2014)	R	B	S	S	2D	R	F	E,U	OFLP	EK	
Altuntas, Selim, and Dereli (2014)	R	B	S	S	2D	R	F	E,U	OFLP	MP	
Azadeh, Nazari, and Charkhand (2015)	R	B	S	S	2D	R	V	E,U	OFLP	EK	2.b
Bukchin and Tzur (2014)	G	B,D	S	S	2D	R,I	V	E,U	OFLP	MP	
Hong, Seo, and Xiao (2014)	G	B	S	S	2D	R	V	U	MRLP	MP	2.a, 3.b
Hungerländer (2014)	G	B	S	S	2D	R	F	U	SRLP	MP	3.a
Jiang, Ong, and Nee (2014)	R	D	S	S	2D	R	F	E,U	OFLP	MP	
Kaveh and Safari (2014)	G	B	S	S	2D	R	F	U	SRLP	MP	
Moatari-Kazerouni, Chinniah, and Agard (2015b)	R	B	S	S	2D	R	F	E,U	OFLP	MP	
Neghabi, Eshghi, and Salmani (2014)	G	B	S	S	2D	R	F	E,U	MRLP	MP	
Potočnik et al. (2014)	R	D	S	S	2D	R	F	E	OFLP	EK	
Raja and Anbumalar (2014)	G	D	S	S	2D	R	F	E	MRLP	MP	
Leno, Saravana Sankar, and Ponnambalam (2016)	G	B	S	S	2D	R	F	U	OFLP	MP	3.a
Zhao and Wallace (2014)	G	B	S	S	2D	R	F	E	MRLP	MP	3.b
Zheng (2014)	G	B	S	S	2D	R,I	V	U	OFLP	MP	
Palubeckis (2015a)	G	B	S	S	2D	R	F	U	SRLP	MP	
Caputo et al. (2015)	G	B	S	S	2D	R	F	U	OFLP	MP	
Garcia-Hernandez et al. (2013c)	G	B	S	S	2D	R	V	U	MRLP	MP	
Ghassemi Tari and Neghabi (2015)	G	B	S	S	2D	R	F	U	OFLP	MP	2.a
Gonçalves and Resende (2015)	G	B	S	S	2D	R	V	U	OFLP	MP	2.c, 3.b
Helber et al. (2016)	G	B	M	M	2D	R	F	U	MRLP	MP	2.a
Hungerländer and Anjos (2015)	G	B	S	S	2D	R	F	E	SRLP, DRLP, PRLP, MRLP	MP	2.a, 3.a
Lee (2015)	G	D	S	M	2D	R	F	U	OFLP	MP	
Matai (2015)	G	B	S	S	2D	R	F	E	MRLP	MP	

(continued)

Table 2. Continued.

References	Problem type	Planning phase	Number of facilities	Number of floors	Space consideration	Department shape	Department dimensions	Department area	Material handling configuration	Layout generation approach	Decision-support tools[1]
Palubeckis (2015b)	G	B	S	S	2D	R	F	E	SRLP	MP	3.b
Qudeiri et al. (2015)	G	B	S	S	2D	R	F	U	OFLP	MP	3.a
Salmani, Eshghi, and Neghabi (2015)	G	B	S	S	2D	R	F	U	OFLP	MP	
Saraswat, Venkatadri, and Castillo (2015)	G	B	S	S	2D	R	V	U	OFLP	MP	
Tasadduq, Imam, and Ahmad (2015)	G	B	S	S	2D	R	F	U	OFLP	MP	3.a
Zhao and Wallace (2016)	G	B	S	S	2D	R	F	E	MRLP	MP	
Ahmadi and Akbari Jokar (2016)	G	B	S	S,M	2D	R	M	U	OFLP	MP	2.a, 2.h
Alves, de Medeiros, and Ofelia de Queiroz (2016)	G	B	S	S	2D	R	F	U	OFLP	MP	3.a
Anjos and Vieira (2016)	G	B	S	S	2D	R	V	U	OFLP	MP	2.a, 2.f
Azadeh et al. (2016)	G	B	S	S	2D	R	V	U	OFLP	SP	1.c
Chae and Regan (2016)	G	B	S	S	2D	R	M	U	OFLP	MP	2.a
Che, Zhang, and Feng (2017)	G	B	S	M	2D	R	F	U	MRLP	MP	2.a, 3.b
Choi, Kim, and Chung (2017)	G	B	S	S	2D	R	V	E,U	OFLP	MP	
Glenn and Vergara (2016)	R	B	S	S	2D	R	F	U	OFLP	MP	3.k
Guan and Lin (2016)	G	B	S	S	2D	R	F	U	SRLP	MP	3.b
Horta, Coelho, and Relvas (2016)	G	B	S	M	2D	R	F	E	MRLP	MP	2.a
Hou, Li, and Wang (2016)	G	B	S	S	2D	R	F	U	OFLP	MP	
Huang and Wong (2017)	G	B	S	S	2D	R,I	V	U	OFLP	MP	2.c
Ingole and Singh (2017)	G	B	S	S	2D	R	F	U	MRLP	MP	
Kim, Yu, and Jang (2016)	G	B	S	S	2D	R	F	E	MRLP	MP	4.g
Neghabi and Ghassemi Tari (2016)	G	B	S	S	2D	R	F	U	OFLP	MP	2.a
Paes, Pessoa, and Vidal (2017)	G	B	S	S	2D	R	V	U	OFLP	MP	3.b
Palubeckis (2017)	G	B	S	S	2D	R	F	U	SRLP	MP	3.b
Rubio-Sánchez et al. (2016)	G	B	S	S	2D	R	F	U	SRLP	MP	
Sharma and Singhal (2017)	G	B	S	S	2D	R	-	E,U	all	-	
Sikaroudi and Shahanaghi (2016)	G	B	S	S	2D	R	F	U	OFLP	MP	3.a

(*continued*)

Table 2. Continued.

References	Problem type	Planning phase	Number of facilities	Number of floors	Space consideration	Department shape	Department dimensions	Department area	Material handling configuration	Layout generation approach	Decision-support tools[1]
Xiao et al. (2016)	G	B	S	S	2D	R	V	U	OFLP	MP	
Zhou et al. (2017)	G	B	S	S	2D	R	F	E	MRLP	MP	3.a
Asef-Vaziri, Jahandideh, and Modarres (2017)	G	B	S	S	2D	R	M	U	LLP	MP	3.a
Asef-Vaziri and Kazemi (2018)	G	B	S	S	2D	R,I	F	U	LLP	MP	2.a
Azimi and Soofi (2017)	G	D	S	S	2D	R	F	E	MRLP	MP	3.a
Defersha and Hodiya (2017)	G,R	B	S	S	2D	I	V	U	OFLP	MP	2.a
Gai and Ji (2019)	G	B	S	S	2D	R	V	U	OFLP	MP	2.b, 5.b
Ghassemi Tari and Neghabi (2018)	G	B	S	S	2D	R	F	U	OFLP	MP	2.a
Grobelny and Michalski (2017)	G	B	S	S	2D	R	F	E,U	OFLP	MP	
Kang and Chae (2017)	G	B	S	S	2D	R	V	U	OFLP	MP	3.c
Latifi, Mohammadi, and Khakzad (2017)	R	B	S	S	3D	R	F	U	OFLP	MP	3.a
Ning and Li (2018)	G	B	S	S	2D	R	F	U	SRLP	MP	
Palomo-Romero, Salas-Morera, and García-Hernández (2017)	G	B	S	S	2D	R	V	U	MRLP	MP	3.e
Safarzadeh and Koosha (2017)	G	B	S	S	2D	R	F	U	MRLP	MP	3.a
Tubaileh and Siam (2017)	G	D	S	S	2D	R	F	U	SRLP, DRLP, MRLP	MP	3.a
Xie et al. (2018)	G	B	S	S	2D	R	V	U	OFLP	MP	2.a
Park and Seo (2019)	G	B	S	S	2D	R	F	U	OFLP	MP	3.b
Feng et al. (2018)	G	B,D	S	S	2D	R	F	U	OFLP	MP	2.a, 3.b
Allahyari and Azab (2018)	G	B	S	S	2D	R	F	U	OFLP	MP	
Brunoro Ahumada, Quddus, and Mannan (2018)	G	B	S	S	2D	R	F	E	OFLP	MP	
Durmusoglu (2018)	G	B	S	S	2D	R	-	E,U	all	-	
Ejeh, Liu, and Papageorgiou (2018)	G	B	S	M	3D	R	F	U	OFLP	MP	2.a
Feng and Che (2018)	G	B	S	S	2D	R	F	E,U	MRLP	MP	2.a
Friedrich, Klausnitzer, and Lasch (2018)	G	B	S	S	2D	R	V	U	MRLP	MP	3.c
Jeong and Seo (2018)	G	B	S	S	2D	R	F	U	OFLP	MP	3.b
Kalita and Datta (2018)	G	B	S	S	2D	R	F	U	SRLP	MP	3.d
Kang, Kim, and Chae (2018)	G	B	S	S	2D	R	F	U	LLP	MP	3.b

(*continued*)

Table 2. Continued.

References	Problem type	Planning phase	Number of facilities	Number of floors	Space consideration	Department shape	Department dimensions	Department area	Material handling configuration	Layout generation approach	Decision-support tools[1]
Leno, Saravana Sankar, and Ponnambalam (2018)	G	B	S	S	2D	R	F	U	OFLP	MP	
Liu et al. (2018)	G	B	S	S	2D	R	F	U	OFLP	MP	3.c
Nagarajan et al. (2018)	G	B	S	S	2D	R	F	U	SRLP	MP	
Park, Shin, and Won (2018)	G	D	S	M	3D	R	F	U	OFLP	MP	2.d
Sun et al. (2018)	G	B	S	S	2D	R	F	U	MRLP	MP	3.d
Wang et al. (2018)	G	B	S	S,M	2D	R	F	U	OFLP	MP	3.a
Wu et al. (2018)	G	B	S	M	2D	R	V	U	OFLP	MP	2.c
Hu and Yang (2019)	G	B	S	S	2D	R	F	E	MRLP	MP	
Vázquez-Román et al. (2019)	G	B	S	S	2D	R	F	U	OFLP	MP	2a, 2d, 2.e, 5.c
Abdollahi, Aslam, and Yazdi (2019)	G	B	S	S	2D	R,I	V	U	OFLP	SP	1.d
Chen et al. (2019)	G	B	S	S	2D	R	F	E	MRLP	MP	3.h
Cravo and Amaral (2019)	G	B	S	S	2D	R	F	U	SRLP	MP	3.d
de Lira-Flores et al. (2019)	G	B,D	S	S	2D	R	F	U	OFLP	MP	2.d
Fogliatto et al. (2019)	R	D	S	S	2D	R	F	U	OFLP	EK	
Gulsen, Murray, and Smith (2019)	G	D	S	S	2D	R	F	U	DRLP	MP	2.g
Kim and Chae (2019)	G	B	S	M	2D	R	V	U	LLP	MP	3.c
Klausnitzer and Lasch (2019)	G,R	B	S	S	2D	R	V	U	OFLP	MP	2.a
Kovacs (2019)	R	D	S	S	2D	R	F	U	OFLP	MP	
la Scalia et al. (2019)	G	B	S	S	2D	R	V	U	OFLP	MP	3.a
Le, Dao, and Chaabane (2019)	G	B	S	S	2D	R	F	E	OFLP	MP	
Lin and Wang (2019)	G	B	S	S	2D	R	F	U	OFLP	EK	
Liu and Liu (2019)	G	B	S	S	2D	R	V	U	OFLP	MP	
Ramirez Drada,, Chud Pantoja, and Orejuela Cabrera (2019)	G,R	B	S	S	2D	R	F	U	OFLP	MP	1.a
Singh and Ingole (2019)	G	B	S	S	2D	R	F	E	MRLP	MP	3.a
Suhardi, Juwita, and Astuti (2019)	R	D	S	S	2D	R	F	E	MRLP	EK	4.c
Yang et al. (2019)	G	B	S	S	2D	R	F	U	SRLP	MP	2.c
Zhang et al. (2019)	G	B	S	S	2D	R	F	E	MRLP	MP	
Garcia-Hernandez et al. (2019)	G	B	S	S	2D	R	V	U	MRLP	MP	3.e

[1] Decision-support tools: 1) Computer-aided layout planning tools: 1.a (CRAFT), 1.b (VIP-PLANOPT); 1.c (SPIRAL), 1.d (ALDEP), 1.e (AFLP System); 2) Optimization solvers: 2.a (CPLEX), 2.b (LINGO), 2.c (GUROBI), 2.d (DICOPT), 2.e (CONOPT), 2.f (SNOPT), 2.g (COUENNE), 2.h (KNITRO), 2.i (MINOS), 2.j (BARON), 2.k (SBB); 3) Programming languages: 3.a (MATLAB), 3.b (C++), 3.c (JAVA), 3.d (C), 3.e (Python), 3.f (Visual Basic .NET), 3.g (Tcl/Tk), 3.h (C#), 3.i (DELPHI), 3.j (FORTRAN 90), 3.k (Visual Basic for App); 4) Simulation software: 4.a (VISSIM), 4.b (@Risk), 4.c (ARENA), 4.d (Enterprise Dynamics), 4.e (AIM), 4.f (ProModel), 4.g (Automod), 4.h (Expert fit); 5) Computer-aided design software: 5.a (AUTOCAD), 5.b (CorelDraw), 5.c (TROL).

Table 3. An overview of the FLP considering a dynamic planning approach.

References	Problem type	Planning phase	Planning approach	Number of facilities	Number of floors	Space consideration	Department shape	Department dimensions	Department area	Material handling configuration	Layout generation approach	Decision-support tools[1]
McKendall and Hakobyan (2010)	G	B	F	S	S	2D	R	F	U	OFLP	MP	3.b
Madhusudanan Pillai, Hunagund, and Krishnan (2011)	G	B	R	S	S	2D	R	F	E	OFLP	MP	3.a
YYang, Chuang, and Hsu (2011)	G	B	F	S	S	2D	R	F	E	MRLP	MP	3.d
Abedzadeh et al. (2013)	G	B	F	S	S	2D	R	V	U	MRLP	MP	2.a, 3.a
Guan et al. (2012)	G	B	F	S	S	2D	R	F	E	MRLP	MP	3.a
Jolai, Tavakkoli-Moghaddam, and Taghipour (2012)	G	B	F	S	S	2D	R	F	U	OFLP	MP	
Kia et al. (2012)	G	B,D	F	S	S	2D	R	F	E	MRLP	MP	2.b
McKendall and Liu (2012)	G	B	F	S	S	2D	R	F	E	MRLP	MP	
Azimi and Saberi (2013)	G	B	F	S	S	2D	R	F	U	MRLP	MP	3.a, 4.d
Emami and Nookabadi (2013)	G	B	F	S	S	2D	R	F	E	MRLP	MP	2.j 2.k, 3.a
Hosseini-Nasab and Emami (2013)	G	B	F	S	S	2D	R	F	E	MRLP	MP	3.b
Kaveh, Dalfard, and Amiri (2014)	G	B	F	S	S	2D	R	F	E	MRLP	MP	3.a
Kia et al. (2013)	G	D	F	S	S	2D	R	F	E	MRLP	MP	2.b, 3.f
Mazinani, Abedzadeh, and Mohebali (2013)	G	B	F	S	S	2D	R	M	U	MRLP	MP	
Samarghandi, Taabayan, and Behroozi (2013)	G	B	F	S	S	2D	R	F	U	MRLP	MP	
Chen (2013)	G	B	F	S	S	2D	R	F	E	MRLP	MP	
Bozorgi, Abedzadeh, and Zeinali (2015)	G	B	F	S	S	2D	R	F	E	SRLP	MP	
Chen and Lo (2014)	G	B	F	S	S	2D	R	F	E	MRLP	MP	
Hosseini, Al Khaled, and Vadlamani (2014)	G	B	F	S	S	2D	R	F	E	MRLP	MP	3.a
Kia et al. (2014)	G,R	B	F	S	M	2D	R	F	E	MRLP	MP	2.a
Kulturel-Konak and Konak (2015)	G	B	C	S	S	2D	R	V	U	OFLP	MP	2.a
Nematian (2014)	G	B	R	S	S	2D	R	F	U	SRLP	MP	
Pourvaziri and Naderi 2014)	G	B	F	S	S	2D	R	F	E	MRLP	MP	

(continued)

Table 3. Continued

References	Problem type	Planning phase	Planning approach	Number of facilities	Number of floors	Space consideration	Department shape	Department dimensions	Department area	Material handling configuration	Layout generation approach	Decision-support tools[1]
Derakhshan Asl and Wong (2017)	G	B	F	S	S	2D	R	F	U	OFLP	MP	3.a
Kheirkhah, Navidi, and Bidgoli (2015)	G	B	F	S	S	2D	R	F	E	MRLP	MP	3.a
Li et al. (2015)	G,R	B	F	S	S	2D	R	F	E	MRLP	MP	
Ulutas and Attila Islier (2015)	G	B	F	S	S	2D	R	F	E	MRLP	MP	
Zarea Fazlelahi et al. (2016)	G	B	R	S	S	2D	R	F	E	MRLP	MP	
Hosseini and Seifbarghy (2016)	G	B	F	S	S	2D	R	F	E	MRLP	MP	3.a
Pourvaziri and Pierreval (2017)	G	B	F	S	S	2D	R	F	E	MRLP	MP	
Tayal and Singh (2018)	G	D	F	S	S	2D	R	F	E	SRLP	MP	3.c
Kumar and Singh (2017)	G	B,D	F	S	S	2D	R	F	E	MRLP	MP	2.b
Liu et al. (2017)	G	B	F	S	S	2D	R	F	U	OFLP	MP	3.c
Moslemipour, Lee, and Loong (2017)	G	B	R	S	S	2D	R	F	E	MRLP	MP	3.a
Vitayasak, Pongcharoen, and Hicks (2017)	G	B	F	S	S	2D	R	F	U	MRLP	MP	3.g
Xiao et al. (2017)	G	B	F	S	S	2D	R,I	V	U	OFLP	MP	2.a
Kulturel-Konak (2017)	G	B	F	S	S	2D	R	V	U	OFLP	MP	2.a
Li, Tan, and Li (2018)	G	D	F	S	S	2D	R	F	U	OFLP	MP	
Peng et al. (2018)	G	B	R	S	S	2D	R	F	E	MRLP	MP	3.a
Turanoğlu and Akkaya (2018)	G	B	F	S	S	2D	R	F	E	MRLP	MP	3.a
Vitayasak and Pongcharoen (2018)	G	D	F	S	S	2D	R	F	U	MRLP	MP	3.g
Al Hawarneh, Bendak, and Ghanim (2019)	G	B	F	M	S	2D	R	F	E	MRLP	MP	3.a, 5.a
Pournaderi, Ghezavati, and Mozafari (2019)	G	B	F	S	S	2D	R	F	E	MRLP	MP	
Wei, Yuan, and Ye (2019)	G	D	F	S	S	2D	R	F	U	OFLP	MP	3.c

[1] Decision-support tools: 1) Computer-aided layout planning tools: 1.a (CRAFT), 1.b (VIP-PLANOPT); 1.c (SPIRAL), 1.d (ALDEP), 1.e (AFLP System); 2) Optimization solvers: 2.a (CPLEX), 2.b (LINGO), 2.c (GUROBI), 2.d (DICOPT), 2.e (CONOPT), 2.f (SNOPT), 2.g (COUENNE), 2.h (KNITRO), 2.i (MINOS), 2.j (BARON), 2.k (SBB); 3) Programming languages: 3.a (MATLAB), 3.b (C++), 3.c (JAVA), 3.d (C), 3.e (Python), 3.f (Visual Basic .NET), 3.g (Tcl/Tk), 3.h (C#), 3.i (DELPHI), 3.j (FORTRAN 90), 3.k (Visual Basic for App); 4) Simulation software: 4.a (VISSIM), 4.b (@Risk), 4.c (ARENA), 4.d (Enterprise Dynamics), 4.e (AIM), 4.f (ProModel), 4.g (Automod), 4.h (Expert fit); 5) Computer-aided design software: 5.a (AUTOCAD), 5.b (CorelDraw), 5.c (TROL).

Like Hosseini-Nasab et al. (2018), the literature review performed in this article showed that in the past 10 years, the FLP dynamic planning approach has had less repercussion in the scientific literature than the static approach (SFLP) because only 44 of the 232 articles (18.97%) included it. According to Peng et al. (2018), dynamic layouts can be classified into flexible and robust layouts. However, according to our literature review, a decision was made to include cyclic layouts into these categories.

When planning flexible layouts, an optimum arrangement scheme is designed for each time period to minimise not only the total costs of transporting materials, but also those related to re-layouts of facilities. These dynamic layouts have been more frequently dealt with in the literature in the past decade (38 of 44 articles: 86.36%).

Kulturel-Konak and Konak (2015) introduced cyclic layouts as a special dynamic layouts case. With this approach, the planning horizon is divided into T periods, $t = 1, \ldots, T$. After period T, the material flow matrix among departments returns to its initial state during period $t = 1$. Apart from product demand, the area requirements of some departments may also change seasonally.

In the robust design approach is considered a single layout outline for the whole planning horizon, with different stochastic demand scenarios (Moslemipour, Lee, and Loong 2017). In fact as this unique design is used for each time period, this approach incurs no reorganisation cost. The robust design is not necessarily an optimum design for a given time period, but proves suitable throughout the temporary planning horizon as it minimises the cost of transporting materials (Madhusudanan Pillai, Hunagund, and Krishnan 2011). So the advantage of the robust approach is that it does not incur reorganisation costs, while its disadvantage lies in it not being an optimum design for each time period (Peng et al. 2018). This method is suitable for settings with a high facilities re-layout cost (Moslemipour, Lee, and Loong 2017), such as those firms that need heavy machinery to perform their operations. Despite its importance, this approach has scarcely appeared in the literature about DFLP in the past 10 years (5 of 44 articles, 11.36%).

3.3. Characteristics of facilities

Both complexity and the FLP solution method depend on the characteristics of facilities to a great extent. For example with FLP, it is essential to start with previous knowledge about the number of buildings and floors required inside buildings to perform normal industrial operations, as well as the shape, area and dimensions of departments.

Most of the reviewed research works considered the facility layout design in a single building and/or on a single floor. In practice however, large firms often consider more than one floor, and even several buildings, to perform their operations. Only two research works contemplated several buildings simultaneously in SFLP (Helber et al. 2016; Kaveh, Shakouri, and Zolfaghari 2012), and only one article did so in DFLP (Al Hawarneh, Bendak, and Ghanim 2019). For SFLP, 18 works considered several floors when planning the layout, but only one contemplated these conditions in a dynamic setting (Kia et al. 2014).

Although one of the classic principles of facility layout is to make as much use of space in industrial facilities as possible, the tridimensional space in FLP has scarcely been considered. In fact only three works actually contemplated this requirement in the SFLP context (Ejeh, Liu, and Papageorgiou 2018; Latifi, Mohammadi, and Khakzad 2017; Park, Shin, and Won 2018), and no work did so in the DFLP domain. All the other reviewed works in this study considered space only from a bidimensional viewpoint.

Figure 4 depicts how articles were distributed according to the area, shape and dimensions of departments. Departments can be regularly or irregularly shaped (Ahmadi, Pishvaee, and Jokar 2017). In the first case, which appeared more often in the literature (222 articles, 95.69%), departments were rectangular (Drira, Pierreval, and Hajri-Gabouj 2007). Irregularly shaped departments were generally polygons whose summed inner angles

Figure 4. Distribution of publications based on the a) shape, b) area, c) and dimensions of departments.

came to at least 270° (Drira, Pierreval, and Hajri-Gabouj 2007; Hosseini-Nasab et al. 2018). Of all the works dealing with irregular shapes, one considered departments to be hexagons (Chung and Tanchoco 2010), while the rest contemplated rectangular departments combined to others in the form of non-convex polygons (Asef-Vaziri and Kazemi 2018; Bukchin and Tzur 2014; Defersha and Hodiya 2017).

Regarding areas when planning layouts, departments with exactly equal or different areas can be considered (Feng and Che 2018), and using discrete or continuous optimisation models depends on what these areas are like (Allahyari and Azab 2018).

Three categories were found for department dimensions: fixed or flexible (Xiao et al. 2017) and mixed. For fixed dimensions, the problem is formulated according to the assumption that the width and length of departments must remain intact when arranged in space. When dimensions are considered flexible, the width and length of departments may vary within a pre-set interval during the arrangement process. This variation can be controlled by aspect ratios (proportion between the longest side and the shortest side of each department) (Abdollahi, Aslam, and Yazdi 2019; Friedrich, Klausnitzer, and Lasch 2018; Liu and Liu 2019), area ratios (the minimum proportion that the department area must occupy to the total available area) (Gai and Ji 2019), by ensuring a minimum area (Xie et al. 2018) or by defining the pre-set interval for length or width for departments (Neghabi, Eshghi, and Salmani 2014; Garcia-Hernandez et al. 2019).

3.4. Materials handling system configuration

As seen in Figure 5, according to how the system to transport materials is configured, six facility layout categories are defined (Hosseini-Nasab et al. 2018): single-row layout problem, SRLP; double-row layout problem, DRLP; parallel-row layout problem, PRLP; multi-row layout problem, MRLP; loop layout problem, LLP; open-field layout problem, OFLP. In them we do not include the multi-floor layout classification (multi-floor layout problem, MFLP), which Hosseini-Nasab et al. (2018) consider, because it is believed that each floor can have any of the six afore-mentioned configurations. Nonetheless, the MFLP criterion was independently considered in the FLP classification in accordance with the number of floors (Figure 3).

Figure 6 shows the frequency with which these configurations are dealt with considering that some articles have contemplated more than one scheme. As shown below, OFLP is the most widespread configuration when studying SFLP with 53.19% of cases, followed by MRLP with 32.98%. In DFLP, MRLP stands out with 70.45%, followed next by OFLP with 22.73%. The LLP, DRLP and PRLP configurations have received very little attention under the static planning approach, and no attention under the dynamic approach.

3.5. Problem type

As Figure 3 depicts, layouts can be planned for completely new plants, which are often called greenfield layout designs, or in existing plants, which implies talking about re-layout. In the literature, more attention has been generally paid to the first case, where the layout plan is designed without the influence of the restrictions that normally occur when doing so in an existing facility. Despite its limited importance in the literature, the re-layout problem is more frequent in practice (Kulturel-Konak 2007). Of all the bibliographic sources consulted in this research work, only 11.21% dealt with the second problem (26 articles). Problem

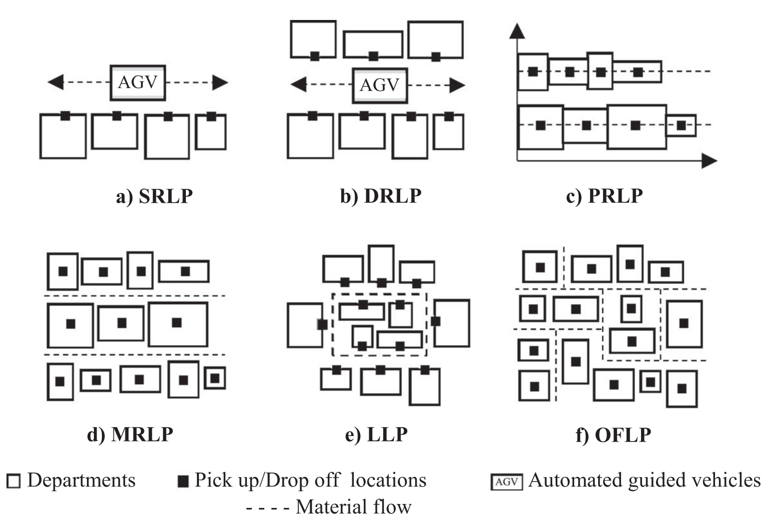

Figure 5. Facilities layout based on the material handling system configuration.

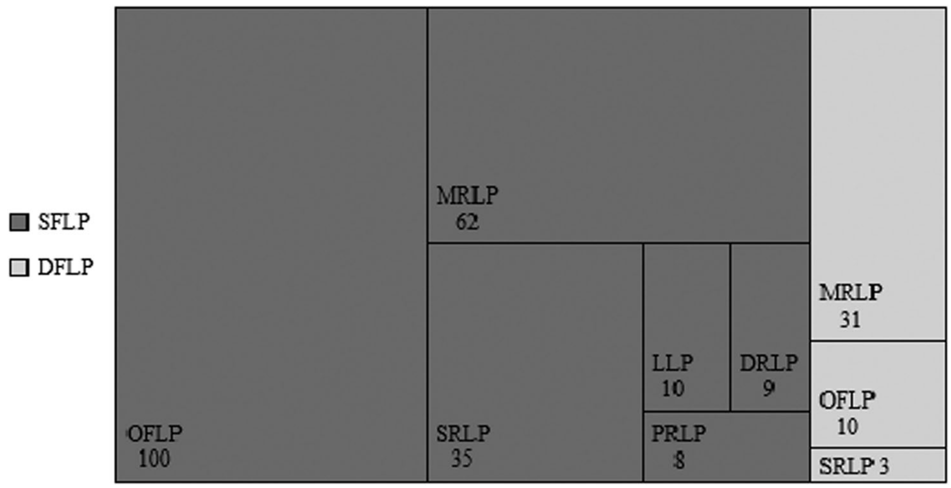

Figure 6. Distribution of publications based on the material handling system configuration.

type, as an FLP classification criterion, was not considered in any former review work as far as the authors know (Drira, Pierreval, and Hajri-Gabouj 2007; Heragu 1992; Hosseini-Nasab et al. 2018; Kouvelis, Chiang, and Kiran 1992; Kouvelis and Kiran 1991; Maganha, Silva, and Ferreira 2019; Meller and Gau 1996; Singh and Sharma 2006).

3.6. Approaches for layout generation

As far as the authors are aware, no approaches for generating alternatives have been identified or dealt with on the whole in any previous review study in the FLP context (Heragu 1992; Kouvelis and Kiran 1991; Kouvelis, Chiang, and Kiran 1992; Hosseini-Nasab et al. 2018; Drira, Pierreval, and Hajri-Gabouj 2007; Singh and Sharma 2006; Meller and Gau 1996). Mathematical programming (MP) has been traditionally covered in-depth as an approach to achieve optimum distribution or a set of acceptable solutions with different FLP variants. Nonetheless, our literature review identified research works that dealt with other approaches for the same objective, such as computer-aided planning tools (SP) or experts' knowledge (EK). We stress that some research works on FLP did not begin by generating layout alternatives, but focused exclusively on testing new assessment approaches for the alternatives generated in former research works (Chung and Tanchoco 2010; Durmusoglu 2018; Jahanshahloo et al. 2013; Maniya and Bhatt 2011; Yang, Deuse, and Jiang 2013b). Figure 7 (a) distributes the articles that contemplated approaches to generate alternatives for both SFLP and DFLP. Given their relevance, FLP formulation approaches using MP are dealt with separately in Section 4 herein.

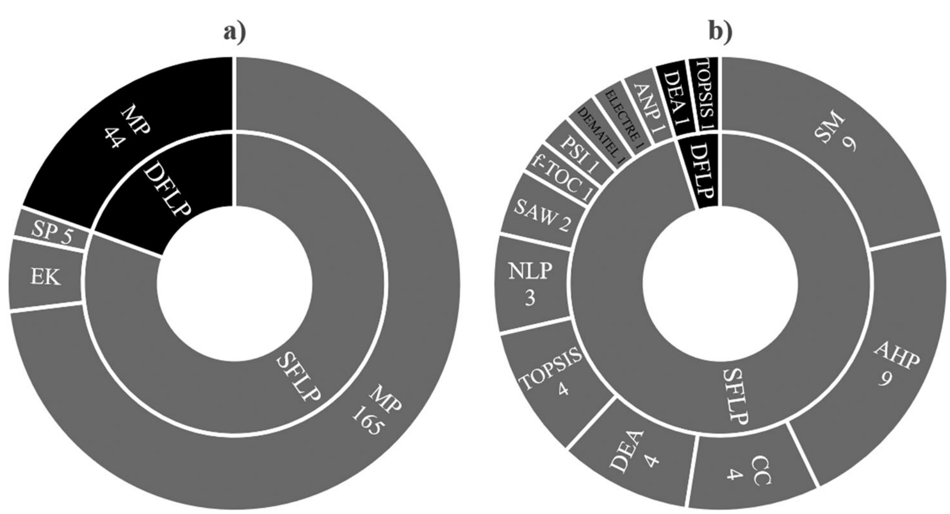

Figure 7. Distribution of publications according to the a) layout generation approach, b) and layout evaluation approach.

4. Mathematical modelling of FLP

When generating layout alternatives, MP was the most widely used method in the reviewed literature. This section explains the current trends in FLP mathematical modelling. Figure 8 shows the characteristics of the identified approaches according to the following classification criteria: problem representation; nature of the objective function; data type; considering demand certainty or demand uncertainty; the employed distance metrics; the considered solution approach. These criteria are described below:

(1) Problem representation. It refers to using discrete or continuous representation when formulating the FLP through mathematical programming-based approaches.
   (a) *Discrete*. The plant floorspace is divided into blocks of equal area and dimensions so that departments can be assigned to one block or more
   (b) *Continuous*. Departments can be located anywhere in the continuous floorspace
(2) Objective function type. It refers to the mathematical description of the objective that is to be maximised or minimised, and is subject to a set of constraints.
   (a) *Single-objective*. When optimising a single-objective function is the aim
   b.1. *Quantitative*. The objective function can be quantitatively measured
   b.2. *Qualitative*. The objective function is categorically measured
   (b) *Multi-objective*. When two objective functions or more are considered to form part of the model
(3) Data type. It refers to the deterministic or non-deterministic nature of the model's parameters and/or variables.
   (a) *Deterministic*. The values assigned to the model's parameters are certainly known
   (b) *Non-deterministic*. The values of parameters are unknown, so it is assumed that they can take values stochastically or by fuzzy sets
(4) Demand. It refers to whether demand is certain or uncertain.
   (a) *Certain*. When demand is known beforehand
   (b) *Uncertain*. When demand is unknown
(5) Distance metrics. This is the way the distance between the points where materials are picked up and dropped off from different production areas of departments is measured
   (a) *Rectilinear*. It is the sum of the differences between the coordenates of two points expres sed in absolute values
   (b) *Euclidean*. It represents the distance in a straight line between two points
   (c) *Squared Euclidean*. Euclidean distance that is squared

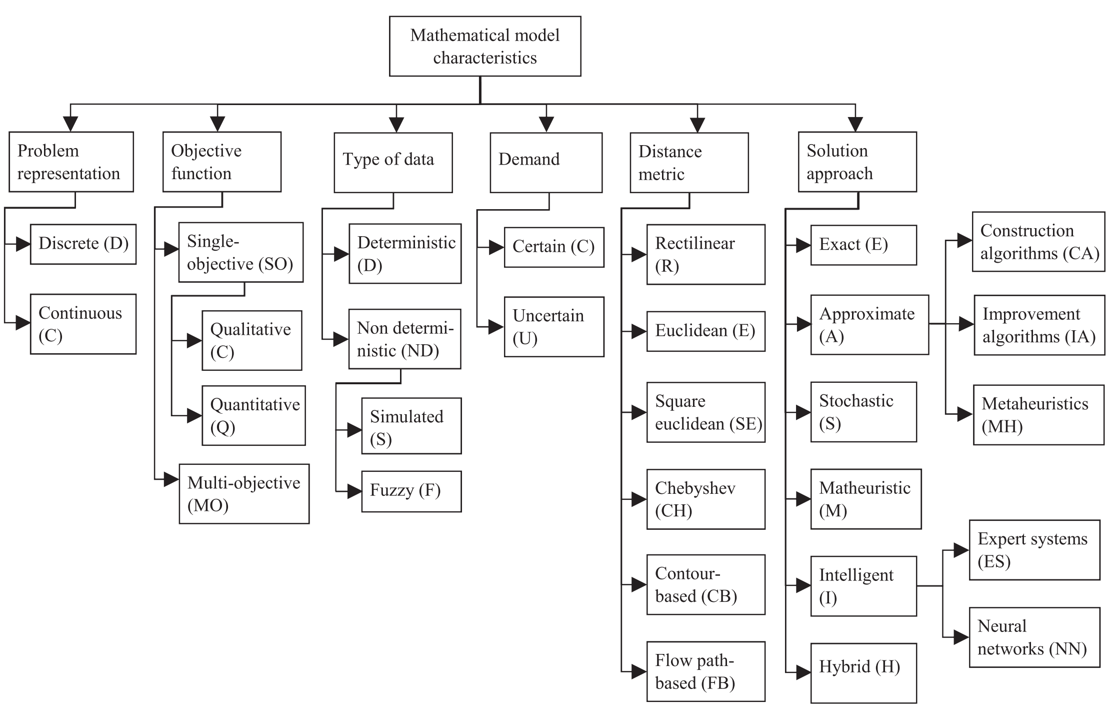

Figure 8. Characteristics of the FLP mathematical models.

    (d) *Chebychev.* The bigger difference between the coordinates of two points on any of their dimensions
    (e) *Contour-based.* The distance that separates the points where materials are picked up and dropped off between two departments along its perimeter or contour
    (f) *Flow path-based.* The distance separating where materials are picked up and dropped off in two departments along the pre-set material flow path
(6) Solution approach. It refers to the method employed to solve the mathematical model.
    (a) *Exact.* An optimal solution is determined
    (b) *Approximate.* It includes a series of heuristic and metaheuristic methods by means of which solutions can be obtained that are not necessarily optimum in acceptable calculation times

        b.1. *Construction algorithms.* This refers to those heuristic algorithms that generate a single design from scratch by selecting and locating departments successively to obtain a complete layout outline

        b.2. *Improvement algorithms.* They include the heuristic algorithms that start with an initial solution and attempt to improve it iteratively by changing locations of departments to obtain an outline to which no improvements can be made

        b.3. *Metaheuristics.* This encompasses the set of algorithms used to obtain approximate solutions for complex combinatorial optimisation problems that cannot be efficiently solved by classic heuristic algorithms. They employ different concepts that derive from artificial intelligence, biological evolution and statistical mechanisms
    (c) *Stochastic.* Simulation is employed by scenarios to supplement other solution approaches
    (d) *Matheuristic.* Algorithms that derive from metaheuristics and MP techniques interoperating
    (e) *Intelligent.* Expert or artificial neural networks are used
    (f) *Hybrid approaches.* Two or more previous approaches are employed

The 209 contributions made to FLP as a mathematical optimisation problem are classified in line with these criteria in Appendix 1 for SFLP, and also in Appendix 2 for DFLP. Likewise, the objective functions and constraints contemplated when formulating the problem are summarised for each case. Figure 9, on the other hand, depicts how these 209 articles were distributed according to the codes defined for each classification category in Figure 8.

4.1. Problem representation

When formulating the FLP mathematical optimisation model, characterising the problem *a priori* in accordance with the categories specified within the conceptual framework presented in Figure 3 is recommended. In particular, the shape and area of departments can be especially relevant because whether a discrete or continuous representation modelling approach is applied will depend on this (Allahyari and Azab 2018). When contemplating regular-shaped equal-area departments, the problem can be formulated using discrete mathematical models for the common objective to optimally assign n departments to n set and discrete locations known *a priori* to, for example, minimise the cost of transporting materials (Xiao et al. 2017). In such cases, the most widely used optimisation model was the quadratic assignment problem (QAP) introduced by Koopmans and Beckmann (1957). For a deeper understanding of the formulation of this model as well as its resolution strategies, readers are referred to Frieze and Yadegar (1983), Cela (1998), Nehi and Gelareh (2007), and Loiola et al. (2007).

Moreover when assuming that departments are irregularly shaped and/or have different area requirements, they can be located anywhere in a planar continuous space available in the facilities to avoid overlapping departments (la Scalia et al. 2019), among other relevant constraints. In this case, the problem's complexity even increases for situations in which only a few departments are to be arranged (Xiao et al. 2017), and tend to be generally formulated by continuous representation modelling approaches. It is sometimes possible to divide departments into common area units (unit cells) and use a discrete approach to deal with the problem (Allahyari and Azab 2018; Huang and Wong 2017).

In the reviewed literature, the most widely used MP approaches in FLP modelling with continuous representation for departments with unequal areas were mixed integer non-linear programming (MINLP) (Gulsen, Murray, and Smith 2019; Vázquez-Román et al. 2019; Yang et al. 2019) in 52.46% of the cases, and mixed integer linear programming (MILP) (Allahyari and Azab 2018; Ejeh, Liu, and Papageorgiou 2018; Kia et al. 2014; Klausnitzer and Lasch 2019; Xiao et al. 2017) with approximately 28%. Albeit less frequently, non-linear programing (NLP) was also used (Anjos and Vieira 2016; Ahmadi and Akbari Jokar 2016; Zhenyuan et al. 2011), as were: linear integer programming (LIP) (Friedrich,

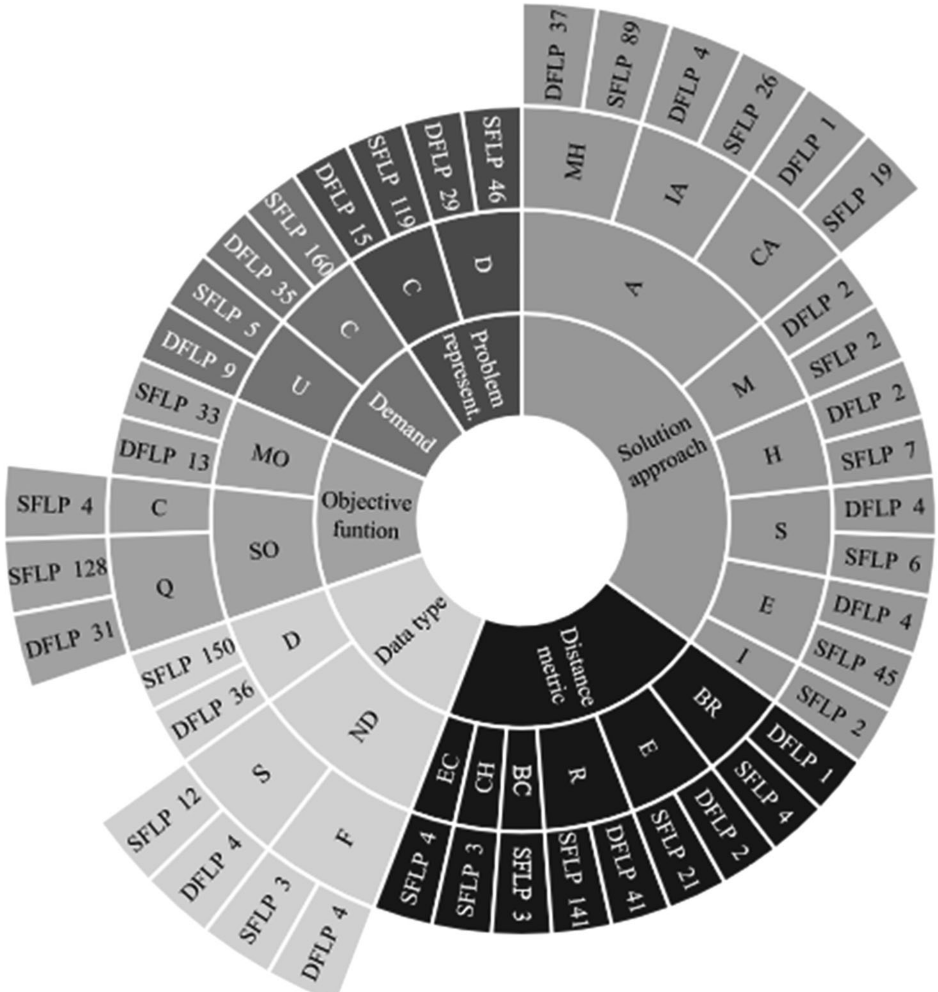

Figure 9. Distribution of publications according to the problem representation, objective function, data type, demand, distance metrics and solution approach.

Klausnitzer, and Lasch 2018; Asef-Vaziri and Kazemi 2018; Samarghandi and Eshghi 2010) and linear programming (LP) (Gai and Ji 2019; Y. J. Xiao et al. 2016; Kulturel-Konak 2012).

Generally speaking, the models proposed in FLP mathematical formulations were subject (see Appendix 1 and Appendix 2) to some of these constraints: (1) budget; (2) area; (3) capacity; (4) non-overlapping; (5) location of pick up and drop off points; (6) orientation of departments; (7) clearance among departments; (8) closeness of departments; (9) ordering of departments; (10) distance between departments; (11) minimum safety distance; (12) quantity of floors; (13) aspect ratio; (14) number of lifts; (15) tridimensional space; (16) location of machines; (17) material flow conservation; (18) level of proximity among departments; (19) number of material handling devices; (20) work in process; (21) material flow demand; (22) length of the piping system to transport fluids; (23) release of toxic gases; (24) hazardous events with a domino effect, like fires or explosions; (25) symmetry-breaking constraints; (26) location of departments adjacent to flow paths; (27) connectivity constraints; (28) area occupied by pumping systems; (29) heat exchanger group constraint; (30) safety instrumented system's life cycle cost; (31) machine availability; (32) number of machines per department; (33) transport time.

Readers are referred to Appendix 3 for some optimisation FLP model formulations.

4.2. Objective function

In the reviewed literature, the minimised objective functions were: (a) materials handling cost; (b) rearrangement cost; (c) construction cost; (d) flow distance; (e) flow path length; (f) transport time; (g) work flow; (h) personnel flow; (i) work in process; (j) total layout area; (k) space demand; (l) space among departments; (m) aspect ratio; (n) land cost; (o) costs related to material handling equipment; (p) costs related to workplace security risks; (q) costs related to machinery operations; (r) risk level associated with the hazardous materials and waste path; (s) makespan; (t) energy losses; (u) financial risk; (v) lost opportunity costs; (w) occupational health/safety risks; (x) number of machines arranged in a linear sequence; (y) entropy.

The maximised objective functions were: (A) the closeness rating among departments; (B) the decision maker's level of satisfaction; (C) distance requests among departments; (D) the hazardous movement; (E) the total material flow among adjancent departments; (F) the area utilisation ratio; (G) work stations' utilisation ratio; (H) the level of preference for assigning facilities to spaces; (J) the level of preference in relation to interactivity among departments.

Approximately 78% of the reviewed articles that had formulated FLP as a mathematical optimisation problem had considered a single-objective function of those previously cited (163 of the 209 articles), which were either quantitative or qualitative (see Appendix 1 and Appendix 2). The present work distinguished between these two categories because some objective functions referenced in the literature represent variables that can be measured on a ratio scale, which confers it its quantitative nature, whereas some objective functions denote variables measured on an ordinal categorical scale and are, thus, classified as qualitative.

Minimising the total materials handling cost (MHC) is the most widespread objective function in FLP optimisation models (62.68%), followed by flow distance minimisation (24.4%), rearrangement cost minimisation (19.62%), maximisation of the closeness rating among departments (10%), and minimisation of the costs related to material handling equipment (8.13%).

Within industrial companies, MHC is a key factor for obtaining optimum layouts (Singh and Ingole 2019), and has been the most widely used quantitative-type objective function to find optimum or suboptimum FLP solutions in the last 10 years (131 articles). When solving any FLP problem however, taking quantitative factors as a single-objective function can generate solutions that are not necessarily feasible because qualitative factors in some industrial contexts and services can be more relevant, such as closeness ratings among departments, flexibility or security.

Simultaneously considering both types of factors as part of a mathematical optimisation model normally requires seeking a compromise solution that falls in line with the decision maker's preferences (Le, Dao, and Chaabane 2019; Che, Zhang, and Feng 2017). This occurs because the objectives to be optimised often clash (Ripon et al. 2013); that is, improving an objective can make another/other objective/s worse, and there is no absolute solution in these cases to simultaneously optimise all objectives (Aiello, La Scalia, and Enea 2013). The mathematical process to seek a compromise solution is known as multi-objective optimisation (Ripon et al. 2013; Aiello, La Scalia, and Enea 2013). In the reviewed literature, only one fifth of the articles published in the SFLP context dealt with the problem by multi-objective optimisation models, and 29.55% did so in the DFLP domain.

4.3. Data type

When solving FLP mathematical optimisation models, some parameters are included for the cost/profit coefficients of the objective function that are related to materials flow, distance covered and unit transport cost, among others, which might be known, or not, *a priori*. When these input data are not known exactly, they need to be estimated given their non-deterministic nature. To do so, simulated data have been used in the literature about FLP (Peng et al. 2018; Brunoro Ahumada, Quddus, and Mannan 2018; Azimi and Soofi 2017), as have fuzzy sets with different membership functions (Safarzadeh and Koosha 2017; Gai and Ji 2019; Nematian 2014).

4.4. Demand type

Demand is a fundamental parameter of production planning models, and the material flow between production departments depends directly on it which is, in turn, an essential parameter in most FLP mathematical optimisation models. The more intense the material flow is among the activity centres participating in the worked object's processing, the closer the proximity must be among them to reduce MHC as much as possible. Thus any mistake in estimating demand could lead to an insufficient layout in relation to these costs (Jithavech and Krishnan 2010).

When considering the re-layout of existing plants, quite accurate demand information may become available. Therefore, the volumes of the deterministic materials flow for the whole planning horizon can be identified through production plans. In such cases, demand is considered to be known, and spatially laying out the elements making up the production system is facilitated in the available space inside industrial facilities. Nonetheless, when layout is planned for completely new facilities and the company possesses no previous information about how demand behaves, production plans begin by estimating demand under uncertainty conditions. In production planning models, uncertainty is modelled by using probability distributions, fuzzy sets, stochastic approaches and robust approaches (Díaz-Madroñero, Mula, and Peidro

2014). Given the strategical-tactical planning interrelation in production and layout planning, the complexity of FLP and, therefore, its modelling and solution approaches, depend on demand being certain or uncertain and its variability throughout the planning horizon to a great extent.

In the revised literature on FLP, 93.3% of works began by assuming that demand was known beforehand and, therefore, the material flow was deterministic. Some authors resorted to simulation by considering several scenarios to describe the effect of fluctuating demand on the material flow (Peng et al. 2018). Other authors modelled demand uncertainty by assuming demand to exactly fit a continuous probability distribution with a known mean and variance that could be uniform (Jithavech and Krishnan 2010), beta (Zhao and Wallace 2014), normal (Moslemipour, Lee, and Loong 2017; Tayal and Singh 2018) or exponential (Vitayasak, Pongcharoen, and Hicks 2017; Vitayasak and Pongcharoen 2018). To the same end, the queueing theory (Pourvaziri and Pierreval 2017) or fuzzy sets with different membership functions (Kaveh, Dalfard, and Amiri 2014; Samarghandi, Taabayan, and Behroozi 2013) have also been used.

4.5. Distance metrics

As minimising total MHC is the most widespread objective function in FLP optimisation models, the location of the points in each department where materials are picked up and dropped off, plus the distance metrics to be considered, are fundamental. Generally speaking, total MHC is determined by the summation of multiplying the cost of transporting one flow unit at one distance unit and the total transported volume between the points at which materials are picked up/dropped off in all the departments that take part in the worked object's processing (Komarudin and Wong 2010; McKendall and Liu 2012; Tubaileh and Siam 2017). Nonetheless, when modelling layout in facilities, it is often assumed that the points at which materials are picked up/dropped off are located in the centroid of each department, and the distance among these centroids determines the distance covered by the work flow (Kovacs 2019; Xiao et al. 2016; Zhang et al. 2019). Figure 9 shows that this assumed case was the most widely used one in the reviewed literature.

Such assumptions are, however, incompatible with most real-life layouts. It is more realistic to assume that the points at which materials are picked up/dropped off would be located on the edges of departments, and the work flow would flow along the flow paths or circulation routes that interconnect them (Friedrich, Klausnitzer, and Lasch 2018; Leno, Saravana Sankar, and Ponnambalam 2018). Hence those models that contemplate rectilinear or euclidean distances can generate pseudo-optimal solutions with significantly lower total MHC than those incurred in real production systems where flow covers the distance separating the pick up/drop off points between each pair of departments along its perimeter or contour (metric CB), or along the preset material flow path (metric FB). These last two approaches were two of the least frequently employed in the literature.

5. Solution approach

FLP is classified as a non-polynomial hard problem according to the computational complexity theory because no algorithm exists that provides an optimal solution in an reasonable polynomial time (Grobelny and Michalski 2017). Despite this degree of complexity, some authors have contributed acceptable solutions with realistic calculation times by applying a range of techniques, from exact techniques to last-generation heuristic ones.

The methods generally followed to seek optimal or quasi-optimal solutions for FLP can be classified as exact, approximate, stochastic and intelligent (Hosseini-Nasab et al. 2018). As Figure 8 depicts, hybrid and matheuristic approaches are added to these categories because they have been identified in the solution approaches put forward in the revised literature.

The approximate approaches corresponded to heuristic algorithms. In the FLP context, heuristic methods are classified as construction, improvement or metaheuristic algorithms (Drira, Pierreval, and Hajri-Gabouj 2007; Hosseini-Nasab et al. 2018). In the past 10 years, the most popular approximate methods to solve FLP optimisation models have been metaheuristic algorithms. In the reviewed literature, we identified that 28 of these algorithms were applied in 68% of the articles that used discrete mathematical optimisation models, and in 64.18% of those that employed continuous models. In general, the most frequently used algorithms were genetic algorithms, simulated annealing, particle swarm, tabu search, ant colony and variable neighbourhood search, which collectively corresponded to about 80% of all cases. A more detailed description of these algorithms for SFLP and DFLP is found in Appendix 4. All the other identified heuristic algorithms were chosen as the solution approach for 5.33% and 12.12% of the articles that used discrete and continuous optimisation models, respectively.

It is well-known that the FLP complexity level exponentially increases according to the number of entities (departments, work cells, workstations, machines) to be arranged (Vitayasak, Pongcharoen, and Hicks 2017; Turanoğlu and Akkaya 2018). For this purpose, the solution approaches that generate quasi-optimal or approximate solutions were the most widespread in large-scale problems. For a few entities however, exact solution approaches fulfilled their purpose in acceptable calculation times. Along these lines, it is stressed that Palubeckis (2012) successfully applied branch and bound (B&B) to a QAP solution for an SRLP problem with 35 departments, whereas Huang and Wong (2017) did so to solve an MILP by contemplating an OFLP configuration for 11 departments. Asef-Vaziri and Kazemi (2018) applied branch and cut (B&C) to solve an LIP model applied to the classic problems put forward by other authors, which included between 61 and 310 departments according to an LLP configuration. Hernández Gress et al. (2011) solved an MILP model for seven departments by following an OFLP outline using a block layout, while Amaral and Letchford (2013) applied the same method along with B&C to solve an LP model, which they applied to several test problems with 5–30 departments with an SRLP outline. Hungerländer and Rendl (2013) and Hungerländer (2014) applied semidefinite relaxation to solve SDP models with an SRLP configuration. Hungerländer and Anjos (2015) followed a similar solution approach, which was also applied to DRLP, PRLP and MRLP configurations. Jankovits et al. (2011) used both semidefinite relaxation and convex relaxation to solve SDP models with an OFLP configuration.

To the authors' knowledge, in the revised literature the largest numbers of departments optimally arranged in a facility layout design according to the materials handling system configuration were: 42 for SRLP (Hungerländer and Rendl 2013), 10 for DRLP (Hungerländer and Anjos 2015), 23 for PRLP (Amaral 2013), 20 for MRLP (Feng and Che 2018), 310 for LLP (Asef-Vaziri and Kazemi 2018), and 100 for OFLP (Anjos and Vieira 2016).

An emerging approach to solve mathematical optimisation models that can be considered for FLP is matheuristics; in other words, those algorithms that derive from the metaheuristics and MP techniques interoperation. Kulturel-Konak and Konak (2013) developed a hybrid solution approach called GA/LP, which combines a genetic algorithm (GA) with LP to solve an MINLP model. Kulturel-Konak and Konak (2015) performed a large-scale local search (LSLS) based on simulated annealing (SA) hybridisation and MILP, which they called LS-HSA. Kulturel-Konak (2017) created a matheuristic solution approach based on variable neighbourhood search (VNS) and SA combined with an MINLP model that they called VNSAM. Feng et al. (2018) implemented two hybrid approaches to solve an MINLP model by combining GA and SA, respectively, with LP, which they named GALP and SALP. As far as the authors of this work know, no matheuristic solution approaches appear in any of the more recent literature review studies (Drira, Pierreval, and Hajri-Gabouj 2007; Heragu 1992; Hosseini-Nasab et al. 2018; Kouvelis, Chiang, and Kiran 1992; Kouvelis and Kiran 1991; la Scalia, Micale, and Enea 2019; Maganha, Silva, and Ferreira 2019; Meller and Gau 1996; Singh and Sharma 2006).

6. Approaches for layout evaluation

Assessments are important for identifying the best layout among a finite set of alternatives generated by some of the above-described approaches, or to even detect improvement opportunities in an already existing production system's productivity. The FLP approaches in the literature have focused on generating layout alternatives and very few advances have been made in the assessment stage (Shahin and Poormostafa 2011). This is probably why very little attention has been paid to the re-layout of existing facilities because re-layout decisions are usually made as a result of an assessment process when an existing layout does not allow the objectives set by an organisation to be met (Pérez-Gosende 2016).

In our work, 38 articles dealt with assessing facility layout alternatives (16.38%). Towards this objective, these works employed simulation, data envelopment analysis (DEA), non-linear programming models, (NLP), fuzzy constraint theory (f-TOC), simple criteria comparison (CC) or multicriteria decision making methods (MCDM). MCDM were the most widely used in the literature (20 articles, 52.63%). The following methods were found: AHP, (analytic hierarchy process), TOPSIS (technique for order of preference by similarity to ideal solution), ANP (analytic network process), ELECTRE (elimination et choix traduisant la realité), DEMATEL (decision-making trial and evaluation laboratory), PSI (preference selection index) and SAW (simple additive weighting). Although some works followed more than one method, Figure 7(b) shows how the articles that dealt with approaches to assess layout alternatives are distributed.

It is worth stressing that only two works evaluated layout alternatives in the DFLP context. The followed methods in these cases were TOPSIS (Emami and Nookabadi 2013) and DEA (Bozorgi, Abedzadeh, and Zeinali 2015).

7. Decision-support tools

Decision-support tools can play a fundamental role in improving the capability of decision makers to evaluate and decide how suitable different solution alternatives can be regarding as pre-established goals or criteria

Table 4. Computer-aided layout planning tools.

Tool	Brief description	Reference
CRAFT	Uses a distance-based improvement algorithm to search for a planar block layout for up to 40 departments. Not available for commercial use.	Armour and Buffa (1963)
ALDEP	With an adjacency-based construction algorithm, the software can layout up to 63 departments on up to three floors. Not available for commercial use.	Seehof et al. (1966)
SPIRAL	Uses an adjacency-based improvement algorithm to create a planar block layout of unequal-area departments. Not available for commercial use.	Goetschalckx (1992)
VIP-PLANOPT	Web-accesible proprietary software based on a hybrid heuristic-analytical technique that allows high-quality solutions to large-scale problems to be generated at a low computational cost.	Engineering Optimization Software (2011)
AFLP system	Augmented reality-based system for existing shopfloors detailed re-layout planning. Unsuitable for large-scale problems. Not available for commercial use.	Jiang and Nee (2013)

(Taticchi et al. 2015). In this context, when tackling FLPs five different groups of decision-support tools can be considered. Firstly, for those analysts interested in generating several layout alternatives to select the most suitable one to their preferences, computer-aided layout planning tools can be used. Secondly, for small-scale problems formulated through mathematical programming models, optimisation solvers can be employed to find the optimal solution. A third group involves programming the languages needed to code heuristic algorithms to find approximate solutions to large-scale problems. A fourth group comprises simulation software to simulate non-deterministic parameters in mathematical programming models or to evaluate performance in different layout scenarios. Last but not least, to gain intuitive impressions of the obtained layout solutions, computer-aided design software can be useful for representing bidimensional or tridimensional facility layout drawings.

According to the five aforementioned categories, all the decision-support tools used in the articles dealing with SFLP and DFLP are, respectively, identified and classified in Tables 2 and 3. Furthermore, given the relevance of the first group of tools for practitioners, Table 4 briefly describes those used in the revised literature to generate layout alternatives. To know about any other software available in previous research works, readers are referred to the review by Singh and Sharma (2006).

8. Real-world applications

The reviewing process identified that almost 80% of the papers (183 articles) dealt with FLP applied to hypothetical case studies (with randomly generated data) or classic test problems from the literature. Only one fifth (47 articles) addressed real-world case studies. Table 5 shows these applications classified according to industry sector and country. The number of case studies addressed in each article, the planning approach, the number of entities subject to the arrangement process (e.g. departments, work cells, workstations, machines), the number of obtained layout alternatives, the approach followed to both generate and evaluate such alternatives, as well as the type of mathematical model used and its respective solution approach, were included. For space reasons, an extended version of this table, including additional features (e.g. problem type, planning phase, type of material handling system configuration, decision-support tools, main results), can be found in Appendix 5.

Thirty per cent of the identified case studies corresponded to service systems: hospitals (Cheng and Lien 2012a; 2012b; Lin et al. 2015; Helber et al. 2016; Fogliatto et al. 2019; Lin and Wang 2019); a courier terminal (Alsyouf et al. 2012); an airport (Lee and Tseng 2012); a railway station (Lee 2012); a pharmacy (McDowell and Huang 2012); a hospital kitchen (Moatari-Kazerouni, Chinniah, and Agard 2015b); an academic building (Che, Zhang, and Feng 2017); equine farms (Glenn and Vergara 2016); a distribution centre (Horta, Coelho, and Relvas 2016). As for fabrication systems, chemical (17%), microelectronics (15%) and metalworking sector industries (11%) were the most widely addressed.

The world's most represented region in these real case studies was East Asia with almost half the cases (49%). In this region, the leading countries were China (21%), Taiwan (15%) and South Korea (13%). Next, in descending order, came Europe (19%), Western Asia (15%), North America (13%) and South America (4%).

It is also worth highlighting that 70% of the cases addressed greenfield plant layout designs, 79% planned block layouts, 94% contemplated constant product demand throughout the planning horizon (i.e. SFLP) and 64% adopted an open-field materials handling system configuration. Furthermore, 72% of the cases used mathematical programming to generate layouts, mainly through QAP (24%) and MIP (36%) modelling approaches, which were solved mostly with metaheuristic algorithms (45%).

9. Discussion

In today's industrial context, industrial FLP must be flexible enough in time to face uncertain demand, adopt new technologies, allow new processes to be set up and produce a large product nomenclature in increasingly

Table 5. Real-world FLP applications.

References	Industrial sector	Country	# Case studies	Planning approach	Entities (n)	Layout generation approach	Layout candidates	Layout evaluation approach	Mathematical model	Solution approach
Alsyouf et al. (2012)	m	Sweden	1	S	n = 14	EK	3	SAW		
Eben-Chaime, Bechar, and Baron (2011)	a	Israel	1	S	376 ≤ n ≤ 410	EK	4	CC		
Park et al. (2011)	b	Korea	2	S	n = 7,10	MP	1		MILP	E
Tuzkaya et al. (2013)	c	Turkey	1	S	n = 19	MP			QAP	A(MH)
Vasudevan and Son (2011)	d	USA	1	S	n = 6	EK	4	SM		
Yang, Chang, and Yang (2012)	e	Taiwan	1	S	1 ≤ n ≤ 4	EK	10	MCDM		
Lee and Tseng (2012)	m	Taiwan	1	S	n = 32	MP			LP	H(S,MH)
Cheng and Lien (2012a)	m	Taiwan	1	S	n = 28	MP			QAP	A(MH)
Cheng and Lien (2012b)	m	Taiwan	1	S	n = 28	MP			QAP	A(MH)
Lee (2012)	m	Taiwan	1	S	n = 16	MP			QAP	H(S,MH)
McDowell and Huang (2012)	m	USA	1	S	n = 15	EK	4	SAW		
Garcia-Hernandez et al. (2013a)	g,f	Spain	2	S	n = 11,12	MP	11,8		MILP	A(MH)
Garcia-Hernandez et al. (2013b)	g	Spain	2	S	n = 10,11	MP	9		MILP	A(MH)
Hadi-Vencheh and Mohamadghasemi (2013)	e	Taiwan	1	S	n = 10	SP	18	NLP		
Jia et al. (2013)	c	China	1	S	n = 12	MP	3	SM	NLP	H(A,S)
Lin et al. (2015)	m	China	1	S	n = 17	EK	2	f-TOC		
Azadeh and Moradi (2014)	e	Iran	1	S	n = 10	SP	21	SM,AHP,		
DEA										
Al-Hawari, Mumani, and Momani (2014)	h	Jordan	1	S	n = 18	EK	3	ANP,AHP		
Azadeh, Nazari, and Charkhand (2015)	b	Iran	1	S	n = 10	EK	45	DEA,SM		
Hong, Seo, and Xiao (2014)	e	Korea	10	S	5 ≤ n ≤ 30	MP			MILP	E,A(IA)
Moatari-Kazerouni, Chinniah, and Agard (2015b)	m	Canada	1	S	n = 12	MP			LP	H(CA,IA)
Ulutas and Attila Islier (2015)	i	Turkey	1	D	n = 54	MP	4		QAP	A(MH)
Helber et al. (2016)	m	Germany	1	S	n = 28	MP			QAP	A(IA)
Lee (2015)	b	Korea	2	S	n = 7	MP			MINLP	A(MH)
Che, Zhang, and Feng (2017)	m	China	1	S	n = 8	MP	3		MILP	A
Choi, Kim, and Chung (2017)	j	Korea	1	S	n = 20	MP			NLP	A(MH)
Glenn and Vergara (2016)	m	U.S.A.	2	S	n = 24,33	MP			LP	A(IA)
Horta, Coelho, and Relvas (2016)	m	Portugal	1	S	not mentioned	MP	3		LIP	E
Hou, Li, and Wang (2016)	c	China	41	S	14 ≤ n ≤ 200	MP			MILP	A(CA)
Huang and Wong (2017)	k	China	1	S	n = 11	MP	1		BMILP	E
Kim, Yu, and Jang (2016)	e	Korea	1	S	n = 16	MP	18	SM	MINLP	A(IA)
Neghabi and Ghassemi Tari (2016)	b	Iran	1	S	n = 6	MP	9		MINLP	E
Latifi, Mohammadi, and Khakzad (2017)	b	Iran	1	S	n = 25	MP	1		MINLP	A(MH)
Durmusoglu (2018)	g	Turkey	1	S	not mentioned	-	10	TOPSIS		
Park, Shin, and Won (2018)	b	Korea	1	S	n = 24	MP	2		MINLP	E
Wang et al. (2018)	b	China	1	S	n = 217	MP	3		NLP	A(MH)
Wu et al. (2018)	k	China	18	S	5 ≤ n ≤ 154	MP			MIQP	A(CA,IA)
Li, Tan, and Li (2018)	c	China	1	D	n = 12	MP	2		NLP	A(MH)
Hu and Yang (2019)	e	China	1	S	n = 18	MP	5		NLP	A(MH)
Abdollahi, Aslam, and Yazdi (2019)	e	Taiwan	1	S	n = 10	SP	18	NLP		
de Lira-Flores et al. (2019)	b	Mexico	1	S	n = 9	MP	6		MINLP	E
Fogliatto et al. (2019)	m	Brazil	1	S	n = 18	EK	5	AHP		
Kovacs (2019)	l	Hungary	1	S	n = 11	MP	8	CC	LP	A(CA)
Le, Dao, and Chaabane (2019)	k	Canada	1	S	n = 25	MP	3		QAP	A(MH)
Lin and Wang (2019)	m	China	1	S	n = 8	EK	2	AHP		
Ramirez Drada,, Chud Pantoja, and Orejuela Cabrera (2019)	c	Colombia	1	S	n = 17	MP	14	TOPSIS	QAP	A
Al Hawarneh, Bendak, and Ghanim (2019)	k	U.A.E.	1	D	n = 12	MP	4		BILP	A(IA)

Note: Industrial sector: a (agrifood), b (chemical), c (metalworking), d (automotive), e (microelectronics), f (meat-processing), g (recycling), h (woodworking), i (footwear), j (shipbuilding), k (construction); l (electronics assembly), m (services).

smaller lots. Considering static production conditions as in, for example, the demand remaining constant throughout the temporary planning horizon does not match reality, but is, however, the most widely considered planned approach in the scientific literature on FLP. Thus researchers should pay more attention to study FLP in dynamic environments.

The intention behind planning flexible or cyclic layouts in the DFLP context is to design an optimum layout for each time period to minimise total MHC and those related to facility rearrangements. Nonetheless, the reviewed works that dealt with these planning approaches did not contemplate the opportunity costs incurred while implementing re-layouts. Likewise, most of the works that covered DFLP (approx. 93%) started by assuming that companies had unlimited budgets to put into practice any changes related to layouts from one time period to another when, in fact, budgets for such purposes are always limited. So considering budget constraints when formulating layout optimisation models in dynamic settings is suggested.

Most works into FLP sought design solutions for completely new facilities. With layouts for already existing facilities, the task is just as complex, or even more complicated, given the presence of constraints and additional objectives. Implementing changes of an existing layout requires further investment, delays or having to completely interrupt production plans while the re-layout lasts.

It is noteworthy that most of the scientific literature about FLP examined the block layout or the detailed phase separately. They paid very little attention to analyse both phases in a hierarchical or concurrent manner as part of the same study. Separately dealing with these phases incurs the risk of the first phase outcomes limiting the second phase, or *vice versa*, especially if we consider that sizes of departments are flexible with a pre-set interval of the aspect/area ratio as a trick to facilitate generating more regular-shaped layouts with mathematical optimisation models.

Despite optimising space inside industrial facilities being considered a classic facility layout principle, analysing space is often considered only from a bidimensional point of view.

The herein reviewed works generally considered facility layout design in only one building and on only one floor. However, large companies frequently contemplated their operations in more than one building and on several floors. So more attention must be paid to FLP modelling by contemplating material handling system configurations that have scarcely been addressed in the literature, such as DRLP, PRLP and LLP.

Despite a large body of scientific literature works on FLP, very few works examined the layout assessment stage, and no references appeared about procedures to objectively diagnose re-layout needs, which is a gap that future research works can consider bridging.

MCDM methods are frequently used in the literature to assess facility layout alternatives. Yet despite them being widespread, MCDM techniques only offer relative measures to compare several layout alternatives. This means they are not useful for assessing the performance of a current layout in industrial facilities; in other words, they do not enable the re-layout requirement to be analysed.

Most FLP optimisation models seek to minimise a single quantitative objective function, and MHC is the most frequent one. In practice however, considering both quantitative and qualitative factors simultaneously can be decisive for many manufacturing or service systems. Qualitative factors like proximity ratings among departments, layout flexibility to integrate future changes, personnel satisfaction, and health and safety (especially with healthcare emergencies requiring interpersonal distancing) must be considered in particular. This will certainly involve the scientific community having to pay more attention to FLP multi-objective mathematical modelling, as the present work demonstrates, which is underrated because single-objective models are normally resorted to.

Of the studies that employed mathematical optimisation models as a preferential approach to generate layout alternatives, approximately 89% considered deterministic and already known parameters. Although this assumption is plausibly suitable for some contexts, obtaining exact cost/profit coefficients of the objective function is hardly likely given the measurement errors and random component that always appear in some forecasting methods, like those based on historic series to forecast demand. Hence the need to more frequently employ methods that model uncertainty in some datasets, like demand, material flow, materials handling unit costs and sizes of facilities. To this end, using probability distributions, fuzzy sets, stochastic and/or robust approaches is recommended.

Similarly, in order to avoid pseudo-optimal solutions when modelling FLP, investigating the formulation and solution of multi-objective mathematical optimisation models is suggested because they allow the following to be concurrently designed by adopting quantitative/qualitative criteria: spatial layout and orientation of the work stations making up the production system; passageways through which the worked object and personnel pass; the points at which the worked object is picked up/dropped off. To do so, more realistic distance metrics than the conventional intercentroid rectilinear or euclidean distances need to be considered. It might be worth contemplating the fact that work flows cover the distance separating the points at which materials between two departments are picked up/dropped off along their perimeter or contour (Leno, Saravana Sankar, and Ponnambalam 2016; Friedrich, Klausnitzer, and Lasch 2018), or along pre-set flow paths (Kim and Chae 2019; Klausnitzer and Lasch 2019).

Given its complexity, the computational time required to solve FLP in any of its variants increases exponentially along with the size of the problem (Vitayasak, Pongcharoen, and Hicks 2017; Turanoğlu and Akkaya 2018). So exact methods are only useful for finding optimum solutions for minor problems. This is why approximate approaches like metaheuristics have been popular for seeking suboptimum solutions in recent years. Nonetheless, it is necessary to keep developing alternative solution approaches and, as this review work identifies, a set of matheuristic algorithms has emerged in recent years for FLP with good results (Feng et al. 2018; Kulturel-Konak 2017; Kulturel-Konak and Konak 2013, 2015). Thus future research that continues to investigate this emerging solution approach is recommended.

Another relevant element worth stressing is that FLP mathematical optimisation models basically focus on solving classic reference problems (the so-called test problems or benchmark instances). They have often been theoretically developed and do not respond to real case studies. This tendency has also been noted in previous research (Meller, Kirkizoglu, and Chen 2010; Ulutas and Attila Islier 2015; Kovacs 2019). Therefore, future research works to model real situations is recommended in order to help bridge the existing gap because very little research about FLP has been conducted in practice.

Last but no least, it is worth noting that most of the computer-aided planning tools used in the revised literature for generating layout alternatives are unavailable for commercial use. So future research needs to develop new web-accessible tools to ease practitioners' effective FLP decision making.

9.1. Managerial implications

Based on what our literature review evidenced and the theme being widely covered, operations managers can obtain a clearer holistic view of the importance of facility planning and its impact on the productivity and efficiency of manufacturing systems to make decisions that allow them to more efficiently perform industrial operations.

When planning facility layouts and guaranteeing the highest possible level of adjacency among the work centres participating in the worked object's processing, MHC is minimised which can, in turn, significantly reduce manufacturing costs. However, as we insist throughout our literature review, concentrating only on minimising quantitative factors, like costs, is far from ideal because other relevant criteria need to be considered, such as suitably using the tridimensional space within facilities to ensure a certain degree of flexibility for future re-layouts, minimum health/safety risks in the workplace, etc.

Evaluating closeness ratings among departments ba sed on qualitative criteria can be done by experts' judgment. This idea is based on the assumption that the number of factors considered by a group is bigger than that considered by one person. Each expert can contribute the idea that he/she has about the matter from his/her knowledge area to general discussion.

All the variants of FLP modelling approaches require analysts having a high level of knowledge about their formulation and solution, which could be achieved through exact, heuristic, stochastic, matheuristic, intelligent or hybrid methods. In turn, these approaches demand making many data collection and calculation efforts. For all these reasons, such tools are not widely employed by operations managers in businesses. Nonetheless, specialised computer-aided planning tools like VIP-PLANOPT (Engineering Optimization Software 2011) can contribute to search for specific solutions to analyse production systems' given needs. Facility layout decisions do not enable empirical research based on trial and error. An objective planning process must exist as background.

Operations managers can take the FLP taxonomy presented herein as a reference and characterise the reality of the manufacturing systems that they administer with it. This, combined with a cost/profit analysis, could lay some solid foundations for short-, mid- and long-term decision making about the feasibility of adopting flexible or robust layouts in line with internal strong/weak points, and in agreement with the threats and opportunities from the immediate business environment where operations are performed.

10. Conclusions

Industrial facility layouts are defined as a process to physically arrange the factors shaping the production system so that they suitably and efficiently fulfil the organisation's strategical objectives. This is considered a strategical decision within business operations planning because its high cost often prevents it from being taken as a feasible option during short time periods, and the efficiency, productivity and competetiveness of manufacturing systems depend on it to a great extent.

Our systematic literature review of 232 scientific articles in the FLP domain allowed us to identify the different reference frameworks that led to a new conceptual framework being proposed to classify FLP based on: problem type (new facilities or re-layout); planning approach (static or dynamic); planning phase (joint or detailed distribution); characteristics of facilities (number of buildings, number of floors, considering the space, shape and area of departments); materials handling system configuration (single-row, double-row, multiple-row, parallel-row, closed-loop and open-field configurations); generating and assessing alternatives.

Generating layout alternatives has been dealt with mainly by mathematical optimisation models, specifically with discrete quadratic programming models for equal-sized departments, or by continuous linear/non-linear mixed integer programming models for departments with unequal areas. Other approaches to generate layout alternatives involve resorting to EK and specialised SP. For FLP mathematical programming approaches, current modelling trends and their solution approaches were identified by bearing in mind: type of mathematical model (discrete, continuous); nature of the objective function (single-objective, multi-objective); data type (deterministic, non-deterministic); consideration of certain/uncertain demand; employed distance metrics (rectilinear, euclidean, squared euclidean, chebychev, contour-based and flow path-based); the adopted solution approach (exact, approximate, stochastic, matheuristic, intelligent and hybrid). Generally speaking, the most widely used solution algorithms were metaheuristic: genetic algorithms, simulated annealing, particle swarm, tabu search, ant colony and variable neighbourhood searches. Here, we have reviewed the literature published by May, 2020. In the meantime, several new studies on the FLP problem have appeared (Liu et al. 2020; Wan et al. 2020; Xiao et al. 2020; Kovács 2020; Ahmadi-Javid and Ardestani-Jaafari 2020) which corroborates the strong interest in this research area.

Finally, the guidelines identified herein for future research are presented: (i) studying in-depth FLP in dynamic settings; (ii) minimising opportunity costs while contemplating re-layouts to cushion the impact of these costs on an organisation's profitability; (iii) considering budget constraints to formulate DFLP optimisation models; (iv) more research into the re-layouts of existing facilities; (v) considering block and detailed layouts as part of the same problem by a hierarchical or concurrent approach; (vi) contemplating the tridimensional space for DFLP and SFLP; (vii) taking into account several floors/buildings in FLP mathematical modelling; (viii) bearing in mind the material handling system configuration in FLP models; (ix) modelling the uncertainty of relevant cost/profit coefficients; (x) conducting more research about the assessment phase of layout alternatives; (xi) developing and applying matheuristic approaches, and those based on artificial intelligence, as alternative solution approaches for FLP models; (xii) using more multi-objective approaches to generate layout alternatives; (xiii) applying the proposed FLP models to real cases; (xiv) developing new commercial computer-aided layout planning tools to ease practitioners' FLP-related decision making.

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