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A conceptual framework for multi-objective facility layout planning by a bottom-up approach

Pablo Pérez-Gosende [a1,b†], **Josefa Mula** [a2*], **and Manuel Diaz-Madroñero** [a3]

[a] Research Centre on Production Management and Engineering (CIGIP) Universitat Politècnica de València, Alarcón, 1, 03801, Alcoy, Alicante, Spain.

[b] Universidad Politécnica Salesiana, Guayaquil, Ecuador.

[a1] *pabpego3@doctor.upv.es*, [a2*] *fmula@cigip.upv.es*, [a3] *fcodiama@cigip.upv.es*

Abstract:

The purpose of this paper is to present a conceptual framework to facilitate academics and practitioners' decision making related to multi-objective facility layout planning (mFLP) by employing a bottom-up approach. Based on a literature survey framed in the mFLP context, this work identified and discussed a set of criteria that have become limitations of the traditional top-down approach. These criteria served as the basis to conceive the proposed conceptual framework. Our conceptual framework formalises FLP as a multi-objective problem by following the two traditional planning phases (block- and detailed phase) in reverse by a bottom-up approach, and by also integrating a third phase, called the refined phase, which has not previously been contemplated in the literature. Apart from identifying the inputs and outputs of each phase, the conceptual framework groups together several objectives related to mFLP that have been recently considered in the literature and formalises and contextualises them according to the planning phase in which they are involved. This is the first time that mFLP is addressed with a bottom-up approach.

Key words:

Plant design, facility layout planning, conceptual framework.

1. Introduction

Facility layout planning (FLP) is one of the most important design decisions in the operations management field (Sun et al., 2018). The successful achievement of organisational goals and the adoption of competitive advantages based on production costs will depend on the adopted layout design to a large extent (Vitayasak et al., 2017). FLP can generally be defined as the process of arranging the elements making up the production system in the physical space in such a way as to fulfil certain relevant objectives. Since the mid-20th century, this topic has attracted the attention of academics and researchers in the broad Industrial Engineering context (La Scalia et al., 2019), and several theories have been developed that seek to obtain feasible layout designs. However, contributions to solve the problem have barely been applied in practice given their high complexity and the assumption of premises that are not very compatible with the industrial operational reality (Meller et al., 2010; Pérez-Gosende et al., 2021).

Traditionally, FLP has been approached in two consecutive phases: (i) block layout (BL); (ii) detailed layout (DL), and this approach is known

†In memorian of Pablo Pérez-Gosende (Matanzas, Cuba, 4 September 1983-Guayaquil, Ecuador, 14 September 2022). Although you are no longer with us, you will never be forgotten. May your memory remain forever on the pages of this article.

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in the literature as the top-down approach (Muther, 1961). However, (Meller et al., 2004) formalised an alternative approach, called bottom-up, in which the problem is reformulated in such a way that detailed ordering scheme alternatives are firstly constructed and then selected for the final arrangement in a block layout. This approach was based on the limited application of the solutions obtained with the traditional top-down approach in real-life case studies. However, the mathematical modelling of this new approach is more complex than the traditional one (Meller et al., 2010).

It is rare to find in the literature mathematical models developed to address both the BL and DL phases simultaneously. Contributions in this area are more frequently made to model one of these two phases (Pérez-Gosende et al., 2021). In doing so, using the material handling cost between each pair of departments or workstations as a single-objective function of a quantitative nature is normal (Hosseini-Nasab et al., 2018). However in real life, FLP is a multi-objective problem due to the large number of factors involved in the final decision (Bozorgi et al., 2015; Singh and Ingole, 2019), which, apart from the material handling cost, include occupational health and safety; waste and hazardous substance management; personnel satisfaction; flexibility for future changes, among others. In this context, this article presents a conceptual framework, proposed in the doctoral dissertation by Pérez-Gosende (2022), to facilitate academics and practitioners' decision making in relation to multi-objective facility layout planning (mFLP) using a bottom-up approach.

The article is organised as follows. Section 2 presents a literature review which identifies a set of criteria that the authors believe have become limitations of the traditional top-down approach. Section 3 presents the conceptual framework to address mFLP by a bottom-up approach. Finally, Section 4 provides the conclusions of this study.

2. Literature review

FLP has a significant impact on the efficiency of production systems and their level of productivity (Kheirkhah et al., 2015; Navidi et al., 2012). Several review studies have addressed FLP to a greater or lesser extent (Al-Zubaidi et al., 2021; Anjos and Vieira, 2017; Hosseini-Nasab et al., 2018; Pérez-Gosende et al., 2020; La Scalia et al., 2019). However, research on many aspects of the problem is still in its early days (Hosseini-Nasab et al., 2018), mainly because decision making in the FLP context is constantly evolving to adapt to technological changes in manufacturing systems, demand volatility in increasingly globalised markets, disruptive events in supply chains, among other factors. Therefore, FLP can adopt many variants depending on the production system's characteristics, the facilities' characteristics, the planning approach, demand uncertainty, among others. A general framework representing the multidimensionality of FLP is depicted in Figure 1, constructed from the taxonomy defined by (Pérez-Gosende et al., 2021).

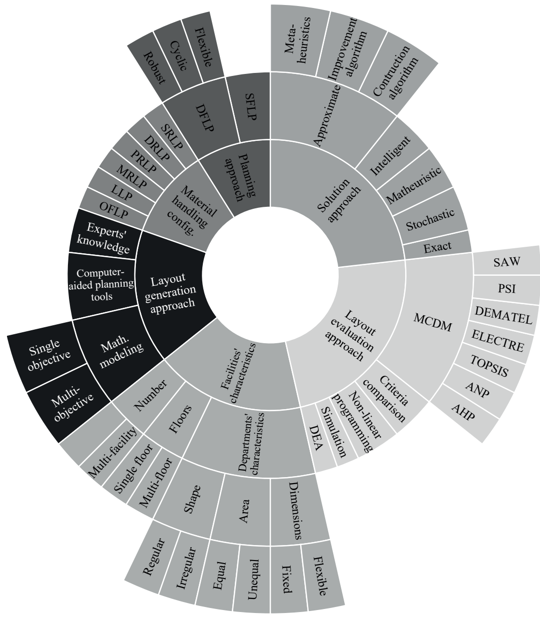

Figure 1. A general framework for addressing FLP. **Abbreviations:** SFLP (static facility layout problem); DFLP (dynamic facility layout problem); SRLP (single-row layout problem); DRLP (double-row layout problem); PRLP (parallel-row layout problem); MRLP (multi-row layout problem); LLP (loop layout problem); OFLP (open-field layout problem); DEA (data envelopment analysis); MCDM (multicriteria decision-making methods); 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).

Apart from its relevance, FLP is no easy problem to solve (Anjos and Vieira, 2017). The generation and selection of the most convenient layout for an organisation is a complex iterative process that depends on the relations between the elements making up its production system. According to the theory of computational complexity, most FLP formulations are considered non-polynomial hard problems (NP-hard) as no solution algorithms provide an optimal solution in a reasonable polynomial time (Grobelny and Michalski, 2018). However, this high degree of difficulty has not stopped different authors from tackling these problems by providing acceptable solutions in realistic computational times.

Traditionally, most FLP solution approaches have followed systematic layout planning (SLP) methodology (Muther, 1961). In fact, (Sharma and Singhal, 2017) concluded that this was the most appropriate approach for handling FLP. According to SLP, as with most engineering design problems, FLP should be based on a hierarchical approach, which starts from the BL and then continues with the DL (Muther, 1961). As part of the BL, the appropriate arrangement scheme is defined for the departments in which productive activities are performed (Asef-Vaziri et al., 2017; Saraswat et al., 2015). In the DL phase, machinery, temporary material storage, personnel workspace, pick-up/drop-off points (P/D) are organised in inside each department, and corridors for the flow of materials throughout the system are added (Xiao et al., 2017). Despite this approach, known as the top-down approach, being widely used in the literature, its application in practice is limited (Meller et al., 2010). Those responsible for layout design in industry do not consider applying a top-down hierarchical approach to be of much value as they consider that the process of determining the BL and DL simultaneously to be more practical (Meller et al., 2004). In this context, it is relevant to consider a reverse approach to that traditionally addressed in the FLP formulation. By this bottom-up approach, the problem would be formulated in such a way that the DL is firstly constructed and then the BL, which would allow a closer approach to the dynamics of this decision process in real-life case studies (Meller et al., 2010). A visual representation of both approaches to address the FLP phases is shown in Figure 2.

Several approaches have appeared to generate layout alternatives in either of the two process phases. Of them, experts' knowledge, computer-aided layout planning tools and mathematical modelling stand out (Pérez-Gosende et al., 2021). The last approach has become very relevant in the scientific literature given its high level of complexity, which is an attractive modelling challenge for analysts (Anjos and Vieira, 2017).

In the industrial manufacturing systems context, the total material handling cost (MHC) is a key factor to obtain optimal layouts (Chen, 2013; Singh and Ingole, 2019) and also to reduce production wastes (Chiarini and Kumar, 2021). Thus, MHC has been the most employed quantitative objective function to search for optimal or suboptimal FLP solutions (Hosseini-Nasab et al., 2018; Pérez-Gosende et al., 2020, 2021). Nevertheless, when solving any plant layout problem, taking quantitative factors as a single objective function may generate solutions that are not necessarily feasible because in some industrial and service contexts, qualitative factors like closeness ratings, flexibility or safety can be more relevant.

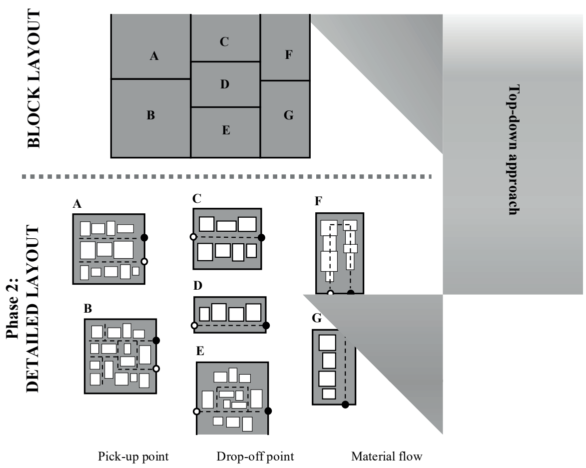

Figure 2. Approaches to address FLP: top-down vs. bottom-up.

The consideration of both types of factors simultaneously as part of a mathematical optimisation model usually requires having to search for a compromise solution in accordance with the decision maker's preferences (Che et al., 2017; Le et al., 2019). This occurs because the objectives to be optimised frequently come into conflict (Ripon et al., 2013), i.e., improving one objective may make others worse. In these cases, there is no absolute solution that optimises all the objectives simultaneously (Aiello et al., 2013). The mathematical process of finding such a compromise solution is known as multi-objective optimisation (Aiello et al., 2013; Ripon et al., 2013). Previously, (Pérez-Gosende et al., 2021) showed that only 22% of the articles that addressed FLP (2010-2019) as a mathematical optimisation model applied a multi-objective approach. Table 1 shows the objectives

Table 1. Survey of papers addressing mFLP.

References	Planning phase BL	Planning phase DL	Objective function[a] Minimise	Objective function[a] Maximise	Case studies	Resolution approachb	Decision-support tools
(Singh and Singh, 2010)	√		7, 6	20, 23	Test problems	WS	LINGO
(Ku et al., 2011)	√		1, 9, 11		Hypothetical case studies	SA-based parallel GA	MATLAB
(Şahin, 2011)	√		1	20	Test problems	SA	Fortran-90
(Singh and Singh, 2011)	√		7	20	Undefined	Three-level AHP-based heuristic approach	LINGO
(Cheng and Lien, 2012)	√			26, 27	Hospital Building	PBA	Not mentioned
(Aiello et al., 2012)	√		1, 4, 11	20	Test problems	Multi-objective GA	Not mentioned
(Jolai et al., 2012)	√		1, 2	20, 22	Test problems	Multi-objective PSO	GAMS
(Navidi et al., 2012)	√		1, 12		Test problems	Game-based SA	MATLAB, LINGO
(Leno et al., 2012)	√		1	20	Test problems	WS, elitist strategy GA	MATLAB
(Abedzadeh et al., 2013)	√		1, 2, 11	20	Test problems	Parallel VNS	GAMS/ CPLEX, MATLAB
(Yang et al., 2013)	√		16, 4, 10		Test problems	NSGA-II	Not mentioned
(Garcia-Hernandez, Pierreval, et al., 2013)	√		7	21	Test problems	Interactive GA	Not mentioned
(Aiello et al., 2013)	√		1, 4, 11	20	Test problems	Multi-objective GA, ELECTRE	Not mentioned
(Emami and Nookabadi, 2013)	√		1, 2	20	Test problems	WS, ε-CM	GAMS/SBB/ BARON, MATLAB
(Garcia-Hernandez, Arauzo-Azofra, et al., 2013a)	√		1, 11	21, 22	Ovine slaughterhouse plant, recycling plant	Interactive GA	Not mentioned
(Garcia-Hernandez, Arauzo-Azofra, et al., 2013b)	√		7	21	Recycling Plants	Interactive GA	Python
(Hathhorn et al., 2013)	√		1, 3		Randomly generated instances	LO	Python/ Gurobi
(Lenin et al., 2013)		√	4, 19, 13		Test problems	Average fitness factor method, GA	C
(Matai et al., 2013)	√		7	20	Test problems	WS, modified SA	LINGO
(Ripon et al., 2013)	√		1	20	Test problems	Multi-objective GA,VNS	Not mentioned
(Samarghandi et al., 2013)	√		1, 2	20	Test problems	Fuzzy-TS, fuzzy-VNS, fuzzy-GA, fuzzy-PSO	Not mentioned
(Jabal-Ameli and Moshref-Javadi, 2014)	√	√	1	25	Test problems	Multi-objective SSA, NSGA-II, ε-CM	CPLEX, MATLAB
(Chen and Lo, 2014)	√		1, 2	20	Test problems	Multi-objective ACO	C++
(Bozorgi et al., 2015)	√		1,2	20, 22	Test problems	DEA	Not mentioned
(Garcia-Hernandez et al., 2015)	√		1	21	Test problems	Interactive GA	Not mentioned
(Kheirkhah et al., 2015)	√		1, 2, 12		Test problems	Bilevel PSO, Coevolutionary algorithm	MATLAB

(Table 1 continues in next page)

(Table 1 continues from previous page)

References	Planning phase		Objective function[a]		Case studies	Resolution approach[b]	Decision-support tools
	BL	DL	Minimise	Maximise			
(Matai, 2015)	√		1, 6, 14	20	Test problems	WS, modified SA	Not mentioned
(Salmani et al., 2015)	√		9	20	Test problems	WS	GAMS
(Saraswat et al., 2015)	√		4, 8, 12		Test problems	Multi-objective SA	CPLEX, C++
(Hosseini and Seifbarghy, 2016)	√		1, 2, 12		Test problems	Multi-objective WFA	MATLAB
(Che et al., 2017)	√		1, 9		Academic building	ε-CM	CPLEX, C++
(Pourvaziri and Pierreval, 2017)	√		1, 2, 12, 8		Hypothetical case study	Cloud-based multi-objective SA, simulation	Enterprise Dynamics
(Azimi and Soofi, 2017)		√	1, 15		Hypothetical case study	NSGA-II, simulation	MATLAB, Enterprise Dynamics
(Tayal and Singh, 2018)		√	1, 2, 6, 14	20	Hypothetical case studies	Hybrid FA/chaotic SA, AHP	Java
(Li et al., 2018)		√	1, 2, 17, 18	24	CNC machine manufacturing unit	ABC, PSO, simulation	CATIA
(Liu et al., 2018)	√		1	20, 24	Test problems	Multi-objective PSO	Java
(Nagarajan et al., 2018)	√		4, 5		Test problems	ABC	Not mentioned
(Chen et al., 2019)	√		15	25	Precast factory	NSGA-II	C#
(Le et al., 2019)	√		1, 2	20	Housing project	ε-CM	MS Excel Solver
(Liu and Liu, 2019)	√		1	20	Test problems	Multi-objective ACO	Java
(Pournaderi et al., 2019)	√		1, 2		Hypothetical case study	NSGA-II, NRGA, multi-objective cloud-based SA	LINGO
(Singh and Ingole, 2019)	√		1	20	Test problems	BBO, non-dominated sorting BBO, NSGA-II	MATLAB
(Wei et al., 2019)		√	1, 2	24	Test problems	Tent mapping, chaotic GA	Java
(Erfani et al., 2020)	√		1, 2, 6	20, 24	Randomly generated instances	NSGA-II	GAMS/ BARON
(Garcia-Hernandez et al., 2020)	√		1	21	Test problems	Interactive CRO	Python
(Liu, Liu, Yan, et al., 2020)	√		1	20	Test problems	Hybrid PO/NT algorithm	Java
(Liu, Liu, Liu, et al., 2020)	√		1	20, 22, 28	Test problems	CSE	Java
(Wan et al., 2020)		√	1, 9		Randomly generated instances	Multi-objective GRASP-LP	C++, CPLEX
(Zhao et al., 2020)	√		1, 9		Hypothetical case study	NSGA-II	MATLAB

[a]Objective functions: 1 (materials handling cost), 2 (rearrangement cost), 3 (construction cost), 4 (flow distance), 5 (flow path length), 6 (transport time), 7 (work flow), 8 (work in process), 9 (total layout area), 10 (space demand), 11 (aspect ratio), 12 (costs related to material handling equipment), 13 (costs related to machinery operations), 14 (risk level associated with the hazardous materials and waste path), 15 (makespan), 16 (energy losses), 17 (lost opportunity costs), 18 (occupational health/safety risks), 19 (number of machines arranged in a linear sequence), 20 (closeness rating among departments), 21 (decision maker's level of satisfaction), 22 (distance requests among departments), 23 (hazardous movement), 24 (area utilisation ratio), 25 (work stations utilisation ratio), 26 (level of preference for assigning facilities to spaces), 27 (level of preference in relation to interactivity among departments, 28 (aspect ratio requests). [b]Resolution methods: WS: weighted sum method; GA: genetic algorithm; PSO: particle swarm optimisation; SA: simulated annealing; VNS: variable neighbourhood search; PBA: particle bee algorithm; SSA: scatter search algorithm; AHP: analytic hierarchy process; NSGA-II: non-dominated sorting genetic algorithm; NRGA: non-dominated ranked genetic algorithm; ε-CM: epsilon-constrained method; LO: lexicographic ordering method; TS: tabu search; ACO: ant colony optimisation; DEA: data envelopment analysis; WFA: water flow algorithm; FA: firefly algorithm; ABC: artificial bee colony algorithm; CRO: coral reefs optimisation; PO: pareto optimisation; NT: niche technology; CSE: configuration space evolutionary algorithm; GRASP: greedy randomised adaptive search procedure; biogeography-based optimisation (BBO); LP: linear programming.

that these papers proposed, as well as their resolution approaches, up to 2020.

Table 1 shows that most of the works addressing mFLP contemplate only one of the classic FLP phases, which is not very helpful for analysts in practice because they must face the facility planning process by addressing both the BL and DL phases. Likewise, some of the objectives considered by the different studies are similar in terms of their description and formulation, so they can be standardised to favour future decisions in the mFLP context.

2.1. Issues limiting real-life mFLP applications

Table 1 shows that only seven of the 49 reviewed papers recreate real-life case studies, which supports the notion that contributions on addressing mFLP by the traditional top-down approach are barely applied in practical contexts. One of the reasons that could support this fact is the assumption that, when mathematically modelling mFLP, assumptions are not altogether compatible with the industrial operational reality. In this line, (Navidi et al., 2012) mentioned that existing multi-objective optimisation models tended to oversimplify reality. Among the commonest assumptions, this paper corroborates: the non-consideration of uncertainty and demand variability along the planning horizon; the assumption that departments have equal areas or flexible dimensions; the use of space only at a two-dimensional level; the consideration of a single floor for performing operations; the arrangement of P/D points in the centroids of departments; the non-integration of corridors for the flow of materials and personnel as part of the layout design in any of its stages; the non-consideration of qualitative criteria, such as occupational health and safety, personnel satisfaction, and flexibility for future relayouts. Table 2 shows these limitations in the revised literature. The rest of this section justifies why such criteria have become limitations for the traditional top-down approach.

When FLP decision making assumes that product demand will remain constant along the planning horizon, the process basically focuses on obtaining a single layout design. In this case, by considering that production conditions are static, the problem is known as static or single-period FLP (SFLP) (Vitayasak et al., 2017). However, this assumption may be impractical in most industrial sectors because it is unlikely that the demand and, therefore, the flow of materials, in the plant will remain constant over time. In an increasingly globalised business environment, it is more realistic to consider dynamic conditions (Bozorgi et al., 2015; Defersha and Hodiya, 2017) mainly due to the constant need to readjust production capacity as a consequence of demand fluctuations, ever shorter product life cycles, the adoption of technological changes in manufacturing systems, disruptive events in supply chains, among other factors (Emami and Nookabadi, 2013; Vitayasak et al., 2017). With this approach, the so-called dynamic or multiperiod FLP (DFLP), a layout is designed for each time period to minimise the total MHC and those costs related to rearrangement of facilities (Pournaderi et al., 2019). In the reviewed literature, as we can see in Table 2, less than one third of the papers addressed mFLP with a dynamic planning approach (28.57%).

Having product demand projections is essential to quantify the flow of materials between production departments, which is one of the key parameters when modelling FLP. In this context, about nine in every ten articles addressing mFLP, assume that demand is known in advance, which may be an unrealistic assumption when designing greenfield plants where historical information on demand behaviour is not generally available. This reason, coupled with volatility of demand in an increasingly globalised world, supports the need to consider its estimation under uncertainty conditions.

When modelling FLP, it is possible to consider departments having the same area or unequal areas (Liu, Liu, Yan, et al., 2020). The first case, usually modelled by discrete optimisation models like QAP (Loiola et al., 2007), is applicable to very few real-world manufacturing systems. In the reviewed literature, 18 of the 20 papers that assumed equal-area departments addressed mFLP in hypothetical case studies or test problems. Planning layouts in a real case study by assuming equal-area departments when in fact they are not, can generate pseudo-optimal solutions with a significantly lower MHC than that which would actually be incurred. Hence, the importance of considering the actual dimensions of departments according to the operations that will take place in them.

The consideration of whether their dimensions are fixed, flexible or mixed when designing layout, is closely related to areas of departments (Pérez-Gosende et al., 2020). For fixed dimensions, the

Table 2. Issues[a] limiting real-life mFLP applications.

References	i	ii	iii	iv	v	vi	vii	viii	ix	x	xi
(Singh and Singh, 2010)	√	√	√		√	√	√	√		√	√
(Ku et al., 2011)	√	√		√	√	√	√	√	√	√	√
(Şahin, 2011)	√	√	√		√	√	√	√	√	√	√
(Singh and Singh, 2011)	√	√	√		√	√	√	√		√	
(Cheng and Lien, 2012)	√	√	√		√		√	√	√		√
(Aiello et al., 2012)	√	√		√	√	√	√	√	√	√	√
(Jolai et al., 2012)		√			√	√		√	√	√	√
(Navidi et al., 2012)	√		√		√	√	√		√	√	√
(Leno et al., 2012)	√	√			√	√			√	√	√
(Abedzadeh et al., 2013)		√		√	√	√	√	√	√	√	√
(Yang et al., 2013)	√	√			√	√	√	√	√	√	√
(Garcia-Hernandez, Pierreval, et al., 2013)	√	√			√	√	√	√	√		√
(Aiello et al., 2013)	√	√		√	√	√	√	√	√	√	√
(Emami and Nookabadi, 2013)		√	√		√	√	√	√	√	√	√
(Garcia-Hernandez, Arauzo-Azofra, et al., 2013a)	√	√		√	√	√	√	√	√		√
(Garcia-Hernandez, Arauzo-Azofra, et al., 2013b)	√	√		√	√	√	√	√	√		√
(Hathhorn et al., 2013)	√	√		√	√		√	√	√	√	√
(Lenin et al., 2013)	√	√	√		√	√	√	√	√	√	√
(Matai et al., 2013)	√	√	√		√	√	√	√	√	√	√
(Ripon et al., 2013)	√	√			√	√	√	√	√	√	√
(Samarghandi et al., 2013)					√	√	√	√	√	√	√
(Jabal-Ameli and Moshref-Javadi, 2014)	√	√			√	√	√	√	√	√	√
(Chen and Lo, 2014)		√	√		√	√	√	√	√	√	√
(Bozorgi et al., 2015)		√	√		√	√	√	√	√	√	√
(Garcia-Hernandez et al., 2015)	√	√		√	√	√	√	√	√		√
(Kheirkhah et al., 2015)		√	√		√	√	√	√	√	√	√
(Matai, 2015)	√	√	√		√	√	√	√		√	√
(Salmani et al., 2015)	√	√			√	√	√	√	√	√	√
(Saraswat et al., 2015)	√	√		√	√	√	√	√	√	√	√
(Hosseini and Seifbarghy, 2016)		√	√		√	√	√	√	√	√	√
(Che et al., 2017)	√	√			√		√	√	√	√	√
(Pourvaziri and Pierreval, 2017)			√		√	√	√	√	√	√	√
(Azimi and Soofi, 2017)	√	√	√		√	√	√	√	√	√	√
(Tayal and Singh, 2018)			√		√	√	√	√		√	√
(Li et al., 2018)		√			√	√	√	√		√	√
(Liu et al., 2018)	√	√			√	√	√	√	√	√	√
(Nagarajan et al., 2018)	√	√			√	√	√	√	√	√	√
(Chen et al., 2019)	√	√	√		√	√	√	√	√	√	√
(Le et al., 2019)	√	√	√		√	√	√	√	√	√	√
(Liu and Liu, 2019)	√	√		√	√	√	√	√	√	√	√
(Pournaderi et al., 2019)		√	√		√	√	√	√	√	√	√
(Singh and Ingole, 2019)	√	√	√		√	√	√	√	√	√	√
(Wei et al., 2019)		√			√	√	√	√	√	√	√
(Erfani et al., 2020)					√	√		√	√	√	√
(Garcia-Hernandez et al., 2020)	√	√		√	√	√	√	√	√		√
(Liu, Liu, Yan, et al., 2020)	√	√		√	√	√	√	√	√	√	√
(Liu, Liu, Liu, et al., 2020)	√	√		√	√	√	√		√	√	√
(Wan et al., 2020)	√	√			√	√	√	√	√	√	√
(Zhao et al., 2020)	√	√				√	√	√	√	√	√

[a](i) single planning period, (ii) demand certainty, (iii) equal-area departments, (iv) flexible dimensions, (v) non-consideration of tridimensional space use, (vi) single-floor facilities, (vii) P/D points located in the centroids of departments, (viii) no aisle structure integrated into the layout, (ix) overlooked occupational health/safety risks, (x) overlooked personnel satisfaction, (xi) disregarded layout flexibility.

problem is formulated according to the assumption that the width and length of departments should remain unchanged during the layout generation process. When dimensions are considered flexible, the lengths of the sides of the departments can vary within a preset interval as long as the minimum area requirement of the department is guaranteed (Xiao et al., 2017). This last assumption facilitates the generation of more regular layouts by employing mathematical optimisation models, minimising unoccupied spaces and consequently, better utilising the available area in the facility. However, this can lead to departments adopting very narrow or too elongated shapes in which operations cannot be carried out correctly in the way they were designed by the process analysts (Jankovits et al., 2011). Approximately one in every four articles considered flexible dimensions when modelling mFLP.

Even though one of the classic principles of FLP is to obtain the maximum possible use of space inside industrial plants, the consideration of three-dimensional space in the mFLP context is scarce. In fact, as Table 2 shows, 48 of the reviewed 49 articles considered space from a two-dimensional point of view by focusing only on obtaining the maximum plant floor area utilisation.

Most research considered layout design in a single floor context. However, it is common for manufacturing systems to consider more than one floor to perform their operations. In this context, only three papers (6%) in the reviewed literature considered multiple floors in the mFLP formulation (Che et al., 2017; Cheng and Lien, 2012; Hathhorn et al., 2013).

As MHC minimisation is one of the most widely used objective functions in FLP optimisation models (Hosseini-Nasab et al., 2018; Pérez-Gosende et al., 2020, 2021), the location of P/D points in each activity centre is a determinant. When modelling FLP, it is common to assume that P/D points are located at the centroid of each department and the distance between these centroids determines the distance travelled by the workflow (approximately 94% of the reviewed papers). These assumptions might work well in manufacturing systems where material transport is performed by gantry cranes (Asef-Vaziri et al., 2017), but they are incompatible with most real-life layout designs, in which P/D points are generally located on the edges of departments, and work flow circulates through the aisles interconnecting them. Hence, the models that consider rectangular or euclidean intercentroid distances can generate pseudo-optimal solutions with significantly lower MHCs than those that would have incurred in real-life situations.

In manufacturing systems, aisles are paths that allow the movement of personnel and the transport of materials between different work areas. The aisle structure contributes to plant layout efficiency due to its impact on reducing the distance travelled by the materials flow, the average flow time and MHCs (Pourvaziri et al., 2021). Therefore, to achieve an adequate plant layout, it is not enough to determine the position of the departments, machines and workstations in the physical space, but it is also essential to integrate the aisle structure design (Friedrich et al., 2018). Excluding works addressing the double-row layout problem, only a few articles in the literature considered the aisle structure design in an integrated manner when designing the plant layout of manufacturing systems while considering single-objective mathematical models (Chang et al., 2006; Gómez et al., 2003; Klausnitzer and Lasch, 2016, 2019; Lee et al., 2005; Pourvaziri et al., 2021), and only three did so in the specific mFLP context (Leno et al., 2012; Liu, Liu, Liu, et al., 2020; Navidi et al., 2012).

A plant layout should not be considered adequate or complete if its design does not consider the prevention of possible safety and health risks for the people who will work in it. Indeed, when designing layout, it is necessary to analyse the possible physical, chemical, biological, ergonomic and psychosocial risks when determining the priorities of proximity among machines, workstations or departments. Similarly, the personnel's satisfaction and possible well-being must be taken into account. Failure to consider these aspects distances the possibility of generating a sustainable layout to the detriment of the social dimension of sustainability (Pérez-Gosende et al., 2020). In the reviewed literature, only six papers (12.24%) acknowledged the importance of considering staff satisfaction when addressing mFLP, and only about one in 10 considered occupational health and safety risks.

Production capacity planning in response to demand variability, decision making to deal with disruptive events in supply chains, adopting new technologies and processes, among other factors, may imply the need to adjust plant layouts. Therefore, it is worth contemplating the highest possible degree of flexibility to allow future changes with minimum effort, the greatest speed, and the least expenditure of resources when planning. In the consulted literature, only one article considered flexibility when dealing with mFLP (Singh and Singh, 2011).

3. Conceptual framework for mFLP

This section presents a conceptual framework for mFLP by considering a bottom-up approach, and starting from an approximation of the two classic FLP phases, but in reverse to the top-down approach and by integrating an additional phase. Here a new vision is provided from a conceptual point of view to mFLP decision making by starting with the limitations identified when analysing the traditional two-phase approach, and thus contributing to facilitate its applicability in real-life case studies.

From this point onwards, and to facilitate the understanding of the conceptual framework, the different departments or areas of activity in the plant are called workcells to group in the same term the different forms of work organisation according to the process flow structures previously defined by the process analyst, regardless of them being job shop, batch shop, assembly line or continuous flow (Ivanov et al., 2017). A workcell is defined as a space delimited by a physical or imaginary boundary where the activities needed for normal manufacturing processes operation are performed.

Figure 3 shows the proposed conceptual framework made up of three phases: (1) intraworkcell layout; (2) macrolayout; (3) refined layout. Each phase is fed with the output from the immediately preceding phase and supplemented with new inputs. In each case, a set of minimisation and maximisation objectives, defined based on the reviewed literature, are suggested to convert inputs into outputs by using decision-support tools. The sections below explain in detail the characteristics of each phase.

3.1. Intraworkcell layout phase

As seen in Figure 3, the conceptual framework starts with the intradepartmental layout phase (intraworkcell layout), which seeks to identify alternative arrangement schemes for each department. These layouts, when defined with a specific orientation referred to as standard orientation, provide the width and length dimensions of each department, as well as the location of P/D

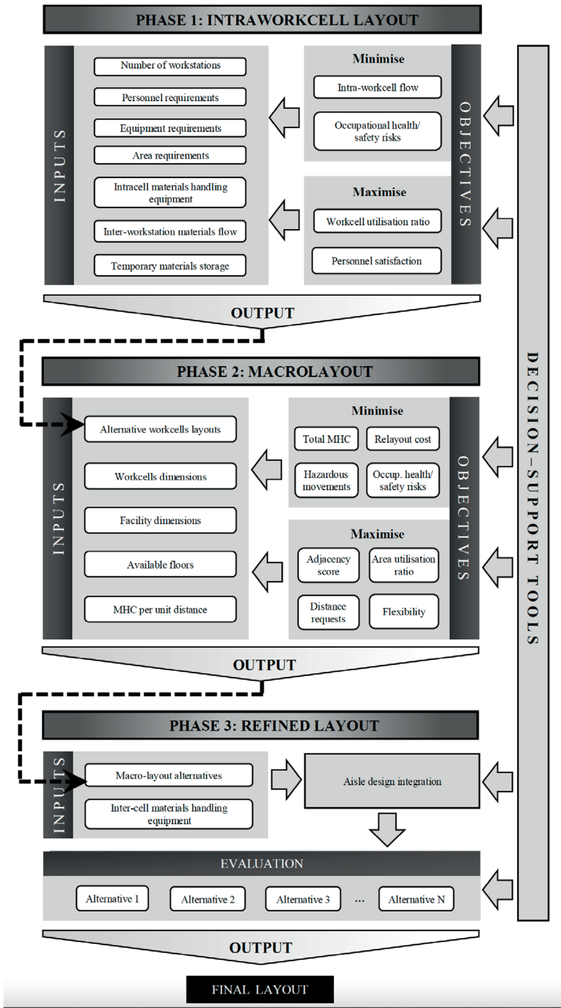

Figure 3. Conceptual framework for mFLP.

points. The inputs for this phase are defined in Table 3.

This phase should include the maximisation and minimisation objectives shown in Table 4, but may include others depending on the analyst's preference. It is important to note that this phase is the equivalent to the DL, which, as part of the traditional top-down approach, is secondly developed after the BL phase.

3.2. Macrolayout phase

The second conceptual framework phase seeks to obtain a finite set of alternative ordering schemes (called macrolayouts) of all the workcells in the available physical space in the plant insofar as to optimise certain relevant objectives. The inputs to this phase are defined in Table 5 and the objectives

Table 3. Inputs to the intraworkcell layout phase.

Inputs	Description
Number of workstations	Number of workstations inside the workcell.
Personnel requirement	Personnel requirements for work inside the cell.
Equipment requirement	Machinery requirements for normal operation performance.
Intracell materials handling equipment	Necessary equipment for transporting and handling materials from one workstation to another, if any.
Interworkstation materials flow	Intensity of materials flow between workstations.
Temporary materials storage	Space required for the temporary storage of materials or products being processed, if any.
Area requirements	Area requirements in the cell for normal operation performance, including the area required for each workstation (area occupied by the machine, machine operation area, maintenance area), the area for storing worktools, the area for temporarily storing materials and/or products being processed, the area for transporting and handling materials.

Table 4. Objectives of the intraworkcell layout phase.

Objectives	Description
Minimise intraworkcell flow distance	Reducing the distance travelled by the work object as much as possible will reduce the MHCs inside the workcell.
Minimise occupational health/ safety risks	The arrangement of the elements making up the production system inside the workcell must reduce as much as possible the safety and health risks for people at work.
Maximise workcell utilisation ratio	The ratio between the area used for performing production activities inside a workcell and the total available area should be as close as possible to one.
Maximise personnel satisfaction	In any case, the best workcell layout would be that which provides the best personnel well-being and favours their self-esteem and personal self-fulfilment.

Table 5. Inputs to the Macrolayout phase.

Inputs	Description
Alternative workcells layouts	Alternative ordering schemes for each workcell in its standard orientation.
Workcells dimensions	Width, and length of each workcell for each alternative arrangement scheme considered in its standard orientation.
Facility dimensions	Available length, width, and height of the facility.
Available floors	Number of floors available for workcell arrangement.
MHC per unit distance	Cost of transporting one unit load one unit distance between the P/D points of two workcells.

to be considered are shown in Table 6. It is important to note that this phase is the equivalent to the BL that, as part of the traditional top-down approach, is done in the first place.

3.3. Refined-layout phase

As previously mentioned, the refined layout phase also includes an evaluation process to define the final distribution alternative based on the decision criteria defined by analysts and stakeholders. The evaluation process may be omitted if a single macrolayout is generated as part of the second phase. However, if a multi-objective mathematical optimisation model is used, as the conceptual framework itself suggests, the purpose is to find a set of Pareto-optimal solutions that can be subjected to a multicriteria evaluation process by considering production system performance aspects and, at the same time, criteria of a subjective nature, such as level of stakeholder satisfaction, which are difficult to mathematically model. Of the methods that can be applied to evaluate layout alternatives, as shown in Figure 2, we find multicriteria decision methods (MCDM), simulation, non-linear programming, data envelopment analysis (DEA) or simply comparing technical and economic/financial criteria.

Table 6. Objectives of the Macrolayout phase.

Objectives	Description
Minimise total materials handling cost	It is determined by summing the product, for each pair of work cells, of the material flow, the distance travelled between P/D points, and the MHC per unit distance. The greatest contribution to production system efficiency is achieved when this cost is minimised.
Minimise rearrangement cost	While operating in dynamic environments, the preferred strategy is to identify a particular layout for each discrete time period making up the planning horizon, and the decision to change a layout from one period to another must consider the minimisation of rearrangement costs.
Minimise occupational health/ safety risks	The arrangement of the various workcells in the available space in the plant should reduce the health and safety risks to people at work as much as possible.
Minimise hazardous movements	Handling hazardous substances throughout the entire production system should be minimised.
Maximise adjacency scores	The assessment of the level of adjacency between each pair of workcells is based on a set of subjective criteria defined by the analyst, which are difficult to quantify. When planning the layout, these considerations, expressed on an ordinal qualitative rating scale, should be met as far as possible.
Maximise distance requests	In certain production systems, it is desirable for some workcells to be sufficiently distant from others because of environmental issues such as: noise, vibration, pollution, aspects related to personnel safety, fire or explosion hazards, among other factors. In such cases, the interdepartmental distance requirements preset by the analyst must be substantially met.
Maximise area utilisation ratio	The ratio of the area occupied by work cells to the total available area in the plant should be as close as possible to one.
Maximise flexibility	This implies considering the highest possible degree of flexibility to allow for future changes made with the least effort, the greatest speed, and the lowest expenditure of resources when planning layouts.

4. Conclusions

This paper presents a conceptual framework to facilitate academics and practitioners' multi-objective facility layout planning (mFLP) decision making. Instead of the framework considering the block layout and detailed layout phases consecutively by the traditional top-down approach, it formalises FLP as a multi-objective problem by following these phases in reverse by a bottom-up approach, and by also integrating a third phase, called the refined layout phase, which has not previously been contemplated in the literature. This is the first time that mFLP is addressed with a bottom-up approach. Hence its novelty.

Apart from identifying the inputs and outputs of each phase, the conceptual framework groups together several objectives related to mFLP that have been recently considered in the literature, and formalises and contextualises them according to the planning phase in which they are involved.

Based on a literature review framed in the mFLP context, this work also identifies a set of criteria that have become limitations of the traditional top-down approach, which serve as the basis to conceive the proposed bottom-up approach. These criteria are: considering a single planning period; estimating demand under certainty conditions; departments with equal areas or flexible dimensions; not considering tridimensional space; single-floor facilities; P/D points located in the centroid of departments; no aisle structure integrated into the final layout; overlooking occupational health and safety risks; ignoring the level of staff satisfaction with the final layout; ignoring the layout's flexibility for future modifications.

By conceiving that the materials flow travels the contour distance separating the P/D points between each pair of workcells (these points are laid at the precise location, and not at the workcells' centroid as it is usually assumed), a more accurate estimation of annual MHCs can be obtained. These costs, as well-known, significantly impact not only total production costs, but any manufacturing system's productivity and operational efficiency. Consequently, a more realistic annual operating costs estimation can be made when projecting net cash flows to assess the economic feasibility of the investment project related to implementing the layout design that results from the decision process.

From the point of view of managerial implications, this conceptual framework can be used as a roadmap for operations managers to holistically analyse how to handle this very important planning problem for the organisation to efficiently function by considering multiple objectives, and to also contribute to bridge the gap of the limited application of the solutions obtained with the traditional top-down approach in real-life case studies.

Finally, future research guidelines are presented: (i) identifying possible analytical modelling approaches of the proposed conceptual framework and validating their resolution approaches in real-life case studies; (ii) identifying the advantages and disadvantages of this framework, and its possible limitations when applying it to different industrial sectors; (iii) incorporate demand uncertainties into the conceptual and analytical mFLP models; (iv) verifying the inclusion of new objectives to tackle the re-layout decisions of already existing plants; (v) determining the feasibility of its application beyond mathematical modelling, and allowing the use of expert judgement and computer-aided layout planning tools; and (vi) creating new computational planning tools to support academics and practitioners in their decision making when addressing all the proposed phases.

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References

Abedzadeh, M., Mazinani, M., Moradinasab, N., & Roghanian, E. (2013), “Parallel variable neighborhood search for solving fuzzy multi-objective dynamic facility layout problem”, *The International Journal of Advanced Manufacturing Technology*, *65*(1–4), 197–211. https://doi.org/10.1007/s00170-012-4160-x

Aiello, G., La Scalia, G., & Enea, M. (2012), “A multi objective genetic algorithm for the facility layout problem based upon slicing structure encoding”, *Expert Systems with Applications*, *39*(12), 10352–10358. https://doi.org/10.1016/j.eswa.2012.01.125

Aiello, G., La Scalia, G., & Enea, M. (2013), “A non dominated ranking Multi Objective Genetic Algorithm and electre method for unequal area facility layout problems”, *Expert Systems with Applications*, *40*(12), 4812–4819. https://doi.org/10.1016/j.eswa.2013.02.026

Al-Zubaidi, S.Q.D., Fantoni, G., & Failli, F. (2021), “Analysis of drivers for solving facility layout problems: A Literature review”, *Journal of Industrial Information Integration*, *21*, p. 100187. https://doi.org/10.1016/j.jii.2020.100187

Anjos, M.F., & Vieira, M.V.C. (2017), “Mathematical optimization approaches for facility layout problems: The state-of-the-art and future research directions”, *European Journal of Operational Research*, *261*(1), 1–16. https://doi.org/10.1016/j.ejor.2017.01.049

Asef-Vaziri, A., Jahandideh, H., & Modarres, M. (2017), "Loop-based facility layout design under flexible bay structures", *International Journal of Production Economics, 193*, 713-725. https://doi.org/10.1016/j.ijpe.2017.08.004

Azimi, P., & Soofi, P. (2017), "An ANN-based optimization model for facility layout problem using simulation Technique", *Scientia Iranica, 24*(1), 364-377. https://doi.org/10.24200/sci.2017.4040

Bozorgi, N., Abedzadeh, M., & Zeinali, M. (2015), "Tabu search heuristic for efficiency of dynamic facility layout problem", *The International Journal of Advanced Manufacturing Technology, 77*(1-4), 689-703. https://doi.org/10.1007/s00170-014-6460-9

Chang, C.-H., Lin, J.-L., & Lin, H.-J. (2006), “Multiple-floor facility layout design with aisle construction”, *Industrial Engineering & Management Systems*, *5*(1), 1–10.

Che, A., Zhang, Y., & Feng, J. (2017), "Bi-objective optimization for multi-floor facility layout problem with fixed inner configuration and room adjacency constraints", *Computers & Industrial Engineering, 105*, 265–276. https://doi.org/10.1016/j.cie.2016.12.018

Chen, G.Y.-H. (2013), "A new data structure of solution representation in hybrid ant colony optimization for large dynamic facility layout problems", *International Journal of Production Economics, 142*(2), 362–371. https://doi.org/10.1016/j.ijpe.2012.12.012

Chen, G.Y.-H., & Lo, J.-C. (2014), "Dynamic facility layout with multi-objectives", *Asia-Pacific Journal of Operational Research, 31*(4), 1450027. https://doi.org/10.1142/S0217595914500274

Chen, C., Huy, D.T., Tiong, L.K., Chen, I.-M., & Cai, Y. (2019), "Optimal facility layout planning for AGV-based modular prefabricated manufacturing system", *Automation in Construction, 98*, 310–321. https://doi.org/10.1016/j.autcon.2018.08.008

Cheng, M.-Y., & Lien, L.-C. (2012), "A hybrid AI-based particle bee algorithm for facility layout optimization", *Engineering with Computers, 28*(1), 57–69. https://doi.org/10.1007/s00366-011-0216-z

Chiarini, A., & Kumar, M. (2021), "Lean Six Sigma and Industry 4.0 integration for Operational Excellence: evidence from Italian manufacturing companies", *Production Planning & Control, 32*(13), 1084–1101. https://doi.org/10.1080/09537287.2020.1784485

Defersha, F.M., & Hodiya, A. (2017), "A mathematical model and a parallel multiple search path simulated annealing for an integrated distributed layout design and machine cell formation", *Journal of Manufacturing Systems, 43*(1), 195-212. https://doi.org/10.1016/j.jmsy.2017.04.001

Emami, S., & S. Nookabadi, A. (2013), "Managing a new multi-objective model for the dynamic facility layout problem", *The International Journal of Advanced Manufacturing Technology, 68*(9-12), 2215-2228. https://doi.org/10.1007/s00170-013-4820-5

Erfani, B., Ebrahimnejad, S., & Moosavi, A. (2020), "An integrated dynamic facility layout and job shop scheduling problem: A hybrid NSGA-II and local search algorithm", *Journal of Industrial & Management Optimization, 16*(4), 1801-1834. https://doi.org/10.3934/jimo.2019030

Friedrich, C., Klausnitzer, A., & Lasch, R. (2018), "Integrated slicing tree approach for solving the facility layout problem with input and output locations based on contour distance", *European Journal of Operational Research, 270*(3), 837-851. https://doi.org/10.1016/j.ejor.2018.01.001

Garcia-Hernandez, L., Arauzo-Azofra, A., Salas-Morera, L., Pierreval, H., & Corchado, E. (2013a), "Facility layout design using a multi-objective interactive genetic algorithm to support the DM", *Expert Systems, 32*(1), 94-107. https://doi.org/10.1111/exsy.12064

Garcia-Hernandez, L., Arauzo-Azofra, A., Salas-Morera, L., Pierreval, H., & Corchado, E. (2013b), "Recycling Plants Layout Design by Means of an Interactive Genetic Algorithm", *Intelligent Automation & Soft Computing, 19*(3), 457-468. https://doi.org/10.1080/10798587.2013.803679

Garcia-Hernandez, L., Palomo-Romero, J.M., Salas-Morera, L., Arauzo-Azofra, A., & Pierreval, H. (2015), "A novel hybrid evolutionary approach for capturing decision maker knowledge into the unequal area facility layout problem", *Expert Systems with Applications, 42*(10), 4697-4708. https://doi.org/10.1016/j.eswa.2015.01.037

Garcia-Hernandez, L., Pierreval, H., Salas-Morera, L., & Arauzo-Azofra, A. (2013), "Handling qualitative aspects in Unequal Area Facility Layout Problem: An Interactive Genetic Algorithm", *Applied Soft Computing, 13*(4), 1718-1727. https://doi.org/10.1016/j.asoc.2013.01.003

Garcia-Hernandez, L., Salas-Morera, L., Carmona-Muñoz, C., Abraham, A., & Salcedo-Sanz, S. (2020), "A novel multi-objective Interactive Coral Reefs Optimization algorithm for the Unequal Area Facility Layout Problem", *Swarm and Evolutionary Computation, 55*, p. 100688. https://doi.org/10.1016/j.swevo.2020.100688

Gómez, A., Fernández, Q.I., De la Fuente García, D., & García, P.J. (2003), "Using genetic algorithms to resolve layout problems in facilities where there are aisles", *International Journal of Production Economics, 84*(3), 271-282. https://doi.org/10.1016/S0925-5273(02)00468-1

Grobelny, J., & Michalski, R. (2018), "Simulated Annealing Based on Linguistic Patterns: Experimental Examination of Properties for Various Types of Logistic Problems", in Wilimowska, Z and Borzemski, L and Swiatek, J (Ed.), *Information Systems Architecture and Technology*, PT III, 657, 336-345. https://doi.org/10.1007/978-3-319-67223-6_32

Hathhorn, J., Sisikoglu, E., & Sir, M.Y. (2013), "A multi-objective mixed-integer programming model for a multi-floor facility layout", *International Journal of Production Research, 51*(14), 4223-4239. https://doi.org/10.1080/00207543.2012.753486

Hosseini, S.S., & Seifbarghy, M. (2016), "A novel meta-heuristic algorithm for multi-objective dynamic facility layout problem", *RAIRO-Operations Research, 50*(4-5), 869-890. https://doi.org/10.1051/ro/2016057

Hosseini-Nasab, H., Fereidouni, S., Ghomi, S.M.T.F., & Fakhrzad, M.B. (2018), "Classification of facility layout problems: a review study", *International Journal of Advanced Manufacturing Technology, 94*(1-4), 957-977. https://doi.org/10.1007/s00170-017-0895-8

Ivanov, D., Tsipoulanidis, A., & Schönberger, J. (2017), *Global Supply Chain and Operations Management. A Decision-Oriented Introduction to the Creation of Value*, Vol. 2, Springer International Publishing, Cham, https://doi.org/10.1007/978-3-319-24217-0

Jabal-Ameli, M.S., & Moshref-Javadi, M. (2014), "Concurrent cell formation and layout design using scatter search", The *International Journal of Advanced Manufacturing Technology, 71*(1-4), 1-22. https://doi.org/10.1007/s00170-013-5342-x

Jankovits, I., Luo, C., Anjos, M.F., & Vannelli, A. (2011), "A convex optimisation framework for the unequal-areas facility layout problem", *European Journal of Operational Research, 214*(2), 199-215. https://doi.org/10.1016/j.ejor.2011.04.013

Jolai, F., Tavakkoli-Moghaddam, R., & Taghipour, M. (2012), "A multi-objective particle swarm optimisation algorithm for unequal sized dynamic facility layout problem with pickup/drop-off locations", *International Journal of Production Research, 50*(15), 4279-4293. https://doi.org/10.1080/00207543.2011.613863

Kheirkhah, A., Navidi, H., & Messi Bidgoli, M. (2015), "Dynamic Facility Layout Problem: A New Bilevel Formulation and Some Metaheuristic Solution Methods", *IEEE Transactions on Engineering Management, 62*(3), 396-410. https://doi.org/10.1109/TEM.2015.2437195

Klausnitzer, A., & Lasch, R. (2016), "Extended Model Formulation of the Facility Layout Problem with Aisle Structure", in Mattfeld, D and Spengler, T and Brinkmann, J and Grunewald, M. (Ed.), *Logistics Management*, Springer, Cham, Switzerland, 89-101. https://doi.org/10.1007/978-3-319-20863-3_7

Klausnitzer, A., & Lasch, R. (2019), "Optimal facility layout and material handling network design", *Computers & Operations Research, 103*, 237-251. https://doi.org/10.1016/j.cor.2018.11.002

Ku, M.-Y., Hu, M.H., & Wang, M.-J. (2011), "Simulated annealing based parallel genetic algorithm for facility layout problem", *International Journal of Production Research, 49*(6), 1801-1812. https://doi.org/10.1080/00207541003645789

La Scalia, G., Micale, R., & Enea, M. (2019), "Facility layout problem: Bibliometric and benchmarking analysis", *International Journal of Industrial Engineering Computations, 10*(4), 453-472. https://doi.org/10.5267/j.ijiec.2019.5.001

La Scalia, G., Micale, R., Giallanza, A., & Marannano, G. (2019), "Firefly algorithm based upon slicing structure encoding for unequal facility layout problem", *International Journal of Industrial Engineering Computations, 10*(3), 349-360. https://doi.org/10.5267/j.ijiec.2019.2.003

Le, P.L., Dao, T.-M., & Chaabane, A. (2019), "BIM-based framework for temporary facility layout planning in construction site A hybrid approach", *Construction Innovation-England, 19*(3), 424-464. https://doi.org/10.1108/CI-06-2018-0052

Lee, K.-Y., Roh, M.-I., & Jeong, H.-S. (2005), "An improved genetic algorithm for multi-floor facility layout problems having inner structure walls and passages", *Computers & Operations Research, 32*(4), 879-899. https://doi.org/10.1016/j.cor.2003.09.004

Lenin, N., Siva Kumar, M., Islam, M.N., & Ravindran, D. (2013), "Multi-objective optimization in single-row layout design using a genetic algorithm", *The International Journal of Advanced Manufacturing Technology, 67*(5-8), 1777-1790. https://doi.org/10.1007/s00170-012-4608-z

Leno, I.J., Saravana Sankar, S., Victor Raj, M., & Ponnambalam, S.G. (2012), "An elitist strategy genetic algorithm for integrated layout design", *The International Journal of Advanced Manufacturing Technology, 66*(9-12), 1573-1589.

Li, J., Tan, X., & Li, J. (2018), "Research on Dynamic Facility Layout Problem of Manufacturing Unit Considering Human Factors", *Mathematical Problems in Engineering*, *2018*, ID 6040561 https://doi.org/10.1155/2018/6040561

Liu, J., & Liu, J. (2019), "Applying multi-objective ant colony optimization algorithm for solving the unequal area facility layout problems", *Applied Soft Computing, 74*, 167-189. https://doi.org/10.1016/j.asoc.2018.10.012

Liu, J., Liu, J., Yan, X., & Peng, B. (2020), "A heuristic algorithm combining Pareto optimization and niche technology for multi-objective unequal area facility layout problem", *Engineering Applications of Artificial Intelligence, 89*, p. 103453. https://doi.org/10.1016/j.engappai.2019.103453

Liu, J., Liu, S., Liu, Z., & Li, B. (2020), "Configuration space evolutionary algorithm for multi-objective unequal-area facility layout problems with flexible bays", *Applied Soft Computing, 89*, p. 106052. https://doi.org/10.1016/j.asoc.2019.106052

Liu, J., Zhang, H., He, K., & Jiang, S. (2018), "Multi-objective particle swarm optimization algorithm based on objective space division for the unequal-area facility layout problem", *Expert Systems with Applications, 102*, 179-192. https://doi.org/10.1016/j.eswa.2018.02.035

Loiola, E.M., de Abreu, N.M.M., Boaventura-Netto, P.O., Hahn, P., & Querido, T. (2007), "A survey for the quadratic assignment problem", *European Journal of Operational Research, 176*(2), 657-690. https://doi.org/10.1016/j.ejor.2005.09.032

Matai, R. (2015), "Solving multi objective facility layout problem by modified simulated annealing", *Applied Mathematics and Computation, 261*, 302-311. https://doi.org/10.1016/j.amc.2015.03.107

Matai, R., Singh, S.P., & Mittal, M.L. (2013), "Modified simulated annealing based approach for multi objective facility layout problem", *International Journal of Production Research, 51*(14), 4273-4288. https://doi.org/10.1080/00207543.2013.765078

Meller, R., Kirkizoglu, Z., & Chen, W. (2010), "A new optimization model to support a bottom-up approach to facility design", *Computers & Operations Research, 37*(1), 42-49. https://doi.org/10.1016/j.cor.2009.03.018

Meller, R., Kleiner, B.M., & Nussbaum, M.A. (2004), "The facility layout problem: a new model to support a bottom-up approach to facility design", *Progress in Material Handling Research*, Material Handling Institute, Charlotte, EUA, 399-414.

Muther, R. (1961), Systematic Layout Planning, Industrial Education Institute, Boston.

Nagarajan, L., Mahalingam, S.K., Gurusamy, S., & Dharmaraj, V.K. (2018), "Solution for bi-objective single row facility layout problem using artificial bee colony algorithm", *European J. of Industrial Engineering, 12*(2), 252. https://doi.org/10.1504/EJIE.2018.090619

Navidi, H., Bashiri, M., & Messi Bidgoli, M. (2012), "A heuristic approach on the facility layout problem based on game theory", *International Journal of Production Research, 50*(6), 1512-1527. https://doi.org/10.1080/00207543.2010.550638

Pérez-Gosende, Pablo (2022). Multi-objective bottom-up approach to dynamic spatial distribution planning in industrial plants [PhD thesis]. Universitat Politècnica de València. https://doi.org/10.4995/Thesis/10251/185800

Pérez-Gosende, P., Mula, J., & Díaz-Madroñero, M. (2020), "Overview of Dynamic Facility Layout Planning as a Sustainability Strategy", *Sustainability, 12*(19), 8277. https://doi.org/10.3390/su12198277

Pérez-Gosende, P., Mula, J., & Díaz-Madroñero, M. (2021), "Facility layout planning. An extended literature review", *International Journal of Production Research*, *59*(12), 1-40. https://doi.org/10.1080/00207543.2021.1897176

Pournaderi, N., Ghezavati, V.R., & Mozafari, M. (2019), "Developing a mathematical model for the dynamic facility layout problem considering material handling system and optimizing it using cloud theory-based simulated annealing algorithm", *SN Applied Sciences, 1*, 832. https://doi.org/10.1007/s42452-019-0865-x

Pourvaziri, H., & Pierreval, H. (2017), "Dynamic facility layout problem based on open queuing network theory", *European Journal of Operational Research, 259*(2), 538-553. https://doi.org/10.1016/j.ejor.2016.11.011

Pourvaziri, H., Pierreval, H., & Marian, H. (2021), "Integrating facility layout design and aisle structure in manufacturing systems: Formulation and exact solution", *European Journal of Operational Research, 290*(2), 499-513. https://doi.org/10.1016/j.ejor.2020.08.012

Ripon, K.S.N., Glette, K., Khan, K.N., Hovin, M., & Torresen, J. (2013), "Adaptive variable neighborhood search for solving multi-objective facility layout problems with unequal area facilities", *Swarm and Evolutionary Computation, 8*, 1-12. https://doi.org/10.1016/j.swevo.2012.07.003

Şahin, R. (2011), "A simulated annealing algorithm for solving the bi-objective facility layout problem", *Expert Systems with Applications, 38*(4), 4460-4465. https://doi.org/10.1016/j.eswa.2010.09.117

Salmani, M.H., Eshghi, K., & Neghabi, H. (2015), "A bi-objective MIP model for facility layout problem in uncertain environment", *The International Journal of Advanced Manufacturing Technology, 81*(9-12), 1563-1575. https://doi.org/10.1007/s00170-015-7290-0

Samarghandi, H., Taabayan, P., & Behroozi, M. (2013), "Metaheuristics for fuzzy dynamic facility layout problem with unequal area constraints and closeness ratings", *The International Journal of Advanced Manufacturing Technology, 67*(9-12), 2701-2715. https://doi.org/10.1007/s00170-012-4685-z

Saraswat, A., Venkatadri, U., & Castillo, I. (2015), "A framework for multi-objective facility layout design", *Computers & Industrial Engineering, 90*, 167-176. https://doi.org/10.1016/j.cie.2015.09.006

Sharma, P., & Singhal, S. (2017), "Implementation of fuzzy TOPSIS methodology in selection of procedural approach for facility layout planning", *The International Journal of Advanced Manufacturing Technology, 88*(5-8), 1485-1493. https://doi.org/10.1007/s00170-016-8878-8

Singh, D., & Ingole, S. (2019), "Multi-objective facility layout problems using BBO, NSBBO and NSGA-II metaheuristic algorithms", *International Journal of Industrial Engineering Computations, 10*(2), 239-262. https://doi.org/10.5267/j.ijiec.2018.6.006

Singh, S.P., & Singh, V.K. (2010), "An improved heuristic approach for multi-objective facility layout problem", *International Journal of Production Research, 48*(4), 1171-1194. https://doi.org/10.1080/00207540802534731

Singh, S.P., & Singh, V.K. (2011), "Three-level AHP-based heuristic approach for a multi-objective facility layout problem", *International Journal of Production Research, 49*(4), 1105-1125. https://doi.org/10.1080/00207540903536148

Sun, X., Lai, L.-F., Chou, P., Chen, L.-R., & Wu, C.-C. (2018), "On GPU Implementation of the Island Model Genetic Algorithm for Solving the Unequal Area Facility Layout Problem", *Applied Sciences-Basel, 8*(9), 1604. https://doi.org/10.3390/app8091604

Tayal, A., & Singh, S.P. (2018), "Integrating big data analytic and hybrid firefly-chaotic simulated annealing approach for facility layout problem", *Annals of Operations Research, 270*(1-2), 489-514. https://doi.org/10.1007/s10479-016-2237-x

Vitayasak, S., Pongcharoen, P., & Hicks, C. (2017), "A tool for solving stochastic dynamic facility layout problems with stochastic demand using either a Genetic Algorithm or modified Backtracking Search Algorithm", *International Journal of Production Economics, 190*, 146-157. https://doi.org/10.1016/j.ijpe.2016.03.019

Wan, X., Zuo, X., Li, X., & Zhao, X. (2020), "A hybrid multiobjective GRASP for a multi-row facility layout problem with extra clearances", *International Journal of Production Research*, 1-20. https://doi.org/10.1080/00207543.2020.1847342

Wei, X., Yuan, S., & Ye, Y. (2019), "Optimizing facility layout planning for reconfigurable manufacturing system based on chaos genetic algorithm", *Production and Manufacturing Research-An Open Acces Journal, 7*(1), 109-124. https://doi.org/10.1080/21693277.2019.1602486

Xiao, Y., Xie, Y., Kulturel-Konak, S., & Konak, A. (2017), "A problem evolution algorithm with linear programming for the dynamic facility layout problem-A general layout formulation", *Computers & Operations Research, 88*, 187-207. https://doi.org/10.1016/j.cor.2017.06.025

Yang, L., Deuse, J., & Jiang, P. (2013), "Multi-objective optimization of facility planning for energy intensive companies", *Journal of Intelligent Manufacturing, 24*(6), 1095-1109. https://doi.org/10.1007/s10845-012-0637-6

Zhao, Y., Lu, J., Yan, Q., Lai, L., & Xu, L. (2020), "Research on Cell Manufacturing Facility Layout Problem Based on Improved NSGA-II", *Computers, Materials & Continua, 62*(1), 355-364. https://doi.org/10.32604/cmc.2020.06396