TESIS DOCTORAL

ENFOQUE MULTIOBJETIVO BOTTOM-UP PARA LA PLANIFICACIÓN DINÁMICA DE LA DISTRIBUCIÓN ESPACIAL EN PLANTAS INDUSTRIALES

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RESUMEN

La planificación de la distribución espacial en plantas industriales (FLP) es una de las decisiones más importantes en el contexto de la dirección de operaciones, y uno de los problemas de mayor discusión en la literatura científica enmarcada en el campo amplio de la ingeniería industrial. Sin embargo, el uso generalizado del enfoque de solución *top-down* tradicional, que se inicia con el diseño de la distribución del conjunto de los departamentos o celdas de trabajo que conforman el sistema de producción y prosigue con la distribución detallada al interior de éstos, parte de asunciones poco compatibles con la realidad operacional industrial que implican ciertas limitaciones para su adopción en la práctica. Esto, unido al hecho de que los modelos matemáticos empleados en la generación de alternativas de *layout* utilizan en su mayoría el coste de manejo de materiales como una función monoobjetivo de carácter cuantitativo, desvirtuando la naturaleza multiobjetiva del problema, acentúa un vacío que genera oportunidades de mejora en la toma de decisiones de planificación del *layout* en la práctica industrial. En este contexto, esta tesis doctoral, respaldada por un estudio minucioso del estado del arte y el análisis de modelos de optimización matemática de referencia, presenta un marco conceptual para la toma de decisiones de planificación del FLP desde una perspectiva multiobjetivo, y un nuevo modelo de optimización multiobjetivo no lineal entero mixto (MOMINLP) para facilitar la toma de decisiones de distribución espacial en plantas industriales metalmecánicas en entornos de demanda dinámicos mediante un enfoque de planificación *bottom-up*, teniendo en cuenta criterios cuantitativos y cualitativos. El modelo propuesto, denominado bottom-up mDFLP, considera tres funciones objetivo que pretenden: (1) minimizar el coste total de manejo de materiales y el coste total de reorganización, (2) maximizar el *rating* de proximidad subjetiva entre departamentos, y (3) maximizar el ratio de utilización de área. El modelo bottom-up mDFLP ha sido validado en una empresa del sector metalmecánico, confirmando un mejor desempeño en los valores de las funciones objetivo respecto a los obtenidos en la distribución en planta actual.

RESUM

La planificació de la distribució espacial en plantes industrials (FLP) és una de les decisions més importants en el context de la direcció d'operacions, i un dels problemes de major discussió en la literatura científica emmarcada en el camp ampli de l'enginyeria industrial. No obstant això, l'ús generalitzat de l'enfocament de solució *top-down* tradicional, que s'inicia amb el disseny de la distribució del conjunt dels departaments o cel·les de treball que conformen el sistema de producció i prossegueix amb la distribució detallada a l'interior d'aquests, part d'assumpcions poc compatibles amb la realitat operacional industrial que impliquen unes certes limitacions per a la seua adopció en la pràctica. Això, unit al fet que els models matemàtics emprats en la generació d'alternatives de *layout* utilitzen en la seua majoria el cost de maneig de materials com una funció monoobjetivo de caràcter quantitatiu, desvirtuant la naturalesa multiobjectiva del problema, accentua un buit que genera oportunitats de millora en la presa de decisions de planificació del *layout* en la pràctica industrial. En aquest context, aquesta tesi doctoral, recolzada per un estudi minuciós de l'estat de l'art i l'anàlisi de models d'optimització matemàtica de referència, presenta un marc conceptual per a la presa de decisions de planificació del FLP des d'una perspectiva multiobjectiu, i un nou model d'optimització multiobjectiu no lineal enter mixt (MOMINLP) per a facilitar la presa de decisions de distribució espacial en plantes industrials metallmecàniques en entorns de demanda dinàmics mitjançant un enfocament de planificació *bottom-up*, tenint en compte criteris quantitatius i qualitatius. El model proposat, denominat bottom-up mDFLP, considera tres funcions objectiu que pretenen: (1) minimitzar el cost total de maneig de materials i el cost total de reorganització, (2) maximitzar el *rating* de proximitat subjectiva entre departaments, i (3) maximitzar el ràtio d'utilització d'àrea. El model bottom-up mDFLP ha sigut validat en una empresa del sector metallmecànic, confirmant un millor acompliment en els valors de les funcions objectiu respecte als obtinguts en la distribució en planta actual.

ABSTRACT

Facility layout planning (FLP) is one of the most critical decisions in operations management and one of the most discussed problems in the scientific literature framed in the broad field of industrial engineering. However, the widespread use of the traditional top-down solution approach, which starts with a block layout design phase and continues with the detailed layout within each work cell making up the production system, is based on assumptions that are not very compatible with the industrial operational reality, which implies certain limitations for its adoption in practice. This issue, together with the fact that the mathematical models used in the generation of layout alternatives mostly use the cost of material handling as a single objective function of a quantitative nature, distorting the multi-objective nature of the problem, accentuates a gap that generates opportunities for improvement in the FLP decision making process in industrial practice. In this context, this doctoral thesis, supported by a thorough study of state of the art and the analysis of benchmark mathematical optimisation models, presents a conceptual framework for FLP planning decision making from a multi-objective perspective and also a new multi-objective mixed-integer non-linear optimisation model (MOMINLP) to facilitate FLP decision making for metal-mechanical industrial plants in dynamic demand environments through a bottom-up planning approach, taking into account quantitative and qualitative criteria. The proposed model, called bottom-up mDFLP, considers three objective functions that aim to: (1) minimising the total material handling cost and the total rearrangement cost, (2) maximising the subjective closeness rating between departments, (3) maximising the area utilisation ratio. The bottom-up mDFLP model has been validated in a company from the metal-mechanical sector, confirming a better performance in the values of the objective functions than those obtained in the current plant layout.

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A mi madre, hermanos y familia, por tanto cariño que les debo.

A los directores de esta tesis doctoral, la Dra. Dña. Josefa Mula Bru y el Dr. D. Manuel Díaz-Madroñero Boluda, por la oportunidad que me dieron de aprender con ellos, por su paciencia, y por su inmenso apoyo en la realización de esta obra.

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CONTENIDO DETALLADO

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CAPÍTULO I

INTRODUCCIÓN

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1 Presentación

La distribución espacial en plantas industriales (*facility layout problem*, FLP), también conocida como distribución en planta, puede definirse como el proceso de ordenamiento físico de todos los factores de producción que conforman el sistema productivo de forma que se cumplan adecuada y eficientemente los objetivos estratégicos de la organización. En el marco de las estrategias de operaciones empresariales, el FLP es considerado una de las decisiones de diseño de mayor importancia (Ghassemi Tari & Neghabi, 2015; Kheirkhah et al., 2015). De igual forma, tiene una repercusión significativa en la eficiencia de los sistemas de fabricación y su nivel de productividad (Altuntas & Selim, 2012; Ku et al., 2011; Navidi et al., 2012).

Una distribución en planta eficaz, debe garantizar el cumplimiento de los programas de producción en el corto, medio y largo plazo, al menor coste, con una adecuada utilización del espacio, y garantizando a la vez, un cierto grado de flexibilidad para futuras redistribuciones y riesgos mínimos de salud y seguridad en el trabajo. Por el contrario, una distribución ineficiente puede generar una simultaneidad de cuellos de botella, congestión y deficiente utilización del espacio, acumulación excesiva de trabajo en proceso, puestos de trabajo ociosos o sobrecargados, ansiedad y malestar de la mano de obra, accidentes laborales y dificultad en el control de las operaciones y del personal (Pérez-Gosende, 2016). Además, cuando no existe un adecuado nivel de cercanía entre los centros de actividad de la organización, se genera un desaprovechamiento de la jornada laboral en actividades de transporte que no aportan valor. Ésta es una de las razones principales por las que aumentan los tiempos de producción y disminuyen los niveles de productividad del trabajo.

Desde la segunda mitad del siglo XX, el FLP ha sido un tema de amplia discusión científica dada su consideración como uno de los problemas clásicos más importantes en el contexto de la dirección de operaciones y la ingeniería industrial. Son varios los estudios de revisión que lo han abordado con una mayor o menor profundidad. La mayoría de estos estudios se enfocan en dimensiones específicas del problema (Ahmadi et al., 2017; Anjos & Vieira, 2017; Keller & Buscher, 2015; Maganha et al., 2019; Moslemipour et al., 2012; Renzi et al., 2014; Saraswat et al., 2015; Saravanan & Kumar, 2013), aunque ha habido otros que lo han abordado de forma general (Drira et al., 2007; Hosseini-Nasab et al., 2018; Meller & Gau, 1996; S. P. Singh & Sharma, 2006). A pesar de esta extensa cobertura científica, la investigación de muchos aspectos del FLP aún se encuentra en su etapa inicial (Hosseini-Nasab et al., 2018). Esto ocurre porque las necesidades de organización espacial en la industria cambian continuamente para adaptarse a los cambios tecnológicos propios de la cuarta revolución industrial, la proliferación de los sistemas ciberfísicos, las necesidades cada vez más demandantes de los mercados, la transición hacia estilos de fabricación más flexibles que permitan una alta variedad de productos en lotes cada vez más pequeños, y a la evolución de las directrices de seguridad y salud en el trabajo, lo que motiva a seguir aportando a su comprensión.

Cuando se planifica la distribución en planta bajo el supuesto de que la demanda se mantendrá constante durante todo el horizonte de planificación, el problema es conocido como de distribución en planta estática o uniperíodo (SFLP). No obstante, en muchos sistemas de producción la consideración de un único diseño puede resultar impráctico, pues es poco probable que el flujo de materiales se mantenga invariable a lo largo del tiempo. En cambio, cuando la demanda es estacional o muy cambiante, es conveniente considerar un diseño de distribución en planta diferente para cada período de tiempo con una demanda diferenciada que conforma el horizonte de planificación. En tal caso, se trataría de un enfoque de planificación dinámico o multiperíodo (DFLP) (Al Hawarneh et al., 2019; Pournaderi et al., 2019; Turanoğlu & Akkaya, 2018). En este sentido, en Hosseini-Nasab et al. (2018) se identificó que el DFLP ha tenido una menor repercusión en la literatura científica que el enfoque SFLP.

En el enfoque estático, SFLP, se determina un único diseño de distribución en planta considerando una demanda constante durante todo el horizonte de planificación, lo que podría no ser muy común en los casos de la realidad empresarial actual. A partir del enfoque dinámico, DFLP, se diseña una distribución en planta óptima para cada período temporal de modo que se minimicen los costes totales de transporte de materiales y los de reordenamiento de las instalaciones (al Hawarneh et al., 2019; Pournaderi et al., 2019; Turanoğlu & Akkaya, 2018). En la práctica, debido a que la reorganización de las instalaciones es un proceso costoso, el enfoque DFLP es empleado con frecuencia para el diseño de la distribución en planta de sistemas de producción que operan en entornos dinámicos (Kumar & Singh, 2017; Wei et al., 2019). No obstante, en cualquiera de los enfoques de planificación mencionados, es necesario recalcar que el FLP no es un problema de fácil resolución desde el punto de vista computacional. La generación y selección de la distribución espacial más conveniente para una organización es un proceso complejo e iterativo que depende de las relaciones que existen entre los elementos que conforman su sistema de producción de bienes o servicios.

De acuerdo con la teoría de la complejidad computacional, el FLP es considerado un problema de optimización NP-hard (*non-polynomial hard problem*), pues en muchas de sus variantes no existen algoritmos de resolución que proporcionen una solución óptima en un tiempo polinómico razonable (Grobelny & Michalski, 2017). Sin embargo, a pesar de su alto grado de complejidad, distintos autores han abordado estos problemas aportando soluciones aceptables con tiempos de cálculo realistas.

En los últimos diez años la distribución en planta ha sido modelada matemáticamente como un problema de asignación cuadrática (QAP) (Peng et al., 2018; Pournaderi et al., 2019; Zhang et al., 2019), a través de programación lineal (LP) (Gai & Ji, 2019; Kulturel-Konak, 2012; Xiao et al., 2016), programación lineal entera (ILP) (al Hawarneh et al., 2019; Feng & Che, 2018; Horta et al., 2016), programación lineal entera mixta (MILP) (Brunoro Ahumada et al., 2018; Ejeh et al., 2018; Klausnitzer & Lasch, 2019), programación no lineal entera (NLIP) (Abdollahi et al., 2019; Anjos & Vieira, 2016; Neghabi et al., 2014), programación no lineal entera mixta (MINLP) (de Lira-Flores et al., 2019; Gulsen et al., 2019; Vázquez-Román et al., 2019), programación semidefinida (SDP) (Hungerländer, 2014; Hungerländer & Anjos, 2015; Hungerländer & Rendl, 2013) y mediante teoría de grafos (Zheng, 2014). Tales modelos, de forma general, han estado sujetos a 36 tipos de restricciones diferentes. Entre ellas las más comunes son las restricciones de área, capacidad, relación de aspecto, orientación de las instalaciones, solapamiento, adyacencia y ubicación de puntos de recepción y despacho de materiales (Pérez-Gosende et al., 2021).

La mayoría de los modelos de optimización de la distribución en planta consideran una única función objetivo, la misma que puede ser de naturaleza cuantitativa o cualitativa. Específicamente, en el contexto de las empresas industriales, el coste total de manejo de materiales (TMHC) es un factor clave para obtener una distribución en planta óptima (Singh & Ingole, 2019), y en los últimos diez años ha sido la función objetivo de tipo cuantitativa más empleada en la búsqueda de soluciones óptimas o subóptimas al FLP en cualquiera de sus variantes (Hosseini-Nasab et al., 2018). Por otro lado, en algunos contextos industriales y de servicios, factores cualitativos como las relaciones de proximidad entre los departamentos (*closeness ratings*), la flexibilidad o la seguridad pueden ser de mayor relevancia. Sin embargo, al resolver cualquier problema de distribución en planta, la consideración de factores cuantitativos o cualitativos como una función objetivo única puede generar soluciones no necesariamente óptimas. En la práctica, la consideración de ambos tipos de factores de forma simultánea puede ser de vital importancia.

Al ser la minimización del TMHC una de las funciones objetivo más comunes en los modelos de optimización de la distribución en planta, los puntos de recepción y despacho de materiales en cada centro de actividad así como las métricas de distancia a considerar son fundamentales. De manera general, el TMHC se determina mediante la sumatoria del producto del coste de transportar una unidad de flujo una unidad de distancia por el volumen total transportado entre los centroides de cada departamento por la distancia total recorrida en forma euclídea o rectangular. Sin embargo, al modelar la distribución en planta, se asume comúnmente que los puntos de recepción y despacho de materiales (P/D) se encuentran en el centroide de cada departamento y la distancia entre estos centroides determina la distancia recorrida por el flujo de trabajo. Estas suposiciones son claramente incompatibles con la mayoría de los diseños de distribución en planta de la vida real. Es más realista asumir que los puntos P/D están ubicados en los bordes de los departamentos y que el flujo de trabajo circula a lo largo de las rutas o vías de circulación que los interconecta. De ahí que los modelos que consideran distancias intercentroides rectangulares o euclídeas puedan generar soluciones subóptimas con TMHC significativamente inferiores a los que se incurrirían cuando el flujo de trabajo recorre la distancia que separa los puntos P/D entre dos departamentos a lo largo de su perímetro o contorno.

Tradicionalmente, la mayoría de enfoques de solución del problema de la distribución en planta han seguido la metodología de planificación sistemática de distribución (*systematic layout planning*, SLP) introducida por Muther (1961). Una investigación reciente concluyó que este era el enfoque más adecuado para manejar problemas de diseño de la distribución en planta (Sharma & Singhal, 2017).

Como la mayoría de los problemas de diseño en ingeniería, el SLP se basa en un enfoque jerárquico. Primeramente, los departamentos son asignados a localizaciones concretas en el espacio físico de la planta, en lo que comúnmente se denomina fase de distribución de conjunto o *block layout*. Posteriormente, tiene lugar la fase de detalle, en la que se procede a la organización de los elementos que conforman el sistema de producción al interior de cada departamento (Bukchin & Tzur, 2014). Este enfoque es también conocido como *top-down approach* (Meller, Kirkizoglu, and Chenb 2010).

Aunque mucho se ha investigado en el tema de la distribución en planta, de acuerdo a Meller et al. (2010) y Potočnik et al. (2014) existen limitadas aplicaciones de los resultados de estas investigaciones en la práctica. Según estos autores, los responsables del diseño de distribución en planta en la industria no consideran de mucho valor la aplicación de un enfoque jerárquico descendente ya que ven más práctico el proceso de determinación de la distribución de conjunto y la distribución detallada de forma simultanea. Otro elemento que sustenta este vacío investigador es que la mayoría de las contribuciones disponibles en la literatura se han concentrado en buscar soluciones al problema considerando casos de estudio hipotéticos o ejemplos numéricos (Pérez-Gosende et al., 2020, 2021), sin considerar las características propias de los sistemas de fabricación de la realidad.

La situación anteriormente descrita afecta, particularmente a las industrias del sector metalmecánico. Un estudio de revisión reciente, demostró que de 232 artículos indexados en la Web of Science considerando la ventana temporal 2010-2019, solo aproximadamente el 20% abordó casos de estudio reales (Pérez-Gosende et al., 2021), y de éstos, solo 5 artículos fueron contextualizados en casos de estudio del sector metalmecánico (Altuntas, Selim, & Dereli, 2014; Jia, Lu, Wang, & Jia, 2013; Li, Tan, & Li, 2018; Ramirez Drada, Chud Pantoja, & Orejuela Cabrera, 2019; Tuzkaya, Gulsun, Tuzkaya, Onut, & Bildik, 2013; Vasudevan & Son, 2011), específicamente, en una fábrica de ascensores, una planta de fabricación de trenes de potencia, una línea de producción de cilindros metálicos, una industria de producción de maquinaria industrial, una unidad de fabricación de máquinas de control numérico computarizado y una empresa productora de muebles metálicos. De aquí se aduce que existe un vacío de conocimiento en el análisis de las decisiones de distribución en planta en este sector industrial de tanta importancia para el desarrollo de la matriz productiva de cada país, pues además de suministrar maquinarias e insumos a otras industrias o actividades económicas, permite generar fuentes de empleo con un alto nivel de calificación. Además, la necesidad del sector por integrar las cadenas de suministro y generar valor agregado da lugar a la transferencia de conocimientos e innovación. A pesar del cierto nivel de ambigüedad en su delimitación (Pérez-Gosende et al., 2017), la industria metalmecánica representa cerca de 16% del producto interno bruto (PIB) industrial en América Latina y proporciona empleo a 23,8 millones de personas en forma directa o indirecta (Alcántara, 2015).

2 Objetivo de la tesis

A partir de lo descrito en el apartado anterior, la presente tesis tiene como objetivo fundamental el desarrollo de un modelo de optimización matemática multiobjetivo que facilite la toma de decisiones de distribución espacial en plantas industriales en entornos de demanda dinámicos mediante un enfoque de planificación *bottom-up* teniendo en cuenta criterios cuantitativos y cualitativos y su validación en el sector metalmecánico.

Para la validación del modelo multiobjetivo de programación no lineal entera mixta (MOMINLP) propuesto, que ha sido denominado bottom-up mDFLP, se ha empleado un caso real. Concretamente, el caso abordado corresponde a una empresa del sector metalmecánico dedicada a la producción de bombas de flujo axial, turbinas, compresores, transportadores de banda y matricería para las empresas procesadoras y envasadoras de camarón de la región costera de Ecuador. En este sentido, el objetivo ha sido validar el modelo diseñado al contrastarlo con la realidad empresarial, sin la intención de resolver un problema puntual en un contexto geográfico concreto, sino de desarrollar un marco de trabajo general aplicable a cualquier empresa del sector metalmecánico a nivel mundial.

Esta tesis se ha desarrollado dentro del Centro de Investigación de Gestión e Ingeniería de Producción (CIGIP) de la Universitat Politècnica de València, en el marco de los proyectos: “Industrial data services for quality control in smart manufacturing (i4Q)” financiado por el programa Horizon 2020 bajo el acuerdo de subvención No. 958205; y los proyectos "Optimización de tecnologías de producción cero-defectos habilitadoras para cadenas de suministro 4.0 (CADS4.0)" financiado por el Ministerio de Ciencia, Innovación y Universidades de España, bajo el acuerdo de subvención RTI2018-101344-B-I00 e “Industrial production and logistics optimization in industry 4.0 (i4OPT)” financiado por la Generalitat Valenciana en el marco del proyecto de grupos de investigación de excelencia PROMETEO/2021/065.

La presente tesis, de forma más específica, trata de:

- Caracterizar, mediante una revisión bibliográfica, las tendencias actuales, deficiencias y directrices para futuras investigaciones en el contexto de la distribución espacial en plantas industriales.
- Formular un marco conceptual como soporte a la toma de decisiones relacionadas con la planificación multiobjetivo de la distribución espacial en plantas industriales con un enfoque de planificación ascendente (*bottom-up approach*), que considere factores cuantitativos y cualitativos.
- Formular un modelo de optimización matemática MOMINLP, denominado bottom-up mDFLP, como soporte a la toma de decisiones de distribución espacial en plantas industriales en entornos dinámicos con un enfoque de planificación ascendente, que permita diseñar de forma concurrente la disposición espacial y la orientación de los centros de actividad que conforman el sistema de producción, así como los puntos de recepción y despacho del objeto de trabajo teniendo en cuenta criterios cuantitativos y cualitativos.
- Identificar soluciones óptimas al modelo multiobjetivo propuesto en el contexto de casos reales de empresas del sector metalmecánico.
- Plantear nuevas líneas de trabajo e investigación.

3 Esquema general de la tesis

Esta tesis se ha dividido en cuatro partes fundamentales que se dividen en los siete capítulos que la componen. Tales partes se describen a continuación:

Parte 1. Estado del arte.

La primera parte acoge dos capítulos relacionados con el estado del arte que, en conjunto, representan el soporte teórico que respalda esta tesis doctoral. El capítulo II presenta una revisión extendida de la literatura científica sobre el FLP desde la perspectiva de la dirección de operaciones. Los 232 artículos revisados se han analizado y clasificado en una amplia taxonomía basada en el tipo de problema, el enfoque y la fase de planificación, las características de las instalaciones de producción, la configuración del sistema de manipulación de materiales y los métodos para generar y evaluar las alternativas de distribución espacial.

El capítulo III, por su parte, ofrece una revisión de la literatura sobre el DFLP, como un caso particular dentro del FLP. En primer lugar, se propone una taxonomía de los artículos revisados basada en las tendencias actuales de la formulación del problema; el enfoque de la modelización matemática (en relación con el tipo de modelo, el tipo de función objetivo, el tipo de restricciones, la naturaleza de la demanda del mercado, el tipo de datos y la métrica de la distancia), y el enfoque de solución considerado. También, se describe como parte de este capítulo, en qué medida la investigación reciente en el contexto del DFLP ha contribuido a la sostenibilidad de las cadenas de suministro al abordar sus tres dimensiones de desempeño: económica, medioambiental y social.

Parte 2. Planteamiento del marco conceptual bottom-up mFLP.

La segunda parte de la tesis incluye, de igual forma, dos capítulos, el IV y el V. En el capítulo IV se analizan detalladamente una serie de modelos de optimización matemática para resolver el FLP considerando factores cuantitativos y cualitativos. Estos modelos sirven como referencia para la posterior propuesta del marco conceptual bottom-up mFLP y, a partir de éste, el modelo analítico MOMINLP bottom-up mDFLP que integra la distribución detallada de los centros de actividad y la distribución de conjunto con un enfoque de planificación dinámico, ascendente, y multiobjetivo.

El capítulo V, por su parte, presenta un marco de trabajo conceptual, denominado bottom-up mFLP, para facilitar a académicos y practicantes la toma de decisiones relacionadas con la planificación multiobjetivo del layout en plantas industriales mediante el empleo de un enfoque ascendente o *bottom-up*.

Parte 3. Planteamiento del modelo analítico bottom-up mDFLP y aplicación en un caso real.

La parte 3 de la tesis la conforma el capítulo VI. Éste introduce un modelo MOMINLP, denominado bottom-up mDFLP, que permite abordar el FLP en empresas que operan en entornos dinámicos desde una perspectiva multiobjetivo considerando un enfoque de planificación ascendente o *bottom-up*. Como parte de este capítulo también se presentan los resultados computacionales de la aplicación del modelo propuesto a un caso de estudio real del sector metalmecánico contrastando los resultados respecto a la distribución en planta actual en términos del coste total de manejo de materiales, el coste total de reorganización, el *rating* de proximidad entre departamentos y el ratio de utilización de área para distintas alternativas de solución.

Parte 4. Conclusiones y líneas futuras de investigación.

Por último, la parte 4 de la tesis, compuesta por el capítulo VII, acoge las conclusiones principales y líneas futuras de investigación que han surgido a partir del desarrollo de este trabajo.

La tesis concluye con el conjunto de fuentes bibliográficas consultadas a lo largo de la investigación doctoral y los anexos relativos a las tablas detalladas de la primera revision bibliográfica, los datos de entrada para la validación del modelo correspondientes al caso de estudio real considerado, así como los resultados de su aplicación.

La Figura I-1 resume el esquema general de la tesis descrito en este apartado.

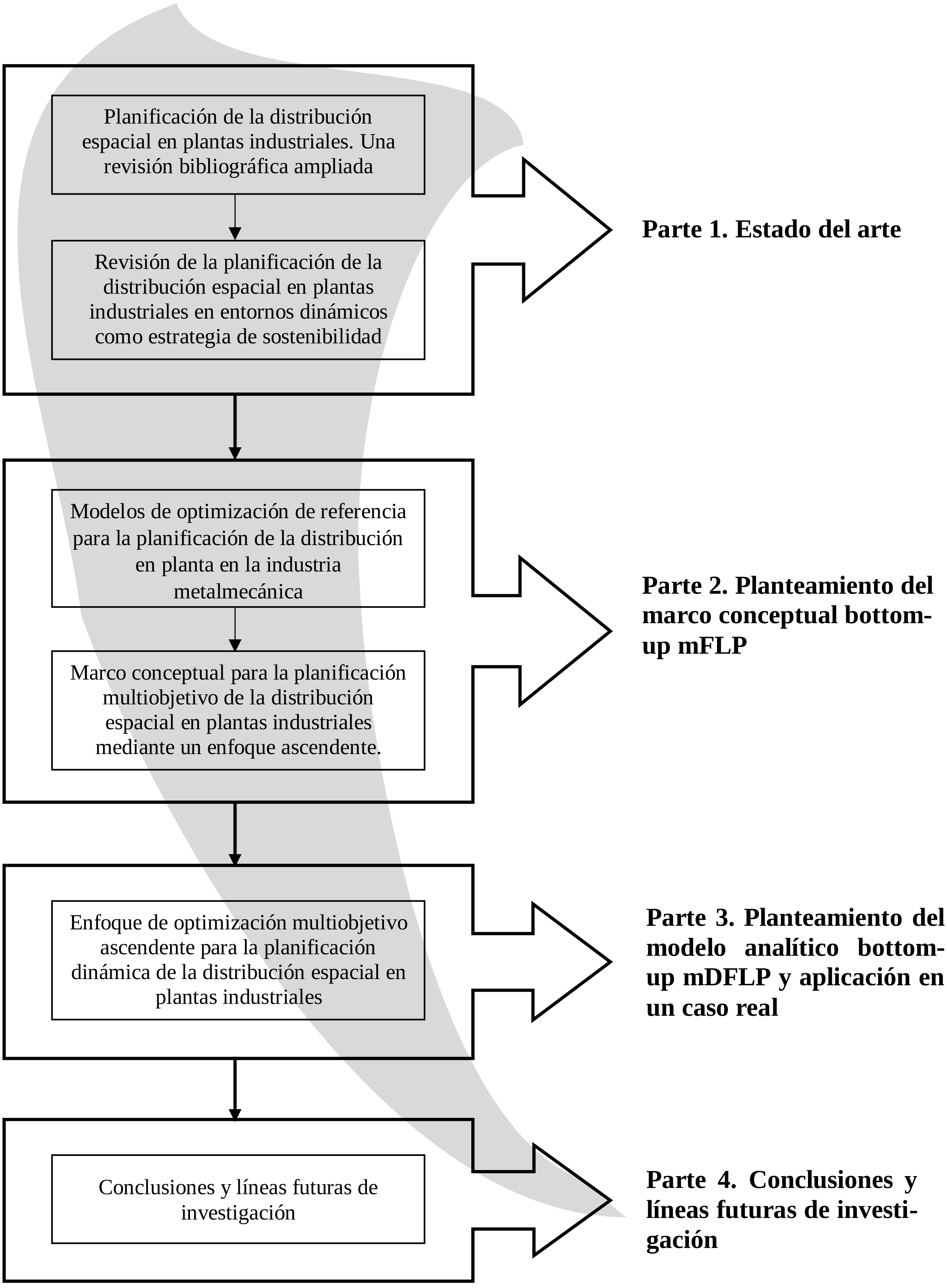

Figura I-1. Esquema general de la tesis.

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CAPÍTULO II

FACILITY LAYOUT PLANNING. AN EXTENDED LITERATURE REVIEW

Este capítulo ha sido publicado en la revista *International Journal of Production Research*, con el título “Facility layout planning. An extended literature review”, en el volumen 59(12), páginas 3777–3816, siendo sus autores, Pablo Alberto Pérez Gosende, Josefa Mula y Manuel Díaz-Madroñero.

CAPÍTULO II

FACILITY LAYOUT PLANNING. AN EXTENDED LITERATURE REVIEW

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 and Neghabi 2015; Kheirkhah et al. 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 II-1 depicts a general framework of FLP, which can also be used by the reader as a guiding thread throughout this article.

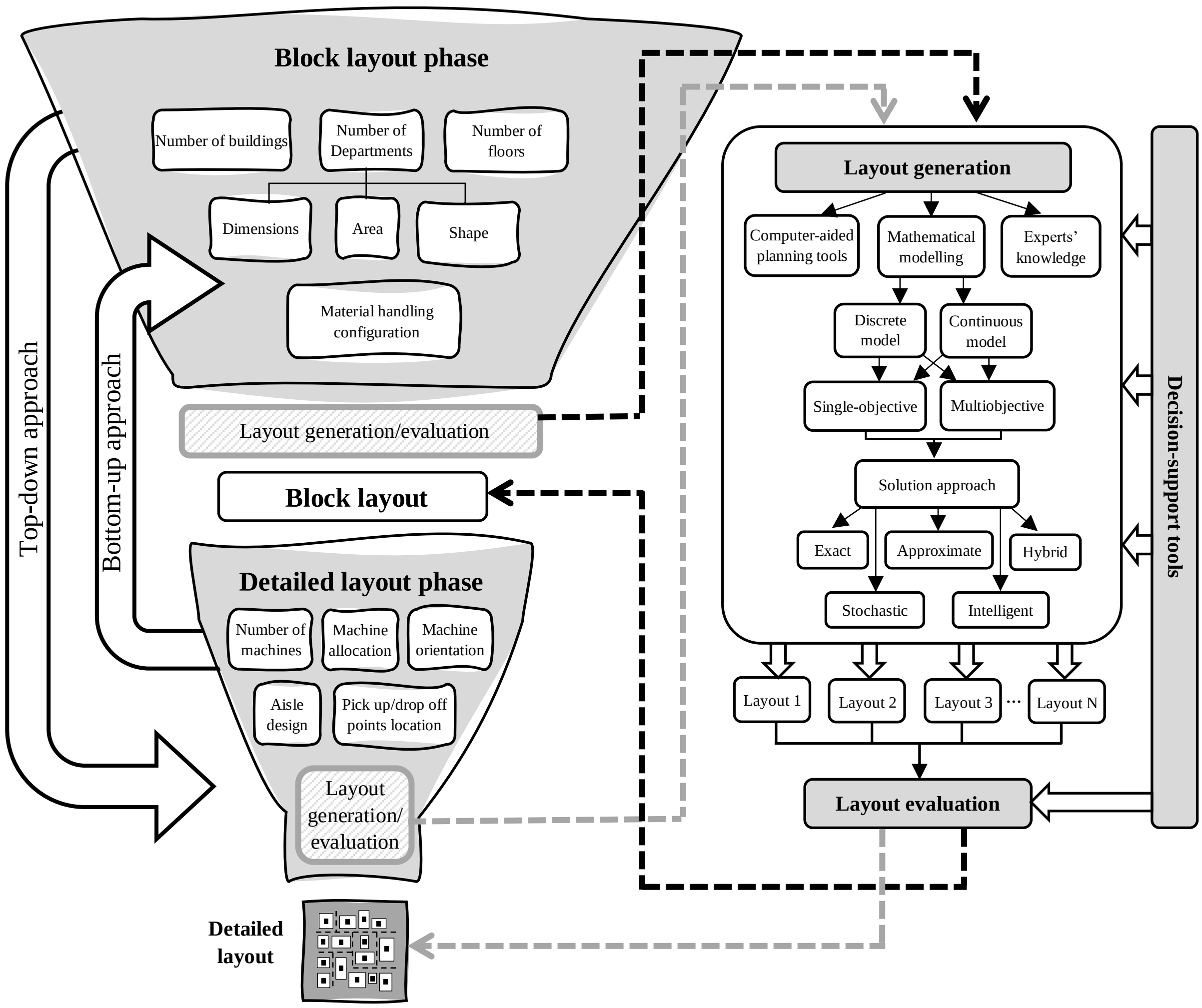

Figure II-1. FLP general framework.

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 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 20th 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 centered 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 Kumar 2013; Ghorbanali 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 II-1.

Table II-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 II-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.

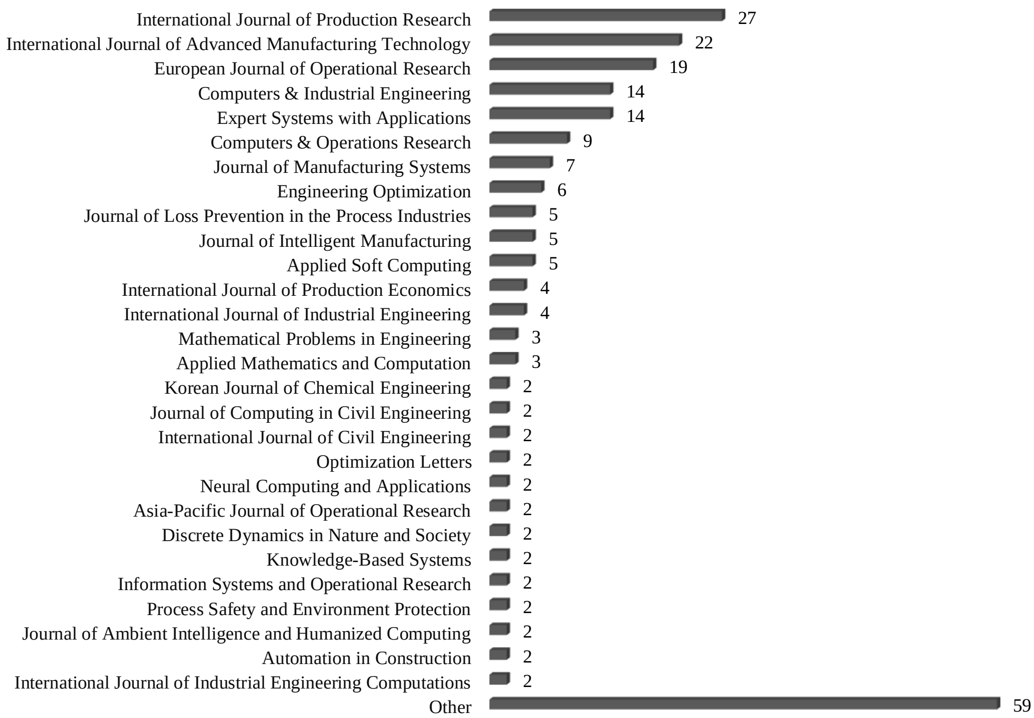

Figure II-2. Distribution of publications per scientific journal.

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, ..., 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

- 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 II-3. According to these criteria, 232 contributions to FLP have been classified. This classification is presented in Table II-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 II-3. In both cases, the codes defined for each classification category in Figure II-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 et al. (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.

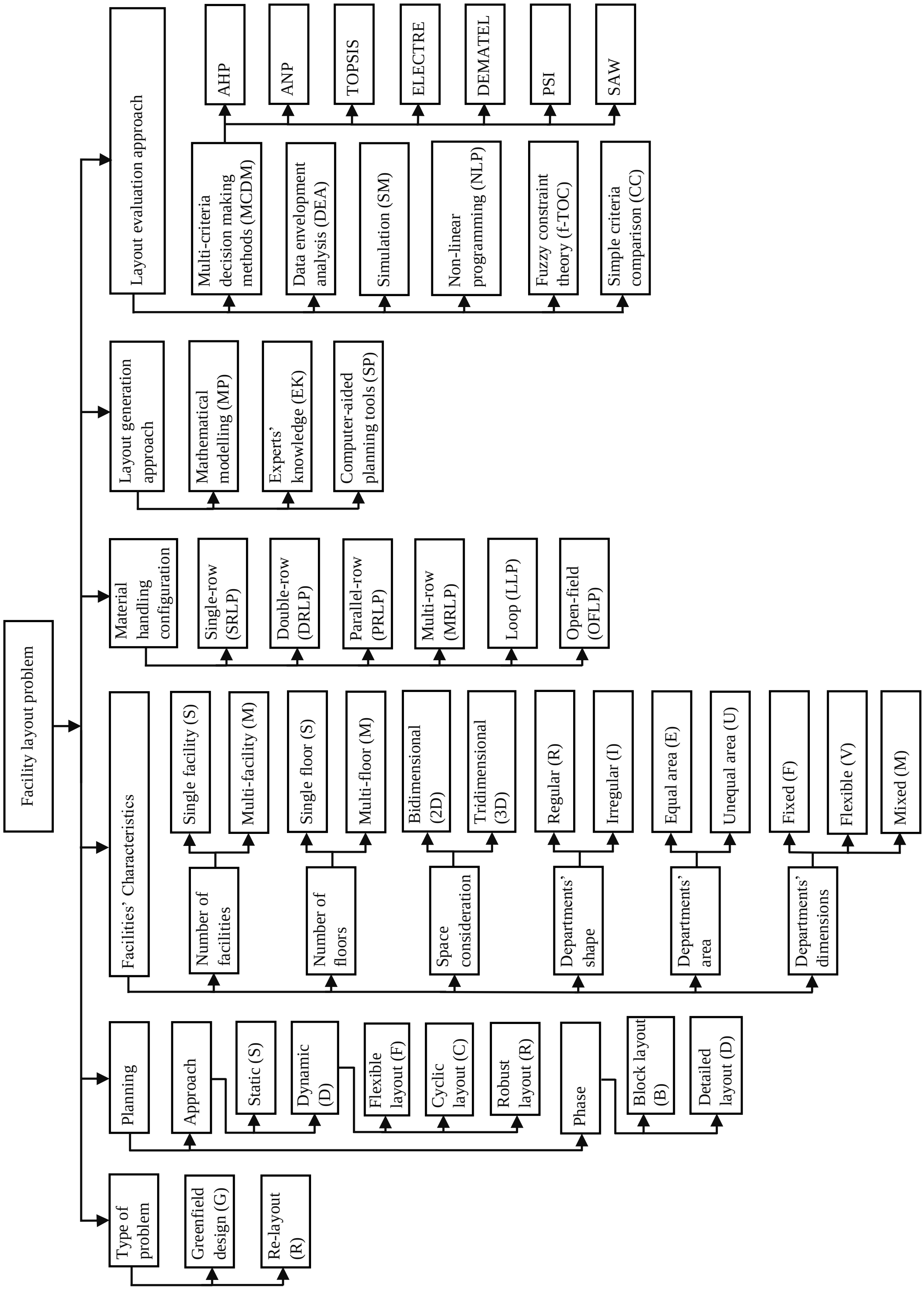

Figure II-3. Classification of the literature on FLP.

Table II-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 et al. (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 et al. (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 et al. (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 et al. (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 et al. (2011)	G	B	S	S	2D	R	F	U	SRLP	MP	
Eben-Chaime et al. (2011)	G	B	S	S	2D	R	F	E	MRLP	EK	
González-Cruz and Gómez-Senent (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 et al. (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
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 et al. (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	

Table II-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]
Lee and Tseng (2012)	R	B	S	S	2D	R	V	E,U	OFLP	MP	4.a
Aiello et al. (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 et al. (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 et al. (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 et al. (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 et al. (2013a)	G	B	S	S	2D	R	F	U	MRLP	MP	
García-Hernández et al. (2013)	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 et al. (2013a)	G	B	S	S	2D	R	F	E	MRLP	MP	
Aiello et al. (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	
García-Hernández et al. (2015)	G	B	S	S	2D	R	V	U	MRLP	MP	
Garcia-Hernandez et al. (2013)	G	B	S	S	2D	R	V	U	MRLP	MP	3.e
Hadi and Ghasemi (2013)	G	B	S	S	2D	R	V	E,U	OFLP	SP	1.c
Hathhorn et al. (2013)	G	B	S	M	2D	R	V	E,U	OFLP	MP	2.c

Table II-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]
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 et al. (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 et al. (2013)	G	B	S	S	2D	R	F	U	OFLP	MP	1.b, 2.a, 3.d
Yang et al. (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
Moatari-Kazerouni et al. (2015a)	G,R	B	S	S,M	2D	R	F	E,U	all	MP	
Al-Hawari et al. (2014)	R	B	S	S	2D	R	F	E,U	OFLP	EK	
Altuntas et al. (2014)	R	B	S	S	2D	R	F	E,U	OFLP	MP	
Azadeh et al. (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 et al. (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 et al. (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 et al. (2015b)	R	B	S	S	2D	R	F	E,U	OFLP	MP	
Neghabi et al. (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 (2016)	G	D	S	S	2D	R	F	E	MRLP	MP	
Leno et al. (2016)	G	B	S	S	2D	R	F	U	OFLP	MP	3.a

Table II-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]
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. (2013)	G	B	S	S	2D	R	V	U	MRLP	MP	
Ghassemi 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	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	
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 et al. (2015)	G	B	S	S	2D	R	F	U	OFLP	MP	
Saraswat et al. (2015)	G	B	S	S	2D	R	V	U	OFLP	MP	
Tasadduq et al. (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 (2016)	G	B	S	S,M	2D	R	M	U	OFLP	MP	2.a, 2.h
Alves et al. (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 et al. (2017)	G	B	S	M	2D	R	F	U	MRLP	MP	2.a, 3.b
Choi et al. (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 et al. (2016)	G	B	S	M	2D	R	F	E	MRLP	MP	2.a
Hou et al. (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 et al. (2016)	G	B	S	S	2D	R	F	E	MRLP	MP	4.g
Neghabi and Ghassemi (2016)	G	B	S	S	2D	R	F	U	OFLP	MP	2.a
Paes et al. (2017)	G	B	S	S	2D	R	V	U	OFLP	MP	3.b

Table II-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 (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
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 et al. (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 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 et al. (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 et al. (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 et al. (2018)	G	B	S	S	2D	R	F	E	OFLP	MP	
Durmusoglu (2018)	G	B	S	S	2D	R	-	E,U	all	-	
Ejeh et al. (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 et al. (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 et al. (2018)	G	B	S	S	2D	R	F	U	LLP	MP	3.b
Leno et al. (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

Table II-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]
Nagarajan et al. (2018)	G	B	S	S	2D	R	F	U	SRLP	MP	
Park et al. (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 et al. (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 et al. (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 et al. (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 et al. (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 et al. (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 II-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, Hunagund and Krishnan (2011)	G	B	R	S	S	2D	R	F	E	OFLP	MP	3.a
Yang, 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 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 S. 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, 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	
Derakhshan Asl and Wong (2017)	G	B	F	S	S	2D	R	F	U	OFLP	MP	3.a
Kheirkhah, Navidi and Messi 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 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

Table II-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]
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).

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 re-layouts (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.

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).

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, $t = 1, ..., T$. 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 et al. 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 et al. 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 et al. 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 et al. 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 et al. 2018; Latifi et al. 2017; Park et al. 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 II-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 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).

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

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 et al. 2019; Friedrich et al. 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 II-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 II-3).

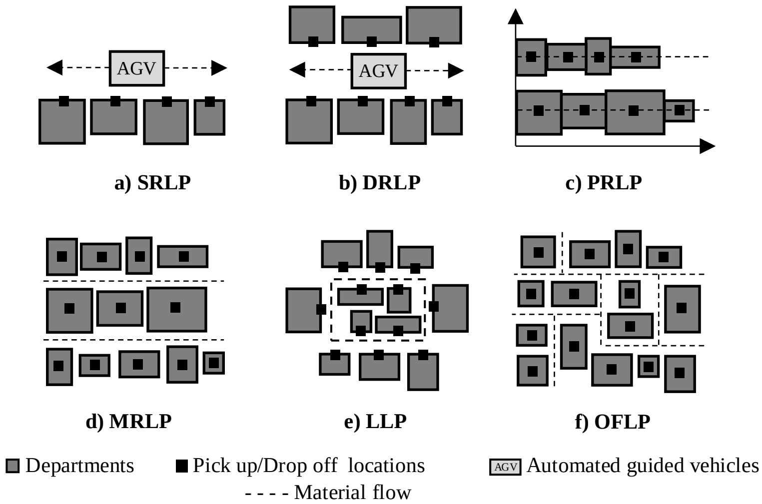

Figure II-5. Facilities layout based on the material handling system configuration.

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

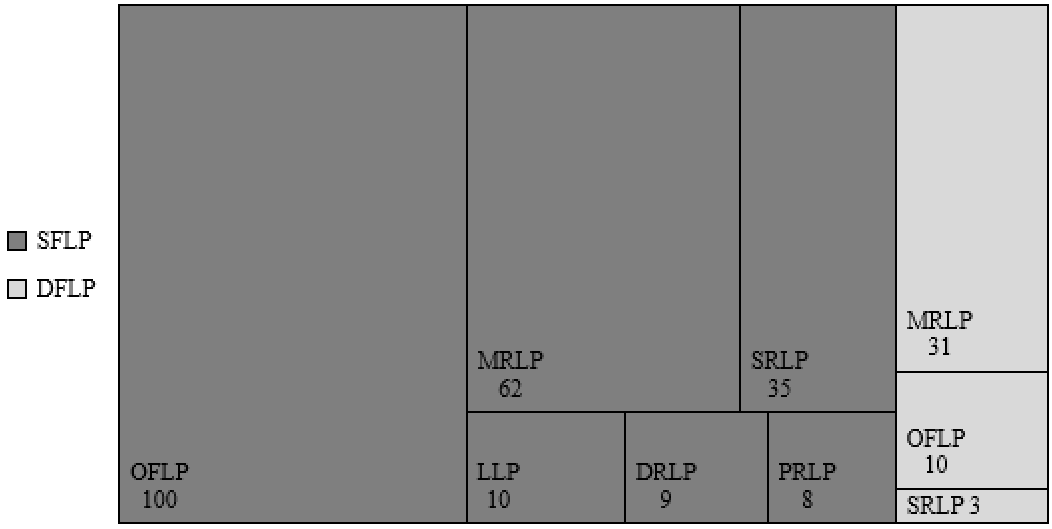

Figure II-6. Distribution of publications based on the material handling system configuration.

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 et al. 2013b). Figure II-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.

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 II-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 expressed in absolute values
   b. *Euclidean.* It represents the distance in a straight line between two points
   c. *Squared Euclidean.* Euclidean distance that is squared
   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

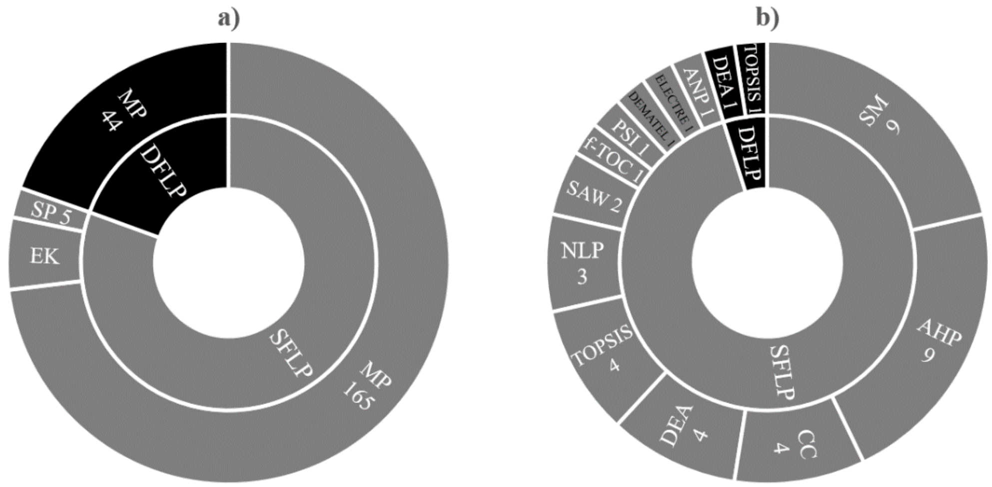

Figure II-7. Distribution of publications according to the a) layout generation approach, b) and layout evaluation approach.

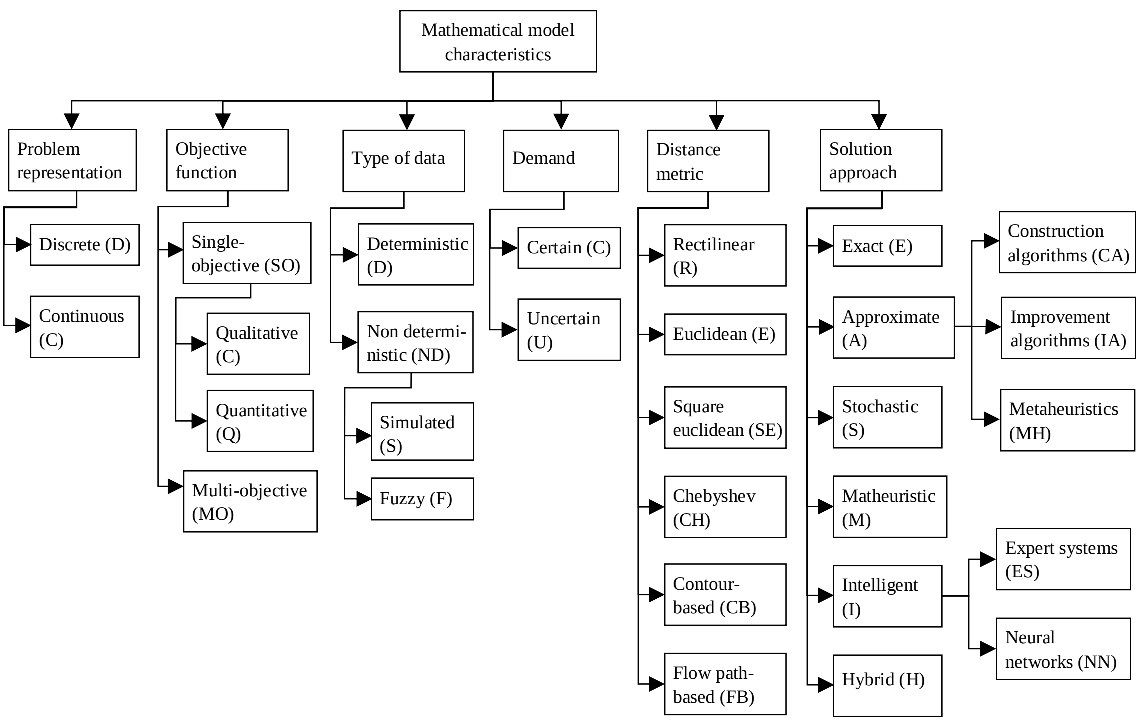

Figure II-8. Characteristics of the FLP mathematical models.

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

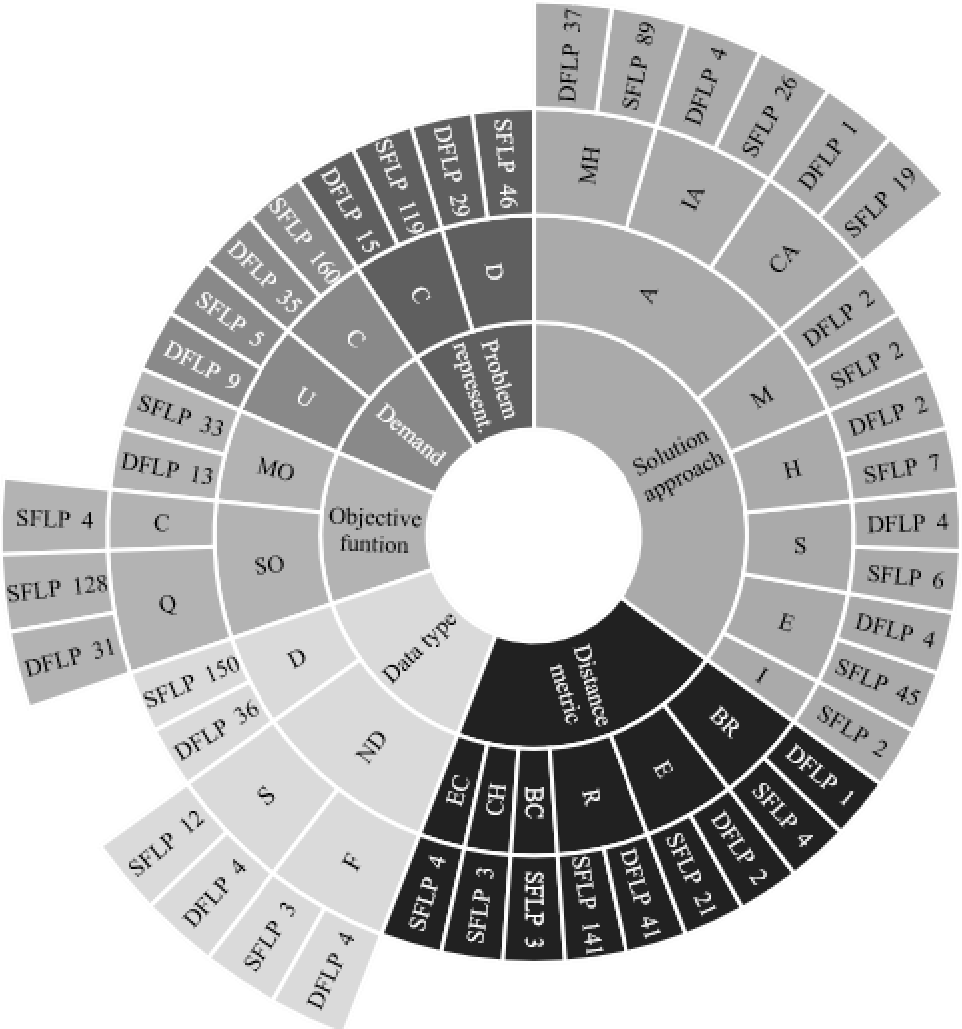

Figure II-9. Distribution of publications according to the problem representation, objective function, data type, demand, distance metrics and solution approach.

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 II-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 et al. 2019; Vazquez-Roman, Diaz-Ovalle, Jung, and Castillo-Borja 2019; Yang et al. 2019) in 52.46% of the cases, and mixed integer linear programming (MILP) (Allahyari and Azab 2018; Ejeh et al. 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, 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 I and Appendix II) 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.

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 I and Appendix II). 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 et al. 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 et al. 2014; Samarghandi et al. 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 II-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, 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 pre-set 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 II-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 III. 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 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 et al. 2007; Heragu 1992; Hosseini-Nasab et al. 2018; Kouvelis et al. 1992; Kouvelis and Kiran 1991; La Scalia, Micale, and Enea 2019; Maganha et al. 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 II-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 (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 Table II-2 and Table II-3. Furthermore, given the relevance of the first group of tools for practitioners, Table II-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 II-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 IV.

Table II-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)

Table II-5. Real-world FLP applications.

References	Industrial sector	Country	# Case studies	Planning approach	Entities (n)	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)

Table II-5. (continued)

References	**Industrial sector**	**Country**	**# Case studies**	**Planning approach**	**Entities (n)**	**Generation approach**	**Layout candidates**	**Layout evaluation approach**	**Mathematical model**	**Solution approach**
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		
García-Hernández et al. (2013)	g,f	Spain	2	S	n=11,12	MP	11,8		MILP	A(MH)
Garcia-Hernandez et al. (2013)	g	Spain	2	S	n=10,11	MP	9		MILP	A(MH)
Hadi-Vencheh and Mohamad-ghasemi (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 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

Table II-5. (continued)

References	**Industrial sector**	**Country**	**# Case studies**	**Planning approach**	**Entities (n)**	**Generation approach**	**Layout candidates**	**Layout evaluation approach**	**Mathematical model**	**Solution approach**
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, and Orejuela (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).

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 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, 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 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 based 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 15, 2020. In the meantime, several new studies on the FLP problem have appeared (Liu et al. 2020; Wan et al. 2020; Yiyong Xiao et al. 2020; Kovács 2020; Ahmadi-Javid and Ardestani-Jaafari 2020) which corroborates the growing 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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CAPÍTULO III

OVERVIEW OF DYNAMIC FACILITY LAYOUT PLANNING AS A SUSTAINABILITY STRATEGY

Este capítulo ha sido publicado en la revista *Sustainability*, con el título “Overview of Dynamic Facility Layout Planning as a Sustainability Strategy”, en el volumen 12(9), 8227, siendo sus autores, Pablo Alberto Pérez Gosende, Josefa Mula y Manuel Díaz-Madroñero.

CAPÍTULO III

OVERVIEW OF DYNAMIC FACILITY LAYOUT PLANNING AS A SUSTAINABILITY STRATEGY

1 Introduction

The facility layout problem (FLP) is a well-known design problem that deals with the physical arrangement process of all the production factors that comprise the production system insofar as the organization's strategic objectives are adequately and efficiently met. Within the business operations strategies framework, the FLP is considered one of the most important design decisions (Ghassemi Tari & Neghabi, 2015; Kheirkhah & Bidgoli, 2016). It also has a significant impact on the efficiency and productivity level of manufacturing systems (Altuntas & Selim, 2012; Ku et al., 2011; Navidi et al., 2012), and has, therefore, become a widely discussed topic in the scientific literature since the second half of the 20th century (Hosseini-Nasab et al., 2018). To date, however, its contribution to sustainability within the supply chain management framework is not sufficiently highlighted in the literature.

Although sustainable supply chain management (SSCM) is a relatively new concept (Carter & Rogers, 2008), it has increasingly drawn the attention of business and academia (Barbosa-Póvoa et al., 2018; Carter & Washispack, 2018; V. Roy et al., 2018; Tonelli et al., 2013). Sustainability has been interpreted by industry and scientific literature with different terms and approaches (Sánchez-Flores et al., 2020). Nevertheless, the common point in these definitions is their consideration of three fundamental pillars, namely economic, environmental, and social, which have become the so-called triple bottom line of sustainability (Carter & Rogers, 2008; Ford & Despeisse, 2016; Kamble et al., 2018; Khuntia et al., 2018).

The environmental dimension of sustainability lies in the conservation of the natural environment and the conscious use of its resources so that they remain for future generations (Roy et al., 2020). The social dimension is related to human capital and actions performed to safeguard its health and safety, respect its rights and ethical principles, and increase social well-being (Morais & Silvestre, 2018). The economic dimension is associated with increasing cost-efficiency, business opportunities, operational stability, and economic well-being (Stindt, 2017).

Due to growing pressure from investors, clients, and governments to reduce the environmental impact of their operations, companies have increased their commitment to incorporating sustainable practices in their operations management (Khuntia et al., 2018; Sánchez-Flores et al., 2020). However, there is still some way to go in the gradual transition from traditional to sustainable supply chains. Opportunities for improvement need to be exploited from all possible angles, and with that goal in mind, to the authors' opinion, introducing the triple bottom line perspective into facility layout planning may result in a significant contribution.

When the layout is planned according to the assumption that demand will remain constant throughout the planning horizon, the problem is known as the static facility layout problem (SFLP). This approach has been recommended for production systems with low rearrangement costs (Moslemipour et al., 2017). However, when a single design is contemplated, it may be impractical in most industrial sectors because it is unlikely that the materials flow remains unchanged over time. Companies need to constantly adapt to changing market needs. To do so, they increase or contract their productive capacity, change or update its technology, create new products and services, and improve or implement new processes. In this context, the need to sufficiently adopt dynamic layouts is almost mandatory (Emami & S. Nookabadi, 2013). With this approach, named the dynamic facility layout problem (DFLP), an optimal layout is adopted for each period so that all the material handling costs and the facilities rearrangement costs are minimized (al Hawarneh et al., 2019; Pournaderi et al., 2019; Turanoğlu & Akkaya, 2018).

A recent study showed that layout planning performed by the dynamic planning approach has been less discussed in the scientific literature (Hosseini-Nasab et al., 2018). Furthermore, since 2012, to the authors' knowledge, there has not been published any other literature review focused on DFLP (Moslemipour et al., 2012). By considering all this, as well as the growing trend in literature review studies on SSCM combined with different related topics (Boar et al., 2020; Ford & Despeisse, 2016; Ghobakhloo, 2020; Kamble et al., 2018; Khuntia et al., 2018; Sánchez-Flores et al., 2020; Tebaldi et al., 2018; Tseng et al., 2019), this article presents an overview of the DFLP literature and its contribution to sustainability in supply chain management from the triple bottom line perspective in the last 10 years (2010–2019).

The remainder of the paper is structured as follows. Section 2 describes the review methodology. Section 3 and Section 4 respectively present the current trends in DFLP formulation and DFLP mathematical modeling. Section 5 discusses which sustainability dimensions in supply chain management have been included in DFLP formulation according to the revised literature. Future research directions are provided in Section 6 and, finally, Section 7 offers the study conclusions.

2 Review Methodology

To accomplish the study objective, we adopted the systematic literature review (SLR) process introduced by Denyer and Tranfield (Denyer & Tranfield, 2009) as it has been effectively proven in other recent studies related to the supply chain management area (Masi et al., 2017; Novais et al., 2019; Zavala-Alcívar et al., 2020). This review methodology includes five steps: (i) Formulating research question(s); (ii) identifying studies; (iii) selecting and evaluating studies; (iv) analyzing and synthesizing; (v) presenting the results and discussion (Denyer & Tranfield, 2009).

As a starting point for our SLR process, the following research questions (RQ) were formulated: (RQ1) What is the current state of knowledge on problem formulation and mathematical modeling, and the solution approach to DFLP in the last decade?; (RQ2) what has DFLP contributed to SSCM from a triple bottom line perspective?; (RQ3) what are the gaps and future research directions that can be identified based upon existing works?

The relevant bibliography was collected considering the scientific articles published in the journals indexed in the Science Citation Index Expanded (SCIE) of the Web of Science (WoS), which is the world's leading scientific citation search and analytical information platform (K. Li et al., 2018). The time window considered was 2010–2019. The employed keywords were: Facility(ies) layout problem; facility(ies) layout design; facility(ies) layout planning; plant(s) layout design; facility(ies) design; facility(ies) planning; dynamic layout; cyclic layout; robust layout; and reconfigurable layout. According to these search criteria, the WoS indicated 59 related scientific articles.

After collecting these papers, their abstracts, methodologies, main results, and conclusions were thoroughly examined to determine whether they were relevant to the research questions. This process was based on the analysis of the following exclusion criteria: (a) Papers beyond the operations management scope; (b) papers in which DFLP was not approached by mathematical optimization models.

As a result of this filtering, the remaining 44 articles were analyzed and synthesized to create a taxonomy that integrated, on the one hand, the key characteristics of the problem formulation, mathematical modeling, and solution approaches to DFLP in the last decade and, on the other hand, the inclusion of elements related to the three SSCM pillars, i.e., economic, environmental, and social. Through the resulting taxonomy, the articles were classified to allow current trends and future research guidelines to be discerned in order to ease sustainability-oriented DFLP decision making.

Figure III-1 shows the scientific journals where the 44 selected articles were published. Only three of them have published approximately 30% of the articles that have addressed the DFLP in the last decade.

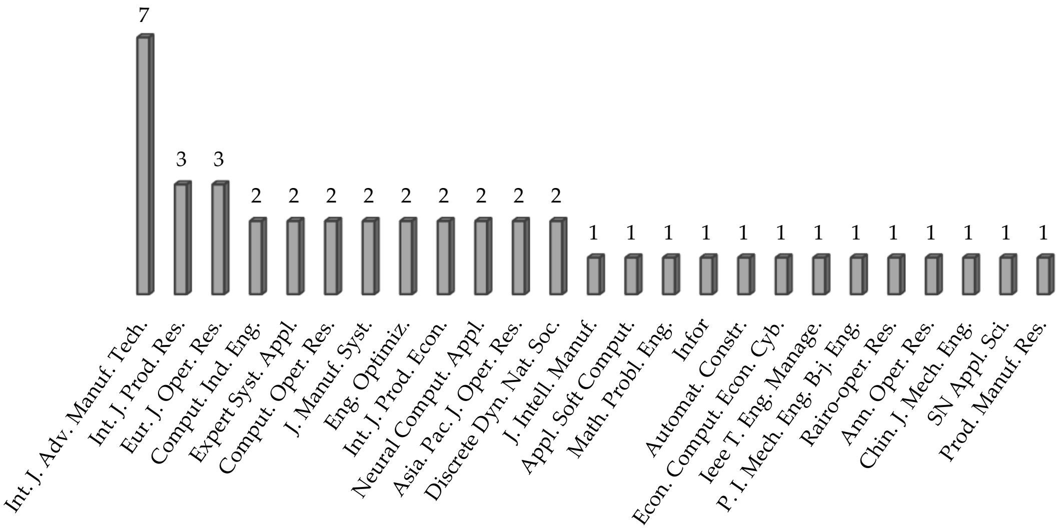

Figure III-1. Distribution of publications by scientific journal.

3 Current Trends in the DFLP Formulation

Dynamic layouts can be classified as flexible, cyclic, or robust layouts. When planning flexible facility layouts, for each time period an optimal layout is designed to minimize both materials handling and re-layout costs. This category has been the one most frequently addressed in the literature (86,36%).

Cyclic layouts were introduced by Kulturel-Konak & Konak (2015) as a special case of dynamic layouts, but have not been researched by any other authors to date. In this approach, the planning horizon is divided into T periods, $t = 1,...,T$. After period T ends, the material flow matrix between departments returns to its initial state in period $t = 1$. In addition to product demand, the area requirements of some departments may also change on a seasonal basis.

In the robust design approach, a single layout is considered for the entire planning horizon with different stochastic demand scenarios. This single design is used for each period and, therefore, there is no rearrangement cost in this approach. A robust layout is not necessarily an optimal layout for a particular time period, but it is suitable over the entire planning horizon since it minimizes the cost of materials handling (Pillai et al., 2011). Therefore, the robust approach has the advantage of not incurring rearrangement costs and the disadvantage of not representing an optimal design for each time period (Peng et al., 2018). This method is appropriate for environments where the cost of rearranging the facilities is high (Moslemipour et al., 2017), such as in the case of companies that require heavy machinery for the development of their operations. Despite its importance, over the last ten years, little coverage has been given to this approach in the DFLP-related literature (11.36%).

Table III-1 shows an overview of how the DFLP has been addressed in the literature. To construct it, the following classification criteria and their respective categories were considered: Problem type: G (greenfield layout design), R (re-layout); Planning phase: B (block layout), D (detailed layout); Planning approach: F (flexible layout, C (cyclic layout), R (robust layout); Number of facilities: S (single-facility), M (multi-facility); Number of floors: S (single-floor), M (multi-floor); Number of departments; Space consideration: B (two-dimensional), T (three-dimensional); Departments shape: R (regular), I (irregular); Departments dimensions: F (fixed), V (flexible); Departments area: E (equal), U (unequal); Material handling configuration: 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).

Table III-1. Overview of the facility layout problem (FLP) considering a dynamic planning approach.

References	**Problem type**	**Planning phase**	**Planning approach**	**Number of facilities**	**Number of floors**	**Number of dept. (n)**	**Space consideration**	**Dept. shape**	**Dept. Dimensions**	**Dept. area**	**Material handling configuration**
Kheirkhah et al. (2015)	G	B	F	S	S	$5 \leq n \leq 60$	B	R	F	E	MRLP
Moslemipour et al. (2017)	G	B	R	S	S	$2 \leq n \leq 9$	B	R	F	E	MRLP
Emami & Nookabadi (2013)	G	B	F	S	S	$4 \leq n \leq 30$	B	R	F	E	MRLP
Al Hawarneh et al. (2019)	G	B	F	M	S	n = 25	B	R	F	E	MRLP
Pournaderi et al. (2019)	G	B	F	S	S	n = 6	B	R	F	E	MRLP
Turanoğlu & Akkaya (2018)	G	B	F	S	S	n = 6,15,30	B	R	F	E	MRLP
Kulturel-Konak & Konak (2015)	G	B	C	S	S	n = 6,12,15	B	R	V	U	OFLP
Pillai et al. (2011)	G	B	R	S	S	n = 5,15,30	B	R	F	E	OFLP
Peng et al. (2018)	G	B	R	S	S	$8 \leq n \leq 125$	B	R	F	E	MRLP
McKendall & Hakobyan (2010)	G	B	F	S	S	$6 \leq n \leq 125$	B	R	F	U	OFLP
Yang et al. (2011)	G	B	F	S	S	n = 10	B	R	F	E	MRLP
Abedzadeh et al. (2013)	G	B	F	S	S	$4 \leq n \leq 12$	B	R	V	U	MRLP
Guan et al. (2012)	G	B	F	S	S	n = 10,20,25	B	R	F	E	MRLP
Jolai et al. (2012)	G	B	F	S	S	n = 6,12	B	R	F	U	OFLP
Kia et al. (2012)	G	B,D	F	S	S	$4 \leq n \leq 10$	B	R	F	E	MRLP
McKendall & Liu (2012)	G	B	F	S	S	$6 \leq n \leq 30$	B	R	F	E	MRLP
Azimi & Saberi (2013)	G	B	F	S	S	n = 6,15,30	B	R	F	U	MRLP
Hosseini & Emami (2013)	G	B	F	S	S	n = 6,15,30	B	R	F	E	MRLP
Kaveh et al. (2014)	G	B	F	S	S	n = 6	B	R	F	E	MRLP
Kia et al. (2013)	G	D	F	S	S	n = 8,10,12	B	R	F	E	MRLP
Mazinani et al. (2013)	G	B	F	S	S	$10 \leq n \leq 20$	B	R	F,V	U	MRLP
Samarghandi et al. (2013)	G	B	F	S	S	$10 \leq n \leq 30$	B	R	F	U	MRLP
Chen (2013)	G	B	F	S	S	n = 6,15,30	B	R	F	E	MRLP
Bozorgi et al. (2015)	G	B	F	S	S	$6 \leq n \leq 30$	B	R	F	E	SRLP
Chen & Lo (2014)	G	B	F	S	S	$6 \leq n \leq 20$	B	R	F	E	MRLP
Hosseini et al. (2014)	G	B	F	S	S	$6 \leq n \leq 30$	B	R	F	E	MRLP
Kia et al. (2014)	G,R	B	F	S	M	$10 \leq n \leq 80$	B	R	F	E	MRLP
Nematian (2014)	G	B	R	S	S	$4 \leq n \leq 15$	B	R	F	U	SRLP

References	Problem type	Planning phase	Planning approach	Number of facilities	Number of floors	Number of dept. (n)	Space consideration	Dept. shape	Dept. Dimensions	Dept. area	Material handling configuration
Pourvaziri & Naderi (2014)	G	B	F	S	S	6 ≤ n ≤ 30	B	R	F	E	MRLP
Derakhshan & Wong (2017)	G	B	F	S	S	n = 8,11,20	B	R	F	U	OFLP
Li et al. (2015)	G,R	B	F	S	S	n = 27	B	R	F	E	MRLP
Ulutas & Islier (2015)	G	B	F	S	S	n = 54	B	R	F	E	MRLP
Zarea Fazlelahi et al. (2016)	G	B	R	S	S	n = 9	B	R	F	E	MRLP
Hosseini & Seifbarghy (2016)	G	B	F	S	S	6 ≤ n ≤ 15	B	R	F	E	MRLP
Pourvaziri & Pierreval (2017)	G	B	F	S	S	n = 8	B	R	F	E	MRLP
Tayal & Singh (2018)	G	D	F	S	S	n = 12	B	R	F	E	SRLP
Kumar & Singh (2017)	G	B, D	F	S	S	n = 5,7,8	B	R	F	E	MRLP
Liu et al. (2017)	G	B	F	S	S	6 ≤ n ≤ 20	B	R	F	U	OFLP
Vitayasak et al. (2017)	G	B	F	S	S	10 ≤ n ≤ 50	B	R	F	U	MRLP
Xiao et al. (2017)	G	B	F	S	S	10 ≤ n ≤ 35	B	R, I	V	U	OFLP
Kulturel-Konak (2017)	G	B	F	S	S	12 ≤ n ≤ 25	B	R	V	U	OFLP
Li et al. (2018)	G	D	F	S	S	n = 12	B	R	F	U	OFLP
Vitayasak & Pongcharoen (2018)	G	D	F	S	S	10 ≤ n ≤ 50	B	R	F	U	MRLP
Wei et al. (2019)	G	D	F	S	S	n = 10	B	R	F	U	OFLP

In the literature, the greenfield layout design has been given greater connotation, although in practice, the problem of existing plants' re-layouts has been more frequent (Kulturel-Konak, 2007). Among the bibliographic sources herein consulted, only 4.55% addressed the last-cited problem (2 articles).

Traditionally, most approaches tackling the facilities layout planning have followed the systematic layout planning methodology (SLP) introduced by (Muther, 1961). A recent study concluded that this was the most appropriate approach to handle facility layout design problems (Sharma & Singhal, 2017). Like most engineering design problems, SLP methodology is based on a hierarchical approach, starting with a block layout phase and followed by a detailed phase (Bukchin & Tzur, 2014; Meller et al., 2010). However, most of the research available in the DFLP context have addressed both phases separately. Only two works have addressed both phases as part of the same problem (Guan et al., 2012; Tayal & Singh, 2018).

Despite the fact that one of the classic principles of facility planning is to obtain the maximum possible use of space inside the industrial plant, the consideration of three-dimensional space in its planning has been scarcely addressed in the context of the DFLP. In fact, all the articles reviewed have considered space only from a two-dimensional point of view.

When planning dynamic layouts, departments may be considered equal-area or unequal-area (Feng & Che, 2018). The selection of discrete or continuous optimization models to generate layout alternatives relies on this assumption (Allahyari & Azab, 2018). The equal-area department problem is usually addressed using discrete optimization models to optimally assign *n* departments to a set of *n* predefined locations (Xiao et al., 2017). Conversely, in the unequal-area layout problem, continuous mathematical models are preferred (Boar et al., 2020; Mazinani et al., 2013; McKendall & Hakobyan, 2010).

Approximately, 64% of the revised literature considered equal-area departments, and the remaining 36% chose the unequal-area approach.

In terms of shape, departments can be regular or irregular (Ahmadi et al., 2017). The first case, which refers to rectangular-shaped departments (Drira et al., 2007; Hosseini-Nasab et al., 2018), has been the most common in the revised literature (98%).

There are two categories of department size: Fixed or flexible (Xiao et al., 2017). In the first case, the width and length of the departments do not vary during the allocation process, while in the second one, they vary in a pre-established interval. Among the articles that handled flexible dimensions, such variability was controlled using aspect ratios, which are the proportion between the longest and shortest side of each department (Hosseini-Nasab et al., 2018).

According to the materials handling system configuration, the MRLP is the most widespread approach in the consulted literature (70.45% of the cases). In contrast, less attention has been paid to the OFLP and the SRLP with 22.73% and 6.82% of the cases, respectively. In the last 10 years, the DFLP has not been addressed for any of the other known configurations.

Most published research has considered the layout design in the single building and/or single floor context. However, large companies often operate on more than one floor, and even in several buildings. Only one work has simultaneously planned a layout for several buildings (al Hawarneh et al., 2019), and only one article has considered several floors (Kia et al., 2014).

4 Current Trends in the Mathematical Modeling of the DFLP

The DFLP has been classified as an NP-hard optimization problem (non-deterministic polynomial time-hard problem) because there is no exact technique that optimally solves the problem in a reasonable polynomial time (Chen & Lo, 2014; Grobelny & Michalski, 2017; McKendall & Hakobyan, 2010). However, despite this degree of complexity, different authors have provided acceptable solutions in realistic calculation times, applying everything from exact techniques to state-of-the-art heuristic algorithms.
Table III-2 shows the characteristics of the modeling approaches to the DFLP identified in the revised literature. Each of the 44 contributions was classified according to the type of mathematical model; the type of objective function: SO (single objective), MO (multi-objective); the demand consideration: C (certain), U (uncertain); the type of data: D (deterministic), N (non-deterministic); the distance metric: R (rectilinear), E (Euclidean), FD (flow path-based distance); and the solution approach: E (exact), A (approximate), S (stochastic), H (hybrid), M (matheuristic). Similarly, for each case, a description of the objective functions is given, as well as the constraints considered in the formulation of the DFLP.

The most widely used mathematical programming approaches in DFLP modeling have been, in decreasing order of frequency: The quadratic assignment problem (QAP) with 45% of the cases; mixed-integer non-linear programming (MINLP) with 20%; mixed-integer linear programming (MILP) with approximately 14%; non-linear programming (NLP) with just over 9%; and linear-integer programming (LIP) with almost 7%. However, fuzzy stochastic programming model (FSPM), and bilevel optimization (BLPM), have also been applied, respectively, to the specific cases of SRLP and MRLP configurations.

The mathematical models generally used have been subject to 18 different types of constraints, of which the most widely used, in order of frequency, are: Area restrictions (93.18%); non overlapping between departments (36.36%); number of material handling devices (11.36%); budget (6.82%); capacity (6.82%); pick up/drop off point locations (6.82%); departments orientation (6.82%); and clearance between departments (6.82%). Moreover, most DFLP optimization models consider a single quantitative objective function that simultaneously involves material handling costs and rearrangement costs. However, for some industrial and service companies, qualitative factors like closeness ratings among departments, layout flexibility or safety issues may be more relevant. Only 31.82% of the revised literature have addressed the DFLP with multi-objective optimization models.

Table III-2. Characteristics of the mathematical models used in the formulation of the dynamic facility layout problem (DFLP).

References	**Type of model[1]**	**Type of objective function**	**Objective function[2]**	**Constraints[3]**	**Demand**	**Type of data**	**Distance metric**	**Solution approach**
Kheirkhah et al. (2015)	BLPM	MO	a,b,g	2,6,15	C	D	R	A
Moslemipour et al. (2017)	QAP	SO	a	2	U	D	R	E,A
Emami & Nookabadi (2013)	QAP	MO	a,b,L	2	C	D	R	A
Al Hawarneh et al. (2019)	LIP	SO	a,b	2,6	C	D	E	A
Pournaderi et al. (2019)	QAP	MO	a,b	1,15	C	D	R	A
Turanoğlu & Akkaya (2018)	QAP	SO	a,b	2	C	D	R	A
Kulturel-Konak & Konak (2015)	MINLP	SO	a,b	2,6	C	D	R	M
Pillai et al. (2011)	QAP	MO	a,b	2	C	D	R	A
Peng et al. (2018)	QAP	SO	a,b	15	U	N	R	A,S
McKendall & Hakobyan (2010)	MILP	SO	a,b	2,6,9	C	D	R	A
Yang et al. (2011)	MILP	SO	a,b	2	C	D	R	A
Abedzadeh et al. (2013)	MILP	MO	a,b,f,L	2,6,8	C	D	R	A
Guan et al. (2012)	QAP	SO	a,b	2	C	D	FD	A
Jolai et al. (2012)	MINLP	MO	a,b,L,M	2,6,7,9	C	D	R	A
Kia et al. (2012)	MINLP	SO	a,b,h	2,3	C	D	R	E,A
McKendall & Liu (2012)	QAP	SO	a,b	2	C	D	R	A
Azimi & Saberi (2013)	QAP	SO	a,b	2	C	D	R	A
Hosseini & Emami (2013)	QAP	SO	a,b	2	C	D	R	A
Kaveh et al. (2014)	QAP	SO	a,b	2	U	D,N	R	A,S
Kia et al. (2013)	MINLP	SO	a,b,h	2,3,12,13	C	D	R	E,A
Mazinani et al. (2013)	MILP	SO	a,b	2,6,8,9	C	D	R	A
Samarghandi et al. (2013)	NLP	MO	a,b,L	2	U	D,N	R	A
Chen (2013)	QAP	SO	a,b	2	C	D	R	A
Bozorgi et al. (2015)	QAP	MO	a,b,L,M	2	C	D	E	A
Chen & Lo (2014)	QAP	MO	a,b,L	2	C	D	R	A
Hosseini et al. (2014)	QAP	SO	a,b	2	C	D	R	A
Kia et al. (2014)	MILP	SO	a,b,h	2,3,11,12,13, 14	C	D	R	A
Nematian (2014)	FSPM	SO	a	2,6,10	C	N	R	H
Pourvaziri & Naderi (2014)	QAP	SO	a,b	2	C	D	R	A
Derakhshan & Wong (2017)	MINLP	SO	a,b	2,6	C	D	R	A
Li et al. (2015)	MINLP	SO	a,b	1,2	C	D	R	A
Ulutas & Islier (2015)	QAP	SO	a,b	2	C	D	R	A
Zarea Fazlelahi et al. (2016)	QAP	SO	a,b	2	U	D	R	A
Hosseini & Seifbarghy (2016)	NLP	MO	a,b,g	2,15,18	C	D	R	A

References	Type of model[1]	Type of objective function	Objective function[2]	Constraints[3]	Demand	Type of data	Distance metric	Solution approach
Pourvaziri & Pierreval (2017)	QAP	MO	a,b,g,e	2,4,7,15	U	D,N	R	A
Tayal & Singh (2018)	QAP	MO	a,b,d,i,L	2	U	N	R	A
Kumar & Singh (2017)	QAP	SO	a,b	16	C	D	R	A
Liu et al. (2017)	MINLP	SO	a,b	2,6	C	D	R	H
Vitayasak et al. (2017)	LIP	SO	a,b	2,6,10	U	D,N	R	A
Xiao et al. (2017)	MILP	SO	a,b	2,5,6,17	C	D	R	A
Kulturel-Konak (2017)	MINLP	SO	a,b	2,5,6,7	C	D	R	M
Li et al. (2018)	NLP	MO	a,b,j,k, N	1,2,6	C	D	R	A
Vitayasak & Pongcharoen (2018)	LIP	SO	c	2,6	U	D	R	A
Wei et al. (2019)	NLP	MO	a,b,N	2,6,10	C	D	R	A

[1] Type of model: QAP (quadratic assignment problem), BLPM (bi-level programming model), LIP (linear-integer programming), MILP (mixed-integer linear programming), MINLP (mixed-integer non-linear programming), NPL (non-linear programming), FSPM (fuzzy stochastic programming model).

[2] In describing the objective functions, lowercase letters stand for minimization objectives and uppercase letters indicate maximization objectives: a (materials handling cost), b (rearrangement cost), c (flow distance), d (transport time), e (work in process), f (aspect ratio), g (costs related to the material handling equipment), h (costs related to machinery operations), i (risk level associated with the hazardous materials and waste path), j (lost opportunity costs), k (occupational health/safety risks), L (closeness ratings among departments), M (distance requests among departments), N (area utilization ratio).

[3] Constraints: 1 (budget), 2 (area), 3 (capacity), 4 (work in process), 5 (distance), 6 (non-overlapping), 7 (pick up and drop off location points), 8 (aspect ratio), 9 (orientation), 10 (clearance among departments), 11 (demand satisfaction), 12 (machine availability), 13 (location of machines), 14 (material flow conservation), 15 (number of material handling devices), 16 (number of machines per department), 17 (symmetry-breaking constraints), 18 (transport time).

The solution approaches applied to the DFLP can be generally categorized into exact, approximate, stochastic, and intelligent (Hosseini-Nasab et al., 2018). In addition, matheuristic and hybrid approaches have been added to these categories, as they have been identified among the solution approaches employed in the revised literature.

Given the NP-hard nature of the problem, very few authors have managed to find optimal solutions, and those who have attempted to have used the branch and bound method (Kia et al., 2012, 2013) or dynamic programming for a few machines or departments (Moslemipour et al., 2017). Therefore, most authors have considered seeking suboptimal solutions for larger problems by applying heuristic algorithms. Among these, the most popular methods have been metaheuristic algorithms. In the reviewed literature, 17 of these algorithms were applied to solve DFLP optimization models, of which the most frequent were simulated annealing, genetic algorithms, particle swarm optimization, variable neighborhood search, and tabu search with 16, 13, 6, 5, and 4 papers, respectively. A summary of the above analysis is shown in Table III-3.

It is also important to emphasize the growing tendency to focus the DFLP analysis on more powerful resolution algorithms applied in fictitious problems or classic test problems that do not respond to real-world case studies. Conversely, the following works have addressed the problem in several industries: Footwear (Ulutas & Islier, 2015); textile

(Xiao et al., 2017); metalworking (Li et al., 2018); construction (Al Hawarneh et al., 2019).

Table III-3. Review of metaheuristic algorithms[1] used in the resolution of the DFLP.

References	i	ii	iii	iv	v	vi	vii	viii	ix	x	xi	xii	xiii	xiv	xv	xvi	xvii
Kheirkhah et al. (2015)			√														
Moslemipour et al. (2017)	√																
Emami & S. Nookabadi, 2013)	√	√									√						
Pournaderi et al., 2019)	√	√															
Turanoğlu & Akkaya, 2018)	√														√		
Turanoğlu & Akkaya, 2018)	√																
Pillai et al., 2011)	√																
Peng et al., 2018)		√															
McKendall & Hakobyan, 2010)					√												
Yang et al., 2011)		√															
Abedzadeh et al., 2013)				√													
Guan et al., 2012)				√													√
Jolai et al., 2012)			√														
Kia et al., 2012)	√																
McKendall & Liu, 2012)					√												
Azimi & Saberi, 2013)			√														
Hosseini-Nasab & Emami, 2013)	√		√														
Kaveh et al., 2014)	√	√															
Kia et al., 2013)	√																
Mazinani et al., 2013)		√															
Samarghandi et al., 2013)		√	√	√	√												
Chen, 2013)						√											
Bozorgi et al. (2015)					√												
Chen & Lo (2014)						√											
(Hosseini et al. (2014)	√			√								√					
Kia et al. (2014)		√															
Pourvaziri & Naderi (2014)	√	√															
Derakhshan Asl & Wong (2017)			√														
Li et al. (2015)	√																
Ulutas & Islier (2015)								√									
(Zarea Fazlelahi et al. (2016)		√															
Hosseini & Seifbarghy (2016)													√				
Pourvaziri & Pierreval (2017)	√																
Tayal & Singh (2018)	√								√								
Vitayasak et al. (2017)		√								√							
Xiao et al. (2017)														√			
Kulturel-Konak 2017)	√			√													
Li et al. (2018)							√										
Vitayasak & Pongcharoen (2018)		√														√	
Wei et al. (2019)		√															

[1] i (simulated annealing), ii (genetic algorithms), iii (particle swarm optimization), iv (variable neighborhood search), v (tabu search), vi (ant colony optimization), vii (artificial bee colony algorithm), viii (artificial immune system), ix (firefly algorithm), x (backtracking search algorithm), xi (differential evolution), xii (imperialist competitive algorithm), xiii (water flow-like algorithm), xiv (problem evolution algorithm), xv (bacterial foraging optimization), xvi (teaching-learning-based optimization), xvii (electromagnetism-like mechanism).

5 Contributions of dynamic facility layout planning to supply chain sustainability

This section discusses how research into dynamic facility layout planning has addressed the triple bottom line of SSCM.

As shown in Table III-4, the 44 analyzed articles focused mainly on the economic dimension, and only 9% simultaneously addressed socio-economic aspects. Aspects related to the environmental dimension of sustainability were not explicitly identified in the revised literature.

Table III-4. Aspects related to the economic (E) and social (S) dimensions of sustainability in the formulation of DFLP.

References	E	S	Description
Kheirkhah et al. (2015)	√		(1) Minimization of materials handling costs and facility rearrangement costs. (2) Minimization of the need for new material handling devices during peak demand periods. (3) Minimization of the number of idle material handling devices during low demand periods.
Moslemipour et al. (2017)	√		(1) Minimization of materials handling costs.
Emami & Nookabadi (2013)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Al Hawarneh et al. (2019)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Pournaderi et al. (2019)	√		(1) Minimization of materials handling costs and facility rearrangement costs. (2) Reduction in the number of material handling devices needed. (3) Consideration of budget limitations when planning the layout design.
Turanoğlu & Akkaya (2018)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Kulturel-Konak & Konak (2015)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Pillai et al. (2011)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Peng et al. (2018)	√		(1) Minimization of materials handling costs and facility rearrangement costs. (2) Reduction in the number of material handling devices needed.
McKendall & Hakobyan (2010)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Yang et al. (2011)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Abedzadeh et al. (2013)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Guan et al. (2012)	√		(1) Minimization of the materials handling costs and facility rearrangement costs.
Jolai et al. (2012)	√	√	(1) Minimization of materials handling costs and facility rearrangement costs. (2) Maximization of distance requests among departments to avoid exposing workers to occupational health/safety risk factors like noise, heat or vibration.

References	E	S	Description
Kia et al. (2012)	√		(1) Minimization of materials handling costs and facility rearrangement costs. (2) Minimization of machinery operations costs.
McKendall & Liu (2012)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Azimi & Saberi (2013)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Hosseini & Emami (2013)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Kaveh et al. (2014)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Kia et al. (2013)	√		(1) Minimization of materials handling costs and facility rearrangement costs. (2) Minimization of machinery operations costs.
Mazinani et al. (2013)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Samarghandi et al. (2013)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Chen (2013)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Bozorgi et al. (2015)	√	√	(1) Minimization of materials handling costs and facility rearrangement costs. (2) Maximization of distance requests among departments to avoid exposing workers to occupational health/safety risk factors like noise or vibration.
Chen & Lo (2014)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Hosseini et al. (2014)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Kia et al. (2014)	√		(1) Minimization of materials handling costs and facility rearrangement costs. (2) Minimization of machinery operations costs.
Nematian (2014)	√		(1) Minimization of materials handling costs.
Pourvaziri & Naderi (2014)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Derakhshan & Wong (2017)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Li et al. (2015)	√		(1) Minimization of materials handling costs and facility rearrangement costs. (2) Consideration of budget limitations when planning the layout design.
Ulutas & Islier (2015)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Zarea Fazlelahi et al. (2016)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Hosseini & Seifbarghy (2016)	√		(1) Minimization of materials handling costs, the machines rearrangement costs, and the fixed costs related to the material handling equipment.
Pourvaziri & Pierreval (2017)	√		(1) Minimization of materials handling costs (including costs generated by the transportation devices while traveling empty) and machines rearrangement costs. (2) Minimization of work in process.
Tayal & Singh (2018)	√	√	(1) Minimization of materials handling costs, machines rearrangement costs and transport time. (2) Minimization of the risk level associated with hazardous materials and waste paths.
Kumar & Singh (2017)	√		(1) Minimization of materials handling costs and the rearrangement costs. (2) Reduction in the number of machines per department.

References	E	S	Description
Liu et al. (2017)	√		(1) Minimization of the materials handling costs and facility rearrangement costs.
Vitayasak et al. (2017)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Xiao et al. (2017)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Kulturel-Konak (2017)	√		(1) Minimization of materials handling costs and facility rearrangement costs.
Li et al. (2018)	√	√	(1) Minimization of materials handling costs, facility rearrangement costs (including relocation and setup costs), and lost opportunity costs during the relocation time. (2) Consideration of budget limitations when planning the layout design. (3) Maximization of the area utilization ratio in the production facility. (4) Implementation of the safe and comfort human-machine interaction. (5) Minimization of the risk of workers' physical and mental damage.
Vitayasak & Pongcharoen (2018)	√		(1) Minimization of the flow distance, which has a significant impact on materials handling costs.
Wei et al. (2019)	√		(1) Minimization of materials handling costs and the equipment replacement cost. (2) Maximization of the area utilization ratio in the production facility.

The optimization of materials handling cost, which equals the sum of the flow-weighted transportation costs between each pair of departments, was the most frequently addressed economic goal when planning facility layouts. Materials handling cost is primarily an efficiency indicator, and one that is difficult to meaningfully transform into a monetary unit (Hathhorn et al., 2013) and yet, for manufacturing companies, it is reported to account for 20–50% of the total operational costs (Tomkins et al., 2010). Thus, when engaging layout planning decisions, analysts often prioritize the proximity among those departments, machines, or workstations with a greater material flow intensity to reduce the total production costs and contribute to increase organization competitiveness.

Another economic goal that is frequently considered in the DFLP decision-making context was minimizing the cost of reallocating facilities, workstations, and/or machines between consecutive planning periods when adopting flexible or cyclic layouts (95% of the revised literature).

Aspects related to the social dimension of sustainability in the reviewed literature were related mostly to ensuring safer working environments. In this vein, some authors considered satisfying the minimum safety distance requirements between departments to avoid workers' exposure to safety/occupational health risk factors, such as noise, heat, or vibrations (Bozorgi et al., 2015; Jolai et al., 2012), while others considered designing waste disposal routes or reducing the associated risks in handling hazardous materials (Tayal & Singh, 2018). Another significant contribution was to contemplate a synthetic index to evaluate the physical and psychological loads to which the workers could be exposed in different layout scenarios, apart from their working posture and the level of difficulty to perform tasks (Li et al., 2018).

Although no aspects related to the environmental dimension of sustainability are explicitly identified in the revised literature, it is important to point out that certain elements of the environmental dimension are favored implicitly when developing an efficient layout plan. For instance, in an attempt to reduce the distance covered by the workflow to minimize material handling costs, a contribution to reducing fuel and energy use in material handling devices could be made.

6 Guidelines for future research

In the current industrial context, where transitioning from traditional cost-oriented supply chain to sustainable supply chain is almost mandatory, considering static production conditions such as constant customer demand throughout the planning time horizon is no realistic assumption, but has been the most frequently addressed planning strategy in the scientific literature related to FLP (Hosseini-Nasab et al., 2018). To help to bridge this gap, this article provides some current trends and future research guidelines.

In the revised literature, plant layout decisions in dynamic environments focused exclusively on two of the three performance dimensions that make up the triple bottom line of sustainability: Economic and social. Consequently, future research should address how to incorporate aspects related to the environmental dimension of sustainability (e.g., savings in electricity and fuel use) into the process of designing and evaluating greenfield and brownfield layout plans.

It is also important to stress that despite attempts being made to consider the social dimension of sustainability in dynamic facility layout planning, the authors believe that they are still scarce. Further efforts need to be made include an analysis of physical, chemical, biological, and ergonomic risks when determining closeness priorities among departments machines and workstations. In the same vein, it is worth analyzing to what extent allocation over the industrial floorspace of the elements making up the production/service system could contribute to the humanization of work and to favor workers' (and costumers') well-being, self-fulfillment, and self-esteem; increase intrinsic motivation; reduce physical and mental stress; avoid exposure to psychosocial risks. Undoubtedly, this is a gap that future research should continue to bridge.

When planning flexible and cyclic layouts, future research should consider the opportunity costs incurred while the re-layout is being projected. Future papers should pay more attention to brownfield layout planning.

As most of the scientific literature in the DFLP context deals with block layout and detailed layout separately, it would be more useful in practice for operations managers to consider both phases as part of the same problem with a hierarchical approach. Future research should also prioritize modeling real-world case studies to help to bridge the gap of the limited application of FLP research in practice, as previously noted by Meller et al. (2010).

Although one of the classic layout planning principles is space optimization, no research has considered the three-dimensional space to deal with the DFLP. Similarly, future research could model the DFLP by considering material handling system configurations that have not yet been addressed in that context, such as the DRLP, PRLP, and LLP.

Although the research works herein analyzed have generally considered the DFLP in the single building and single floor contexts, large companies often consider more than one property and several floors to undertake their operations. This represents a challenge for DFLP mathematical modeling and suggests a gap that future works must bridge. Likewise, most DFLP optimization models seek to minimize a single objective function of a quantitative nature. Yet in practice, the consideration of quantitative and qualitative factors simultaneously can be decisive for many manufacturing or service enterprises. This certainly implies that the scientific community should pay more attention to the multi-objective mathematical modeling of the DFLP. To this end, the development and application of more powerful matheuristic approaches could constitute a promising resolution strategy.

7 Conclusions

In this study, we promoted facility layout planning by taking dynamic environments as an alternate strategy to contribute to supply chain sustainability. Yet despite the popularity of this topic among researchers in the operations management field, we found that knowledge gaps still have to be bridged regarding the balanced inclusion of the dimensions making up the so-called triple bottom line. To date, the scientific community's contributions to decision making in the DFLP context have concentrated primarily on the economic dimension of sustainability, and on the social dimension to a lesser extent. We found no explicit mention of the environmental dimension in the reviewed literature.

The DFLP deals with the search for a set of feasible facility layouts through multiple time periods by minimizing the materials handling and rearrangement costs. To our knowledge reaches, since (Moslemipour et al., 2012), there has not been published any literature review focused on DFLP. Thus, this study has presented a literature review on the DFLP considering a time window from 2010 to 2019. Furthermore, we depicted to what extent recent research in the DFLP context has contributed to supply chain sustainability by addressing its three dimensions of performance: Economic, environmental, and social.

The relevant bibliography was collected from the WoS database considering only journal articles. Such publications were filtered based on the authors' critical judgments, discarding those that did not address the problem from the field of operations management. The 44 selected papers were analyzed and synthesized to allow the discerning of current trends and future research guidelines.

In the DFLP-related literature, the greenfield layout design has been given greater connotation than the re-layout problem. Most of the revised researches have addressed the block and detailed phases separately. Multi-row layout problem is the most widespread approach used according to the materials handling system configuration. Most published research has considered the layout design in a single building and a single floor. The most widely used mathematical programming approaches in DFLP modeling have been the quadratic assignment problem and mixed-integer programming. More than two thirds of the revised literature have addressed the DFLP with single-objective optimization models. The applied solution approaches can be categorized into exact, approximate, stochastic, matheuristic, and hybrid methods. Given the NP-hard nature of the DFLP, most authors have tried to solve it by applying metaheuristic algorithms. Among these, the most popular methods were the simulated annealing, genetic algorithms, particle swarm optimization, and variable neighborhood search. Additionally, there is a growing tendency to focus the DFLP analysis on more powerful resolution algorithms applied in fictitious problems that do not respond to real-world case studies.

When making decisions related to facility layout planning, there are several recommendations that operations managers can consider based on this review study. On the one hand, they can understand the unfeasibility of maintaining static layout configurations if they operate in rapidly changing markets. It is possible that by adopting flexible layouts, increased labor productivity and production processes efficiency could compensate for the annual rearrangement costs, which would translate into lower total production costs and the possible adoption of competitive advantages that would lead to higher levels of profitability. Even in the case that the estimated re-layout costs are high due to the operation of heavy machinery, to cite an example, the planning of a robust plant layout could generate the same effect in the medium term. Therefore, diagnosing the productivity and efficiency improvement opportunities associated with the organization of the elements that make up the production or service systems in the physical space can be a crucial strategy to achieve the economic sustainability of companies' operations in the medium and long term.

On the other hand, the results of this study could encourage practitioners to facilitate their layout decision-making from a holistic perspective, not only considering the economic factor but also elements of environmental and social nature, for this way to contribute to sustainable supply chain management. That could also aid in enhancing the company's reputation among current and potential customers, investors, suppliers, government entities, and other interested parties already committed to sustainable development.

Despite its significance, the scientific community and operations management professionals should be aware that this study is not exempt from certain limitations. According to the exclusion criteria indicated in Section 2, this review study focused only on those papers that have addressed DFLP through mathematical optimization models. In this sense, other approaches could also be employed for generating feasible solutions to DFLP, such as analytical approaches based on expert's knowledge or computer-aided planning tools. Another limitation of the study was the collection of research articles published in journals indexed in WoS database. Here, the search could be extended to other highly visible scientific databases such as Scopus, EBSCO, and IEEE Xplore, among others.

The guidelines for future research here identified are: (i) To consider the opportunity costs incurred when planning flexible and cyclic layouts; (ii) to contemplate the brownfield layout planning; (iii) to consider the block layout and the detailed layout phases as part of the same problem with a hierarchical approach; (iv) to prioritize modeling real-world case studies to bridge the gap of the limited application of FLP research in practice; (v) to consider the three-dimensional space when dealing with the DFLP; (vi) to develop material handling system configurations that have not yet been addressed in the DFLP context, such as the DRLP, PRLP, and LLP; (vii) to address the DFLP in multi-building and multi-floor contexts; (viii) to formulate multi-objective mathematical models of the DFLP considering quantitative and qualitative factors simultaneously; (ix) to develop and to apply more powerful matheuristic approaches as solution strategies to those models; (x) to integrate the economic, environmental, and social sustainable aspects into DFLP models.

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CAPÍTULO IV

REFERENCE OPTIMISATION MODELS FOR FACILITY LAYOUT PLANNING IN THE METAL-MECHANIC INDUSTRY

Este capítulo es una extensión de la ponencia titulada "Reference optimisation models for facility layout planning in the metal-mechanic industry", presentada en el evento 16th International Conference on Industrial Engineering and Industrial Management (ICIEIM) – XXVI Congreso de Ingeniería de Organización (CIO2022) celebrado durante los días 7 y 8 de julio de 2022 en la ciudad de Madrid, España. La ponencia está siendo revisada para su eventual inclusión en las actas del congreso, las que serán publicadas en la serie de libros *Lectures Notes on Data Engineering and Communications Technologies* de la editorial Springer (ISSN 2367-4520, Print ISSN 2367-4512), siendo sus autores Pablo Alberto Pérez Gosende, Josefa Mula y Manuel Díaz-Madroñero.

CAPÍTULO IV

REFERENCE OPTIMISATION MODELS FOR FACILITY LAYOUT PLANNING IN THE METAL-MECHANIC INDUSTRY

1 Introduction

Facility layout planning (FLP) involves the process of finding the best arrangement scheme for the elements making up the production system so that certain relevant qualitative and quantitative factors are satisfied (Pérez-Gosende et al., 2021). Given its importance and its impact on organisations' productivity and competitiveness, FLP is an important stream of research in the production management and industrial engineering field (Hosseini-Nasab et al., 2018). However, contributions to solve FLP have barely been applied in practice (Meller et al., 2010). This is mainly because most of the contributions available in the literature have concentrated on finding solutions to the problem by considering test instances or hypothetical case studies (Pérez-Gosende et al., 2020, 2021).

The situation described above particularly affects metal-mechanic industries. A recent review has shown that of the 232 articles indexed in the Web of Science (WoS) for the 2010-2019 time window, approximately 20% have addressed real case studies, of which only five have dealt with case studies in the metal-mechanic sector (Pérez-Gosende et al., 2021).

In this context, the present article seeks to analyse optimisation models that can constitute a reference framework for creating a new optimisation model that facilitates layout planning decisions in metal-mechanic companies.

The metal-mechanic industry was chosen as the focus of this research because its broad scope (Pérez-Gosende et al., 2017) makes it a fundamental link in the productive matrix of each country since, in addition to supply machinery and inputs to other industries or economic activities, it generates sources of employment with a high level of qualification.

The chapter is organised as follows. Section 2 presents the strategy to select reference optimisation models, as well as the considered inclusion criteria. Section 3 shows the selected models description, its notation and assumptions. Section 4 presents a comparative analysis between the selected reference models. Finally, Section 5 ends with the conclusions drawn from the study.

2 Collection of reference models

The starting point to identify relevant reference models was the literature review by Pérez-Gosende et al. (2021). It includes an analysis of the mathematical optimisation models for the different FLP variants in 209 research articles of the 232 articles published in the 2010-2019 time window in the journals indexed in the WoS. The purpose is to identify good practices in formulating FLP as a mathematical optimisation problem that can: serve as a reference to formulate a new optimisation model to fit the operating conditions of the metal-mechanic industries; and facilitate FLP decision making for these companies in practice.

When modelling the FLP as an optimisation problem, it is possible to consider that departments have the same area or have unequal areas (Liu et al., 2020). The first case, usually modelled by discrete optimisation models such as the quadratic assignment problem (QAP) (Loiola et al., 2007), applies to very few real manufacturing systems. Specifically, planning the layout in the metal-mechanical sector assuming equal-area departments when they are not can generate solutions with total material handling costs (TMHC) significantly lower than those incurred in reality. Hence, it is crucial to consider the departments' actual dimensions according to the operations that will take place in them. In those cases considering unequal-area departments when formulating the FLP, optimisation models allowing layout representation in the continuous space are generally used (Mazinani et al., 2013; McKendall & Hakobyan, 2010), enabling operating conditions simulation closer to reality.

Taking into account the above-mentioned arguments, the inclusion criteria considered in the models' selection were to: (1) be recently published (time window: from 2010 to date); (2) include elements aligned with the operating conditions of metal-mechanic industries, such as rectangular, unequal-area and free-oriented departments; and (3) address the plant layout representation in the continuous space.

The selected reference models were then characterised according to the following analysis criteria: a) planning approach; b) planning phase; c) departments' dimensions; d) material handling configuration; e) location of pick-up/drop-off (P/D) points; f) representation technique used to allocate departments in the continuous space; g) model type; h) objective function type; and i) objective function description.

3 Reference models

The five selected benchmark optimisation models by applying the inclusion criteria were:

- Model A: Meller et al. (2010)
- Model B: McKendall & Hakobyan (2010)
- Model C: Mazinani et al. (2013)
- Model D: Abedzadeh et al. (2013)
- Model E: Jolai et al. (2012)

The assumptions of the models are as follows:

i. Product demands are known and static throughout the planning horizon (for model A) or vary over time for each time period making up the planning horizon (for models B, C, D and E).
ii. The material flow intensities between departments are known for each time period.
iii. The facility's dimensions are known and remain fixed over the entire planning horizon.
iv. Departments are laid out considering a continuous representation of the plant floor.
v. The number of departments required for production processes to operate normally is known.
vi. Departments may adopt horizontal or vertical orientations.
vii. Departments are rectangular shaped with unequal areas and must fit in the available area of the plant without them overlapping.
viii. Department areas are fixed for each period but may vary from one period to another (for model B, C and D).
ix. A maximum aspect ratio is used for the purposes of controlling department shapes (for model C and D).
x. Departments are assigned in parallel bays with varying widths. If a department is assigned to a bay, it must be completely filled (for model C and D).
xi. In each department, a finite set of ordering schemes can be generated according to the analyst's preference (for model A)
xii. Each department has an input and output point through which the receipt and dispatch of materials take place. These points are located at the department

centroid (for models B, C and D) or at the department boundaries (for model A and E).

The notation used in the models are presented in Table IV-1.

Table IV-1. Notation used in reference models' formulation.

Indices:		Models
i, j	Departments ($i, j = 1, \ldots, N$)	A, B, C, D,E
k	Alternative department designs ($k = 1, \ldots, K$)	A
r	Deparment orientation ($r = 1, \ldots, 4$)	A
t	Time periods ($t = 1, \ldots, T$)	B, C, D, E
m	Image (m = 0, 1)	A
q	Bays ($q = 1, \ldots, B_t$)	C, D
$\pm$	Pair of sequences	A
Parameters:		
f_{ij}	Material flow between departments *i* and *j*	A
f_{tij}	Material flow between departments *i* and *j* in time period *t*	C, D
C_{tij}	Cost to transport materials a unit distance (m) between department *i* and *j* in time period *t*	B, C, D, E
RC_{ti}	Fixed cost of rearranging department *i* at the beginning of time period *t*	B, C, D, E
VRC_{ti}	Variable cost of rearranging department *i* at the beginning of time period *t*	C, D
L^x, L^y	Length of the plant floor along the x- and y-axis direction	A, B, C, D
Sh_{ti}	Shorter side length of department *i* in time period *t*	B, E
Lg_{ti}	Longer side length of department *i* in time period *t*	B, E
l^x_{ikrm}, l^y_{ikrm}	Length of department *i* along x- and y-axis direction according to the design *k* in the orientation *r* and image *m*	A
$\Delta^{Ix}_{ikrm}, \Delta^{Iy}_{ikrm}$	Distance along x- and y-axis direction of the input point from the lower left-hand corner of department *i* with design k in orientation *r* and image *m*	A
$\Delta^{Ox}_{ikrm}, \Delta^{Oy}_{ikrm}$	Distance along x- and y-axis direction of the output point from the lower left-hand corner of department *i* with design k in orientation *r* and image *m*	A
B_t	Maximum number of parallel bays in time period *t*	C, D
a_{ti}	Area requirement of department *i* in time period *t*	C, D
α_{ti}	Aspect ratio of department *i* in time period *t*	C, D
α^*_{ti}	Best aspect ratio of department *i* in time period *t*	C, D
$l^{max}_{ti} = \min\{L^x, \sqrt{\alpha_{ti} a_{ti}}\}$	Maximum permissible side length of department *i* in time period *t*	C, D
$l^{min}_{ti} = \sqrt{\frac{a_{ti}}{\alpha_{ti}}}$	Minimum permissible side length of department *i* in time period *t*	C, D
AV_{tij}	Adjacency value (0–5) between workcells *i* and *j* at the beginning of time period *t*	E
DR_{tij}	Distance rating between department *i* and department *j* in the beginning of time period *t*	E
DO_{ti} =	$\begin{cases} 0\ if \text{ department } i \text{ in time period } t\ can\ have\ any\ orientation \\ 1\ if \text{ department } i \text{ in time period } t\ is\ restricted\ to\ horizontal\ orient \\ 2\ if \text{ department } i \text{ in time period } t\ is\ restricted\ to\ vertical\ orientati \end{cases}$	B
Ort_{ti} =	$\begin{cases} 0\ if \text{ department } i \text{ in time period } t\ can\ have\ free\ orientation \\ 1\ if \text{ department } i \text{ in time period } t\ is\ restricted\ to\ horizontal\ orient \\ -1\ if \text{ department } i \text{ in time period } t\ is\ restricted\ to\ vertical\ orientc \end{cases}$	E

Decision variables:		
dp^x_{ij}, dp^y_{ij}	Rectilinear distance along the x- and y-axis direction from output point of department *i* to input point of department *j*	A
dc^x_{tij}, dc^y_{tij}	Horizontal and vertical distances between the centers of departments *i* and *j* in time period *t*	B, C, D, E
ds_{ti}	Distance between P/D point and centroid coordinate of department *i* in time period *t*	E
l^x_i, l^y_i	Length of deparment *i* in the x- and y-axis direction	A
l^x_{ti}, l^y_{ti}	The length of department *i* along the x- and y-axis direction in time period *t*	B, C, D, E
h_{tiq}	Height of department *i* in bay *q* in time period *t*	C, D
$\Delta^{Ox}_i, \Delta^{Oy}_i$	Distance along the x- and y-axis direction of the output point from the lower left-hand corner of department *i*	A
$\Delta^{Ix}_i, \Delta^{Iy}_i$	Distance along the x- and y-axis direction of the input point from the lower left-hand corner of department *i*	A
(v^x_i, v^y_i)	Coordinates of the lower left-hand corner of department *i* along the x- and y-axis direction	A
(c^x_{ti}, c^y_{ti})	Coordinates of the centroid of department *i* in time period *t*	B, C, D, E
O^x_i, O^y_i	Coordinate of the output point of department *i* along the x- and y-axis direction	A
I^x_i, I^y_i	Coordinate of the input point of department *i* along the x- and y-axis direction	A
p^x_{ti}, p^y_{ti}	The amount of horizontal and vertical movement for department *i* from time period *t*-1 to *t*	C, D
w_{tq}	Width (the length in the x-axis direction) of bay *q* in time period *t*	C, D
w'_{tq}	Width of department *i* in bay *q* in time period *t*	D
co_{tij}	The length of common boundary between department *i* an *j* in time period *t*	D
co'_{tij}	It is equal to product of co_{tij} and ad_{tij}	D
(up^x_{ti}, up^y_{ti})	Coordinates of the northeast corner of department *i* in time period *t*	D
$(low^x_{ti}, low^y_{ti}$	Coordinates of the southwest corner of department *i* in time period *t*	D
$z^{\pm}_{ij}$	Binary variable determining the order of departments *i* and *j* in the sequence pair ±	A
af_{tij}	Adjacency factor between departments *i* and *j* at the beginning of time period *t*	E
$R_{ikrm} =$	$\begin{cases} 1 & \text{If design k in orientation } r \text{ and image } m \text{ is selected for department} \\ 0 & \text{Otherwise} \end{cases}$	A
$H_{ti} =$	$\begin{cases} 1 & \text{If department } i \text{ has horizontal orientation in time period } t \\ 0 & \text{If department } i \text{ has vertical orientation in time period } t \end{cases}$	B, E
$left_{tij} =$	$\begin{cases} 1 & \text{If department } i \text{ is to the left of department } j \text{ in time period } t \\ 0 & \text{Otherwise} \end{cases}$	B
$below_{tij} =$	$\begin{cases} 1 & \text{If department } i \text{ is bellow department } j \text{ in time period } t \\ 0 & \text{Otherwise} \end{cases}$	B
$r_{ti} =$	$\begin{cases} 1 & \text{If department } i \text{ is rearranged at the beginning of time period } t \\ 0 & \text{Otherwise} \end{cases}$	B, C, D, E
$z_{tiq} =$	$\begin{cases} 1 & \text{If department } i \text{ is assigned to bay } q \text{ in time period } t \\ 0 & \text{Otherwise} \end{cases}$	C, D
$\delta_{tq} =$	$\begin{cases} 1 & \text{If bay } q \text{ is occupied in time period } t \\ 0 & \text{Otherwise} \end{cases}$	C, D
$s_{tij} =$	$\begin{cases} 1 & \text{If department } i \text{ is above department } j \text{ in the same bay in time peric} \\ 0 & \text{Otherwise} \end{cases}$	C, D
$ad_{tij} =$	$\begin{cases} 1 & \text{If departments } i \text{ and } j \text{ have a common boundary in time period } t \\ 0 & \text{Otherwise} \end{cases}$	D
$p'_{ti} =$	$\begin{cases} 1 & \text{If P/D point is in longer edge of department } i \text{ in time period } t \\ 0 & \text{Otherwise} \end{cases}$	E
$p''_{ti} =$	$\begin{cases} 1 & \text{If P/D point is in north} - \text{west edges of department } i \text{ in period } t \\ 0 & \text{If P/D point is in south} - \text{east edges of department } i \text{ in period } t \end{cases}$	E

3.1 Model A (Meller et al., 2010)

Model A, presented in Meller et al. (2010), provides solutions to the static facility layout problem (SFLP), considering a sequence-pair as a technique for representing the departments in the continuous space. The model takes as input a set of detailed layout alternatives for each department that composes the manufacturing system and forms the best possible block layout by defining, for each department, its dimensions, area, orientation, and P/D point locations. The mixed-integer non-linear programming model (MINLP) is given as follows.

Objective function:

$$\text{Minimise:} \quad \sum_i \sum_j f_{ij}\left(dp_{ij}^x + dp_{ij}^y\right) \qquad \text{(IV-1)}$$

Subject to:

$$dp_{ij}^x = \left|O_i^x - I_j^x\right| \qquad \forall i, \forall j \qquad \text{(IV-2)}$$

$$dp_{ij}^y = \left|O_i^y - I_j^y\right| \qquad \forall i, \forall j \qquad \text{(IV-3)}$$

$$0 \le v_i^x \le L^x - l_i^x \qquad \forall i \qquad \text{(IV-4)}$$

$$0 \le v_i^y \le L^y - l_i^y \qquad \forall i \qquad \text{(IV-5)}$$

$$z_{ij}^{\pm} + z_{ji}^{\pm} = 1 \qquad \forall i < j, \forall \pm \qquad \text{(IV-6)}$$

$$z_{ik}^{\pm} \ge z_{ij}^{\pm} + z_{jk}^{\pm} - 1 \qquad \forall (distinct) i, j, k, \forall \pm \qquad \text{(IV-7)}$$

$$v_i^x + l_i^x \le v_j^x + L^x\left(2 - z_{ij}^{+} - z_{ij}^{-}\right) \qquad \forall i \ne j \qquad \text{(IV-8)}$$

$$v_i^y + l_i^y \le v_j^y + L^y\left(1 + z_{ij}^{+} - z_{ij}^{-}\right) \qquad \forall i \ne j, \qquad \text{(IV-9)}$$

$$z_{ijk}^{\pm} \in \{0,1\} \qquad \forall i, \forall j, \forall \pm \qquad \text{(IV-10)}$$

$$\sum_k \sum_{r=1}^{4} \sum_{m=0}^{1} R_{ikrm} = 1 \qquad \forall i \qquad \text{(IV-11)}$$

$$l_i^x = \sum_k \sum_{r=1}^{4} \sum_{m=0}^{1} l_{ikrm}^x R_{ikrm} \qquad \forall i \qquad \text{(IV-12)}$$

$$l_i^y = \sum_k \sum_{r=1}^{4} \sum_{m=0}^{1} l_{ikrm}^y R_{ikrm} \qquad \forall i \qquad \text{(IV-13)}$$

$$\Delta_i^{Ix} = \sum_k \sum_{r=1}^{4} \sum_{m=0}^{1} \Delta_{ikrm}^{Ix} R_{ikrm} \qquad \forall i \qquad \text{(IV-14)}$$

$$\Delta_i^{Iy} = \sum_k \sum_{r=1}^{4} \sum_{m=0}^{1} \Delta_{ikrm}^{Iy} R_{ikrm} \qquad \forall i \qquad \text{(IV-15)}$$

$$\Delta_i^{Ox} = \sum_k \sum_{r=1}^{4} \sum_{m=0}^{1} \Delta_{ikrm}^{Ox} R_{ikrm} \qquad \forall i \qquad \text{(IV-16)}$$

$$\Delta_i^{Oy} = \sum_k \sum_{r=1}^{4} \sum_{m=0}^{1} \Delta_{ikrm}^{Oy} R_{ikrm} \qquad \forall i \qquad \text{(IV-17)}$$

$$I_i^x = v_i^x + \Delta_i^{Ix} \qquad \forall i \qquad \text{(IV-18)}$$

$$I_i^y = v_i^y + \Delta_i^{Iy} \qquad \forall i \qquad \text{(IV-19)}$$

$$O_i^x = v_i^x + \Delta_i^{Ox} \qquad \forall i \qquad \text{(IV-20)}$$

$$O_i^y = v_i^y + \Delta_i^{Oy} \qquad \forall i \qquad \text{(IV-21)}$$

$$R_{ikrm} \in \{0,1\} \qquad \forall i, \forall k, \forall r \in \{1, \dots, 4\}, \forall m \in \{0,1\}. \qquad \text{(IV-22)}$$

The objective function (IV-1) minimises the total material handling cost (TMHC). Constraints (IV-2) and (IV-3) allow calculating the rectilinear distance in the x-axis and y-axis direction between the output point and the input point of each pair of departments. In (IV-4) and (IV-5), a set of constraints to ensure the location of each department within the available floor space is provided. Constraints (IV-6) and (IV-7) ensure that the ordering sequences of each pair of departments are valid. The overlap-prevention constraints between departments based on the sequence-pair representation are shown in (IV-8) and (IV-9). The set of binary constraints for the sequence-pair variables is provided in (IV-10). Constraint (IV-11) ensures that, for each department, only a single design alternative is chosen in all its possible orientations and images. Constraints (IV-12) and (IV-13) define the length of each department in the x- and y-axis directions.

Constraints (IV-14)-(IV-17) allow obtaining the distance of the input and output points from the lower left-hand corner of each department in the x- and y-axis direction. The coordinates of the input and output points are calculated through constraints (IV-18)-(IV-21). Finally, constraint (IV-22) restricts the domain of the binary decision variable $\boldsymbol{R_{ikrm}}$.

3.2 Model B (McKendall & Hakobyan, 2010)

Model B was introduced in McKendall & Hakobyan (2010) to solve the FLP considering a multi-period planning horizon (that is, materials flow between departments does vary by time period). This is known in the literature as the dynamic facility layout problem (DFLP) (Pérez-Gosende et al., 2020). Here, departments may have unequal areas and free orientation, and the goal is to minimize TMHC and total rearrangement costs (TRAC). As said by the authors, this model can only address small-size problems in a reasonable time using exact techniques, so the authors also introduced heuristic methods to obtain approximated block layout solutions. The mixed-integer linear programming model (MILP) is given as follows.

Objective function:

$$\text{Minimise:} \qquad \sum_{t}^{T}\sum_{i=1}^{N}\sum_{j>i}^{N} C_{tij}\left(dc_{tij}^{x} + dc_{tij}^{y}\right) + \sum_{t=2}^{T}\sum_{i=1}^{N} RC_{ti} r_{ti} \qquad \text{(IV-23)}$$

Subject to:

$$(c_{ti}^x + 0.5l_{ti}^x) - (c_{tj}^x - 0.5l_{tj}^x) \le M(1 - left_{tij}) \qquad \forall t, \forall i, \forall j \qquad \text{(IV-24)}$$

$$(c_{ti}^y + 0.5l_{ti}^y) - (c_{tj}^y - 0.5l_{tj}^y) \le M(1 - below_{tij}) \qquad \forall t, \forall i, \forall j \qquad \text{(IV-25)}$$

$$left_{tij} + left_{tji} + below_{tij} + below_{tji} = 1 \qquad \forall t, \forall i, \forall j \qquad \text{(IV-26)}$$

$$c_{ti}^x + 0.5l_{ti}^x \le L^x \qquad \forall t, \forall i \qquad \text{(IV-27)}$$

$$c_{ti}^x - 0.5l_{ti}^x \ge 0 \qquad \forall t, \forall i \qquad \text{(IV-28)}$$

$c_{ti}^{y} + 0.5l_{ti}^{y} \leq L^{y}$	$\forall t, \forall i$	(IV-29)
$c_{ti}^{y} - 0.5l_{ti}^{y} \geq 0$	$\forall t, \forall i$	(IV-30)
$dc_{tij}^{x} \geq c_{ti}^{x} - c_{tj}^{x}$	$\forall t, \forall i, \forall j > i$	(IV-31)
$dc_{tij}^{x} \geq c_{tj}^{x} - c_{ti}^{x}$	$\forall t, \forall i, \forall j > i$	(IV-32)
$dc_{tij}^{y} \geq c_{ti}^{y} - c_{tj}^{y}$	$\forall t, \forall i, \forall j > i$	(IV-33)
$dc_{tij}^{y} \geq c_{tj}^{y} - c_{ti}^{y}$	$\forall t, \forall i, \forall j > i$	(IV-34)
$l_{ti}^{x} = Lg_{ti}H_{ti} + Sh_{ti}(1 - H_{ti})$	$\forall t, \forall i$	(IV-35)
$l_{ti}^{y} = Lg_{ti}(1 - H_{ti}) + Sh_{ti}H_{ti}$	$\forall t, \forall i$	(IV-36)
$h_{ti} = 1$	$\forall t, \forall i, DO_{ti} = 1$	(IV-37)
$h_{ti} = 0$	$\forall t, \forall i, DO_{ti} = 2$	(IV-38)
$c_{ti}^{x} - c_{t-1,i}^{x} \leq Mr_{ti}$	$\forall i, \forall t > 1$	(IV-39)
$-c_{ti}^{x} + c_{t-1,i}^{x} \leq Mr_{ti}$	$\forall i, \forall t > 1$	(IV-40)
$c_{ti}^{y} - c_{t-1,i}^{y} \leq Mr_{ti}$	$\forall i, \forall t > 1$	(IV-41)
$-c_{ti}^{y} + c_{t-1,i}^{y} \leq Mr_{ti}$	$\forall i, \forall t > 1$	(IV-42)
$l_{ti}^{y} - l_{t-1,i}^{y} \leq Mr_{ti}$	$\forall i, \forall t > 1$	(IV-43)
$-l_{ti}^{y} + l_{t-1,i}^{y} \leq Mr_{ti}$	$\forall i, \forall t > 1$	(IV-44)
$c_{ti}^{x}, c_{ti}^{y}, l_{ti}^{x}, l_{ti}^{y}, dc_{tij}^{x}, dc_{tij}^{y} \geq 0$	$\forall t, \forall i, \forall j$	(IV-45)
$H_{ti}, r_{ti}, left_{tij}, below_{tij} \in \{0,1\}$	$\forall t, \forall i, \forall j$	(IV-46)

The first term of the objective function (IV-23) measures TMHC, while the second term allows obtaining the TRAC. Constraints (IV-24)-(IV-26) guarantee that the departments do not overlap, while constrains (IV-27)-(IV-30) ensure departments are within the plant floor limits. Constraints (IV-31)-(IV-34) are used to obtain the rectilinear distances between the centroids of departments. Constraints (IV-35)-(IV-38) allow controlling departments' orientation. Constraints (IV-39)-(IV-44) ensure that if a department has not been rearranged in two consecutive time periods, its dimensions and centroid coordinates do not change. Finally, the non-negativity constraints are presented in (IV-45), while those restricting the domain of the binary decision variables are shown in (IV-46).

3.3 Model C (Mazinani et al., 2013)

Model C was introduced by Mazinani et al. (2013) to address DFLP by using a flexible bay structure (FBS) as an approach for the continual representation of rectangular, unequal-area and free-oriented departments in the floor space without them overlapping. In a plant layout based on FBS, departments are assigned to parallel bays on a plant floor. Due to the model complexity, only small-size instances can be solved to optimality in a reasonable computational time, so the authors proposed a genetic algorithm to solve this optimisation problem.

The TMHC and TRAC are minimised as part of the same objective function in this model. However, unlike TRAC being fixed as often considered in DFLP model formulations, the authors also contemplated variable rearrangement costs associated with the amount of displacement of a department in the space between one time period and another.

The MILP model is presented as follows.

Objective function:

Minimise: $$\sum_{t}^{T}\sum_{i=1}^{N}\sum_{j>i}^{N} C_{tij}f_{tij}\left(dc_{tij}^{+x}+dc_{tij}^{-x}+dc_{tij}^{+y}+dc_{tij}^{-y}\right)+\sum_{t=2}^{T}\sum_{i=1}^{N} RC_{ti}r_{ti} + \sum_{t=2}^{T}\sum_{i=1}^{N} VRC_{ti}\left(p_{ti}^{+x}+p_{ti}^{-x}+p_{ti}^{+y}+p_{ti}^{-y}\right) \quad \text{(IV-47)}$$

Subject to:

$$c_{ti}^{x}-c_{tj}^{x}=dc_{tij}^{+x}-dc_{tij}^{-x} \qquad \forall t,\forall i,\forall j>i \qquad \text{(IV-48)}$$

$$c_{ti}^{y}-c_{tj}^{y}=dc_{tij}^{+y}-dc_{tij}^{-y} \qquad \forall t,\forall i,\forall j>i \qquad \text{(IV-49)}$$

$$c_{ti}^{x}-c_{t-1,i}^{x}=p_{ti}^{+x}-p_{ti}^{-x} \qquad \forall i,\forall t>i \qquad \text{(IV-50)}$$

$$c_{ti}^{y}-c_{t-1,i}^{y}=p_{ti}^{+y}-p_{ti}^{-y} \qquad \forall i,\forall t>i \qquad \text{(IV-51)}$$

$$\sum_{q} z_{tiq}=1 \qquad \forall t,\forall i \qquad \text{(IV-52)}$$

$$w_{tq}=\frac{1}{L^{y}}\sum_{i} z_{tiq}a_{ti} \qquad \forall t,\forall q \qquad \text{(IV-53)}$$

$$l_{ti}^{min}z_{tiq}\le w_{tq}\le l_{ti}^{max}+L^{x}(1-z_{tiq}) \qquad \forall t,\forall i,\forall q \qquad \text{(IV-54)}$$

$$c_{ti}^{x}\ge\sum_{j\le q} w_{tj}-0.5w_{tq}-(L^{x}-l_{ti}^{min})(1-z_{tiq}) \qquad \forall t,\forall i,\forall q \qquad \text{(IV-55)}$$

$$c_{ti}^{x}\le\sum_{j\le q} w_{tj}-0.5w_{tq}+(L^{x}-l_{ti}^{min})(1-z_{tiq}) \qquad \forall t,\forall i,\forall q \qquad \text{(IV-56)}$$

$$\frac{h_{tiq}}{a_{ti}}-\frac{h_{tjq}}{a_{tj}}-\max\left\{\frac{l_{ti}^{max}}{a_{ti}},\frac{l_{tj}^{max}}{a_{tj}}\right\}(2-z_{tiq}-z_{tjq})\le 0 \qquad \forall t,\forall q,\forall i,\forall j>i \qquad \text{(IV-57)}$$

$$\frac{h_{tiq}}{a_{ti}}-\frac{h_{tjq}}{a_{tj}}+\max\left\{\frac{l_{ti}^{max}}{a_{ti}},\frac{l_{tj}^{max}}{a_{tj}}\right\}(2-z_{tiq}-z_{tjq})\ge 0 \qquad \forall t,\forall q,\forall i,\forall j>i \qquad \text{(IV-58)}$$

$$\sum_{i} h_{tiq}=L^{y}\delta_{tq} \qquad \forall t,\forall q \qquad \text{(IV-59)}$$

$$l_{ti}^{min}z_{tiq}\le h_{tik}\le l_{ti}^{max}z_{tiq} \qquad \forall t,\forall i,\forall q \qquad \text{(IV-60)}$$

$$\sum_{i} h_{tiq}=l_{ti}^{y} \qquad \forall t,\forall i \qquad \text{(IV-61)}$$

$$c_{ti}^{y}-0.5l_{ti}^{y}\ge c_{tj}^{y}+0.5l_{tj}^{y}-L^{y}(1-s_{tij}) \qquad \forall t,\forall i,\forall j\ne i \qquad \text{(IV-62)}$$

$$s_{tij}+s_{tji}\le 1 \qquad \forall t,\forall i,\forall j>i \qquad \text{(IV-63)}$$

$$s_{tij}+s_{tji}\ge z_{tiq}+z_{tjq}-1 \qquad \forall t,\forall i,\forall j>i \qquad \text{(IV-64)}$$

$$0.5l_{ti}^{y}\le c_{ti}^{y}\le L^{y}-0.5l_{ti}^{y} \qquad \forall t,\forall i \qquad \text{(IV-65)}$$

$$c_{ti}^{x}-c_{t-1,i}^{x}\le L^{x}r_{ti} \qquad \forall i,\forall t>1 \qquad \text{(IV-66)}$$

$$c_{t-1,i}^{x}-c_{ti}^{x}\le L^{x}r_{ti} \qquad \forall i,\forall t>1 \qquad \text{(IV-67)}$$

$$c_{ti}^{y}-c_{t-1,i}^{y}\le L^{y}r_{ti} \qquad \forall i,\forall t>1 \qquad \text{(IV-68)}$$

$$c_{t-1,i}^{y}-c_{ti}^{y}\le L^{y}r_{ti} \qquad \forall i,\forall t>1 \qquad \text{(IV-69)}$$

$$l_{ti}^{y}-l_{t-1,i}^{y}\le L^{y}r_{ti} \qquad \forall i,\forall t>1 \qquad \text{(IV-70)}$$

$l^y_{t-1,i} - l^y_{ti} \leq L^y r_{ti}$	$\forall i, \forall t > 1$	(IV-71)
$c^x_{ti}, c^y_{ti}, l^x_{ti}, l^y_{ti}, w_{tq}, h_{tiq}, dc^{+x}_{tij}, dc^{-x}_{tij}, dc^{+y}_{tij}, dc^{-y}_{tij}, p^{+x}_{ti}, p^{-x}_{ti}, p^{+y}_{ti}, p^{-y}_{ti} \geq 0$	$\forall t, \forall i, \forall j, \forall q$	(IV-72)
$z_{tiq}, \delta_{tq}, s_{tij}, r_{ti} \in \{0,1\}$	$\forall t, \forall i, \forall j, \forall q$	(IV-73)

The first term of the objective function (IV-47) is used to obtain the TMHC; the second term corresponds to the fixed TRAC, and the third term to the variable TRAC. Constraints (IV-48) and (IV-49) linearise the absolute value functions used to measure the rectilinear distance between the centroids of each pair of departments along the x- and y-axis, respectively. Similarly, constraints (IV-50) and (IV-51) linearise, respectively, the absolute value functions that measure the movement of the centroid of each department along the x- and the y-axis from one time period to another.

Constraint (IV-52)-(IV-65) are very similar to those presented in Konak et al. (2006) for their model for SFLP. Constraint (IV-52) ensures that each department is assigned to a single bay. Constraints (IV-53) and (IV-54) calculate the width of each bay as a function of the departments assigned to each bay. Constraints (IV-55) and (IV-56) determine the position of the centroid of the departments along the horizontal axis. Constraints (IV-53), (IV-55) and (IV-56) also ensure that the departments are within the plant floor boundaries along the horizontal axis. Constraints (IV-57)-(IV-64) are used to determine the position of the departments' centroid along the vertical axis. These constraints also ensure that the departments do not overlap in the vertical axis direction. Constraint (IV-65) guarantees that the departments are within the floor plan boundaries along the vertical axis. Constraints (IV-66)-(IV-71) ensure that the department has the same length, width and centroid coordinate values in any two sequential time periods in which the department is not rearranged. Finally, the non-negativity constraints are presented in (IV-72), while those restricting the binary decision variables' domain are shown in (IV-73).

3.4 Model D (Abedzadeh et al., 2013)

Model D was introduced by Abedzadeh et al. (2013) to address DFLP from a multi-objective perspective considering three ofjectıve functıons, including minimising TMHC and TRAC, maximising the total closeness rating (TCR) and minimising the aspect ratio difference. The model also used FBS to represent in a continuous way the departments in the floor space without them overlapping. For solving this problem, the authors proposed a parallel variable neighbourhood search. The MILP formulatıon is presented as follows.

Objective function:

Minimise:

$$\sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{j>i}^{N} C_{tij} f_{tij}\left(dc^{+x}_{tij} + dc^{-x}_{tij} + dc^{+y}_{tij} + dc^{-y}_{tij}\right) + \sum_{t=2}^{T}\sum_{i=1}^{N} RC_{ti} r_{ti} + \sum_{t=2}^{T}\sum_{i=1}^{N} VRC_{ti}\left(p^{+x}_{ti} + p^{-x}_{ti} + p^{+y}_{ti} + p^{-y}_{ti}\right) \quad \text{(IV-74)}$$

Maximise:

$$\sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{j>i}^{N} D_{tij} co'_{tij} \quad \text{(IV-75)}$$

Minimise:
$$\sum_{t=1}^{T}\sum_{i=1}^{N} dv_{ti}^{+} - dv_{ti}^{-} \quad \text{(IV-76)}$$

Subject to:

$$c_{ti}^{x} - c_{tj}^{x} = dc_{tij}^{+x} - dc_{tij}^{-x} \qquad \forall t, \forall i, \forall j > i \quad \text{(IV-77)}$$

$$c_{ti}^{y} - c_{tj}^{y} = dc_{tij}^{+y} - dc_{tij}^{-y} \qquad \forall t, \forall i, \forall j > i \quad \text{(IV-78)}$$

$$c_{ti}^{x} - c_{t-1,i}^{x} = p_{ti}^{+x} - p_{ti}^{-x} \qquad \forall i, \forall t > i \quad \text{(IV-79)}$$

$$c_{ti}^{y} - c_{t-1,i}^{y} = p_{ti}^{+y} - p_{ti}^{-y} \qquad \forall i, \forall t > i \quad \text{(IV-80)}$$

$$\sum_{q} z_{tiq} = 1 \qquad \forall t, \forall i \quad \text{(IV-81)}$$

$$w_{tq} = \frac{1}{L^{y}} \sum_{i} z_{tiq} a_{ti} \qquad \forall t, \forall q \quad \text{(IV-82)}$$

$$l_{ti}^{min} z_{tiq} \le w_{tq} \le l_{ti}^{max} + L^{x}(1 - z_{tiq}) \qquad \forall t, \forall i, \forall q \quad \text{(IV-83)}$$

$$c_{ti}^{x} \ge \sum_{j \le q} w_{tj} - 0.5 w_{tq} - (L^{x} - l_{ti}^{min})(1 - z_{tiq}) \qquad \forall t, \forall i, \forall q \quad \text{(IV-84)}$$

$$c_{ti}^{x} \le \sum_{j \le q} w_{tj} - 0.5 w_{tq} + (L^{x} - l_{ti}^{min})(1 - z_{tiq}) \qquad \forall t, \forall i, \forall q \quad \text{(IV-85)}$$

$$\frac{h_{tiq}}{a_{ti}} - \frac{h_{tjq}}{a_{tj}} - \max\left\{\frac{l_{ti}^{max}}{a_{ti}}, \frac{l_{tj}^{max}}{a_{tj}}\right\}(2 - z_{tiq} - z_{tjq}) \le 0 \qquad \forall t, \forall q, \forall i, \forall j > i \quad \text{(IV-86)}$$

$$\frac{h_{tiq}}{a_{ti}} - \frac{h_{tjq}}{a_{tj}} + \max\left\{\frac{l_{ti}^{max}}{a_{ti}}, \frac{l_{tj}^{max}}{a_{tj}}\right\}(2 - z_{tiq} - z_{tjq}) \ge 0 \qquad \forall t, \forall q, \forall i, \forall j > i \quad \text{(IV-87)}$$

$$\sum_{i} h_{tiq} = L^{y} \delta_{tq} \qquad \forall t, \forall q \quad \text{(IV-88)}$$

$$l_{ti}^{min} z_{tiq} \le h_{tik} \le l_{ti}^{max} z_{tiq} \qquad \forall t, \forall i, \forall q \quad \text{(IV-89)}$$

$$\sum_{i} h_{tiq} = l_{ti}^{y} \qquad \forall t, \forall i \quad \text{(IV-90)}$$

$$c_{ti}^{y} - 0.5 l_{ti}^{y} \ge c_{tj}^{y} + 0.5 l_{tj}^{y} - L^{y}(1 - s_{tij}) \qquad \forall t, \forall i, \forall j \ne i \quad \text{(IV-91)}$$

$$s_{tij} + s_{tji} \le 1 \qquad \forall t, \forall i, \forall j > i \quad \text{(IV-92)}$$

$$s_{tij} + s_{tji} \ge z_{tiq} + z_{tjq} - 1 \qquad \forall t, \forall q, \forall i, \forall j > i \quad \text{(IV-93)}$$

$$0.5 l_{ti}^{y} \le c_{ti}^{y} \le L^{y} - 0.5 l_{ti}^{y} \qquad \forall t, \forall i \quad \text{(IV-94)}$$

$$c_{ti}^{x} - c_{t-1,i}^{x} \le L^{x} r_{ti} \qquad \forall i, \forall t > 1 \quad \text{(IV-95)}$$

$$c_{t-1,i}^{x} - c_{ti}^{x} \le L^{x} r_{ti} \qquad \forall i, \forall t > 1 \quad \text{(IV-96)}$$

$$c_{ti}^{y} - c_{t-1,i}^{y} \le L^{y} r_{ti} \qquad \forall i, \forall t > 1 \quad \text{(IV-97)}$$

$$c_{t-1,i}^{y} - c_{ti}^{y} \le L^{y} r_{ti} \qquad \forall i, \forall t > 1 \quad \text{(IV-98)}$$

$$l_{ti}^{y} - l_{t-1,i}^{y} \le L^{y} r_{ti} \qquad \forall i, \forall t > 1 \quad \text{(IV-99)}$$

$$l_{t-1,i}^{y} - l_{ti}^{y} \le L^{y} r_{ti} \qquad \forall i, \forall t > 1 \quad \text{(IV-100)}$$

$$w'_{tiq} \le L^{x} z_{tiq} \qquad \forall t, \forall i, \forall q \quad \text{(IV-101)}$$

$$w'_{tiq} \le w_{q} + L^{x}(1 - z_{tiq}) \qquad \forall t, \forall i, \forall q \quad \text{(IV-102)}$$

$$w'_{tiq} \ge w_{q} - L^{x}(1 - z_{tiq}) \qquad \forall t, \forall i, \forall q \quad \text{(IV-103)}$$

$$\sum_q w'_{tiq} = l^x_{ti} \qquad \forall t, \forall i \qquad \text{(IV-104)}$$

$$up^x_{ti} = c^x_{ti} + 0.5l^x_{ti} \qquad \forall t, \forall i \qquad \text{(IV-105)}$$

$$up^y_{ti} = c^x_{ti} + 0.5l^y_{ti} \qquad \forall t, \forall i \qquad \text{(IV-106)}$$

$$low^x_{ti} = c^x_{ti} + 0.5l^x_{ti} \qquad \forall t, \forall i \qquad \text{(IV-107)}$$

$$low^y_{ti} = c^x_{ti} - 0.5l^y_{ti} \qquad \forall t, \forall i \qquad \text{(IV-108)}$$

$$low^x_{ti} - up^x_{tj} \le L^x(1 - ad_{tij}) \qquad \forall t, \forall i, \forall j > i \qquad \text{(IV-109)}$$

$$low^x_{tj} - up^x_{ti} \le L^x(1 - ad_{tij}) \qquad \forall t, \forall i, \forall j > i \qquad \text{(IV-110)}$$

$$low^y_{ti} - up^y_{tj} \le L^y(1 - ad_{tij}) \qquad \forall t, \forall i, \forall j > i \qquad \text{(IV-111)}$$

$$low^x_{tj} - up^y_{ti} \le L^y(1 - ad_{tij}) \qquad \forall t, \forall i, \forall j > i \qquad \text{(IV-112)}$$

$$E^x_{tij} \le up^x_{ti} \qquad \forall t, \forall i, \forall j > i \qquad \text{(IV-113)}$$

$$E^x_{tij} \le up^x_{tj} \qquad \forall t, \forall i, \forall j > i \qquad \text{(IV-114)}$$

$$E^y_{tij} \le up^y_{ti} \qquad \forall t, \forall i, \forall j > i \qquad \text{(IV-115)}$$

$$E^y_{tij} \le up^x_{tj} \qquad \forall t, \forall i, \forall j > i \qquad \text{(IV-116)}$$

$$F^x_{tij} \le low^x_{ti} \qquad \forall t, \forall i, \forall j > i \qquad \text{(IV-117)}$$

$$F^x_{tij} \ge low^x_{tj} \qquad \forall t, \forall i, \forall j > i \qquad \text{(IV-118)}$$

$$F^y_{tij} \le low^y_{ti} \qquad \forall t, \forall i, \forall j > i \qquad \text{(IV-119)}$$

$$F^y_{tij} \ge low^y_{tj} \qquad \forall t, \forall i, \forall j > i \qquad \text{(IV-120)}$$

$$co_{tij} = (E^x_{tij} - F^x_{tij}) + (E^y_{tij} - F^y_{tij})low^y_{tj} + (L^x + L^y) \times (1 - ad_{tij}) \qquad \forall t, \forall i, \forall j > i \qquad \text{(IV-121)}$$

$$co'_{tij} \le (L^x + L^y)ad_{tij} \qquad \forall t, \forall i, \forall j > i \qquad \text{(IV-122)}$$

$$co'_{tij} \le co_{tij} + (L^x + L^y)(1 - ad_{tij}) \qquad \forall t, \forall i, \forall j > i \qquad \text{(IV-123)}$$

$$co'_{tij} \ge co_{tij} - (L^x + L^y)(1 - ad_{tij}) \qquad \forall t, \forall i, \forall j > i \qquad \text{(IV-124)}$$

$$l^{max*}_{ti} - l^{min*}_{ti} - dl_{ti} \ge dv^+_{ti} - dv^-_{ti} \qquad \forall t, \forall i \qquad \text{(IV-125)}$$

$$l^x_{ti} - l^y_{ti} \le dl_{ti} \qquad \forall t, \forall i \qquad \text{(IV-126)}$$

$$l^y_{ti} - l^x_{ti} \le dl_{ti} \qquad \forall t, \forall i \qquad \text{(IV-127)}$$

$$l^x_{ti} - l^y_{ti} \ge dl_{ti} - L_x(slack_{ti}) \qquad \forall t, \forall i \qquad \text{(IV-128)}$$

$$l^y_{ti} - l^x_{ti} \ge dl_{ti} + L_x(1 - slack_{ti}) \qquad \forall t, \forall i \qquad \text{(IV-129)}$$

$$c^x_{ti}, c^y_{ti}, l^x_{ti}, l^y_{ti}, w_{tq}, h_{tiq}, w'_{tiq}, dc^{+x}_{tij}, dc^{-x}_{tij}, dc^{+y}_{tij}, dc^{-y}_{tij}, p^{+x}_{ti}, p^{-x}_{ti}, p^{+y}_{ti}, p^{-y}_{ti}, dl_{ti}, dv^+_{ti}, dv^-_{ti}, up^x_{ti}, up^y_{ti}, low^x_{ti}, low^y_{ti}, F^x_{tij}, E^x_{tij}, F^y_{tij}, E^y_{tij}, co_{tij}, co'_{tij} \ge 0 \qquad \forall t, \forall i, \forall j, \forall q \qquad \text{(IV-130)}$$

$$z_{tiq}, \delta_{tq}, s_{tij}, r_{ti}, ad_{tij}, slack_{ti} \in \{0,1\} \qquad \forall t, \forall i, \forall j, \forall q \qquad \text{(IV-131)}$$

The first term in the objective function (IV-74) applies to material handling costs, the second term to fixed rearrangement costs and the third term to variable rearrangement costs. The objective function (IV-75) aims to maximise the adjacency rate, and the objective function (IV-76) is intended to minimise the difference between the desired and obtained shape ratio.

Constraints (IV-77)-(IV-80) linearise the absolute value term in the rectilinear distance function. Constraints (IV-81)-(IV-94) are very similar to those used in Konak et al. (2006) and Mazinani et al. (2013). Constraint (IV-81) ensures that each department is assigned to one single bay. Constraints (IV-82) and (IV-83) calculate the width of each bay based on the departments assigned to a bay. Constraint (IV-82) represents that the width of each bay is calculated by dividing the sum of the total areas of the departments assigned to each bay on the small side of the location plane towards the y-axis. Constraint (IV-83) stipulates the upper and lower limit of the width of the bays based on the departments assigned to each bay.

Constraints (IV-84) and (IV-85) determine the locations of the department centroids along the x-axis. In this case, it is considered that in the FBS-based layout, the department centre along the x-axis is always located in the centre of the assigned bay. Constraints (IV-82), (IV-84) and (IV-85) ensure that the departments are located within the boundaries of the plant floor along the x-axis.

Constraints (IV-86) to (IV-93) are used to determine the center location of departments along the y-axis. These constraints also avoid departments overlapping along the y-axis. Constraints (IV-86)-(IV-90) calculate the side length of each department along the vertical axis. Constraints (IV-86)-(IV-88) linearise the non-linear relation related to the area of the departments. The department's area is obtained from the product of the department's length along the horizontal axis by the department's length along the vertical axis.

Constraint (IV-94) ensures that the departments along the y-axis must be located within the boundaries of the plant floor. Constraints (IV-95)-(IV-100) guarantee that departments that have not been relocated in two successive time periods have equal length, width and coordinates. These constraints are similar to those that McKendall & Hakobyan (2010) considered in their model.

Constraints (IV-101)-(IV-104) calculate the length of each department towards the x-axis, while constraints (IV-105)-(IV-108) calculate the coordinates of the northeast and southwest points of each department. Constraints (IV-109)-(IV-112) consider the different states having a common boundary. Constraints (IV-113)-(IV-121) are used for calculating the index of the length of the common edge.

Constraints (IV-122)-(IV-124) linearise the objective function regarding the adjacency index maximisation. On the other hand, constraints (IV-125)-(IV-129) linearise the ratio difference objective function. Finally, the non-negativity constraints are presented in (130), while those restricting the binary decision variables' domain are shown in (IV-131).

3.5 Model E (Jolai et al., 2012)

Model E was introduced by Jolai et al. (2012) for addressing multi-objective DFLP with P/D point locations by minimising TMHC and TRAC and maximising total closeness rating (TCR) and distance requests. Unlike models B, C and D, this one considers P/D points located along the departments’ boundaries, allowing TMHC values to be closer to those obtained in real-life layout planning (Friedrich et al., 2018). For solving this problem, the authors used exact techniques for small-size instances and a multi-objective particle swarm optimisation algorithm to find suboptimal solutions for medium and large instances. The MINLP formulation is presented as follows.

Objective function:

Minimise:
$$\sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{j\neq i}^{N} C_{tij}\Big((dc_{tij}^{x}+dc_{tij}^{y})+(sgn_{ti}ds_{ti}+sgn_{tj}ds_{tj}\Big) \qquad \text{(IV-132)}$$

Minimise:
$$\sum_{t=2}^{T}\sum_{i=1}^{N} RC_{ti}r_{ti} \qquad \text{(IV-133)}$$

Maximise:
$$\sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{j\neq i}^{N} AV_{tij}af_{tij} \qquad \text{(IV-134)}$$

Maximise:
$$\sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{j\neq i}^{N} DR_{tij}(dc_{tij}^{x}+dc_{tij}^{y}) \qquad \text{(IV-135)}$$

Subject to:

$c_{ti}^{x}-0.5l_{ti}^{x}\geq 0$	$\forall t,\forall i$	(IV-136)
$c_{ti}^{x}+0.5l_{ti}^{x}\leq L^{x}$	$\forall t,\forall i$	(IV-137)
$c_{ti}^{y}-0.5l_{ti}^{y}\geq 0$	$\forall t,\forall i$	(IV-138)
$c_{ti}^{y}+0.5l_{ti}^{y}\leq L^{y}$	$\forall t,\forall i$	(IV-139)
$dc_{tij}^{x}=\left\|c_{ti}^{x}-c_{tj}^{x}\right\|$	$\forall t,\forall i,\forall j\neq i$	(IV-140)
$dc_{tij}^{y}=\left\|c_{ti}^{y}-c_{tj}^{y}\right\|$	$\forall t,\forall i,\forall j\neq i$	(IV-141)
$l_{ti}^{x}-Lg_{ti}H_{ti}+Sh_{ti}(1-H_{ti})$	$\forall t,\forall i$	(IV-142)
$l_{ti}^{y}-Lg_{ti}(1-H_{ti})+Sh_{ti}H_{ti}$	$\forall t,\forall i$	(IV-143)
$H_{ti}=1$ If $Ort_{ti}=1$	$\forall t,\forall i$	(IV-144)
$H_{ti}=0$ If $Ort_{ti}=-1$	$\forall t,\forall i$	(IV-145)
$r_{ti}=\begin{cases}1 \text{ If } c_{t-1,i}^{x}\neq c_{ti}^{x} \;\; or \;\; c_{t-1,i}^{y}\neq c_{ti}^{y} \;\; or \;\; H_{t-1,i}\neq H_{ti}\\ 0 \text{ Otherwise}\end{cases}$	$\forall t,\forall i$	(IV-146)
$c_{ti}^{x},c_{ti}^{y},l_{ti}^{x},l_{ti}^{y},dc_{tij}^{x},dc_{tij}^{y}\geq 0$	$\forall t,\forall i,\forall j$	(IV-147)
$H_{ti},r_{ti},p'_{ti},p''_{ti}\in\{0,1\}$	$\forall t,\forall i$	(IV-148)

The objective function (IV-132) minimises the total material handling costs, while function (IV-133) minimises the TRAC. Functions (IV-134) and (IV-135), on the other hand, are maximisation functions and modify, respectively, the TCR and the distance requests forced by the planner in the layout design. The distance between the centroid and the P/D point of a department (ds_{tj}) included in the objective function (IV-132) depends on H_{ti}, p'_{ti} and p''_{ti}, and can be derived from Table IV-2. According to the relative location of departments i and j, the ds_{tj} value is either positive or negative, indicated by the sign variable in Table IV-2. In addition, the adjacency factor value af_{tij} in the objective function (IV-134), depends on the distance between the centroids of two departments and is given by Table IV-3. Adjacency values (AV_{tij}) are given in Table IV-4.

Table IV-2. Values of ds_{ti} and sgn_{ti} variables (Jolai et al., 2012).

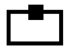
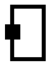
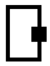
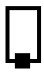
Orientation	Longer/ shorter	North-west/ South-east	Shape	ds_{ti}	Relative location between departments *i* and *j*	sgn_{ti}
$H_{ti} = 1$	$p'_{ti} = 1$	$p''_{ti} = 1$		l^x_{ti}	$If\ c^y_{ti} < c^y_{tj}$	–
					$If\ c^y_{ti} > c^y_{tj}$	+
		$p''_{ti} = 0$		$-l^x_{ti}$	$If\ c^y_{ti} < c^y_{tj}$	–
					$If\ c^y_{ti} > c^y_{tj}$	+
	$p'_{ti} = 0$	$p''_{ti} = 1$		$-l^y_{ti}$	$If\ c^x_{ti} < c^x_{tj}$	–
					$If\ c^x_{ti} > c^x_{tj}$	+
		$p''_{ti} = 0$		l^y_{ti}	$If\ c^x_{ti} < c^x_{tj}$	–
					$If\ c^x_{ti} > c^x_{tj}$	+
$H_{ti} = 0$	$p'_{ti} = 1$	$p''_{ti} = 1$		$-l^y_{ti}$	$If\ c^x_{ti} < c^x_{tj}$	–
					$If\ c^x_{ti} > c^x_{tj}$	+
		$p''_{ti} = 0$		l^y_{ti}	$If\ c^x_{ti} < c^x_{tj}$	–
					$If\ c^x_{ti} > c^x_{tj}$	+
	$p'_{ti} = 0$	$p''_{ti} = 1$		l^x_{ti}	$If\ c^y_{ti} < c^y_{tj}$	–
					$If\ c^y_{ti} > c^y_{tj}$	+
		$p''_{ti} = 0$		$-l^x_{ti}$	$If\ c^y_{ti} < c^y_{tj}$	–
					$If\ c^y_{ti} > c^y_{tj}$	+

Table IV-3. Range of adjacency factor values between departments *i* and *j* (Jolai et al., 2012).

Adjacency factor	Relationship condition
$af_{tij} = 1$	$If\ 0 < dc^x_{tij} + dc^y_{tij} \leq 1/6(L^x + L^y)$
$af_{tij} = 0.8$	$If\ 1/6(L^x + L^y) < dc^x_{tij} + dc^y_{tij} \leq 1/3(L^x + L^y)$
$af_{tij} = 0.6$	$If\ 1/3(L^x + L^y) < dc^x_{tij} + dc^y_{tij} \leq (L^x + L^y)/2$
$af_{tij} = 0.4$	$If\ 1/2(L^x + L^y) < dc^x_{tij} + dc^y_{tij} \leq 2/3(L^x + L^y)$
$af_{tij} = 0.2$	$If\ 2/3(L^x + L^y) < dc^x_{tij} + dc^y_{tij} \leq 5/6\ (L^x + L^y)$
$af_{tij} = 0$	$If\ 5/6(L^x + L^y) < dc^x_{tij} + dc^y_{tij} \leq (L^x + L^y)$

Table IV-4. Adjacency values assigned to adjacency requirements (Jolai et al., 2012).

Adjacency requirement	AV_{tij}	Relationship description
X	0	Undesirable
U	1	Unimportant
O	2	So-so
I	3	Desirable
E	4	Very desirable
A	5	Extremely desirable

Constraints (IV-136)-(IV-139) ensure that departments do not exceed the plant floor boundaries. Constraints (IV-140) and (IV-141) calculate the distance between departments' centroids. These constraints are similar to the four presented by McKendall & Hakobyan (2010). Constraints (IV-142) and (IV-143) compute the length and width of the departments according to their orientations. Constraints (IV-144) and (IV-145) ensure that the departments' orientations forced by the analyst are respected. Constraint (IV-146) shows that any change in a department leads to a rearrangement cost. Finally, constraints (IV-147) and (IV-148) restrict the domain of the decision variables.

4 Comparative analysis

The results of comparing the previously mentioned models according to the analysis criteria (planning approach; planning phase; departments' dimensions; material handling configuration; location of P/D points; representation technique used to allocate departments in the continuous space; model type; objective function type; and objective function description), are summarised in Table IV-5.

Table IV-5. Reference models' characteristics.

Model	Reference	Planning approach	Planning phase	Dept. dimensions	Material handling configuration	P/D points location	Representation technique	Model type	Objective function type	Objective function description
A	Meller et al., (2010)	S	B,D	V	OFLP	C	SP	MINLP	SO	a
B	McKendall & Hakobyan (2010)	D	B	F	OFLP	C	-	MILP	SO	a,b
C	Mazinani et al. (2013)	D	B	M	MRLP	C	FBS	MILP	SO	a,b
D	Abedzadeh et al. (2013)	D	B	V	MRLP	C	FBS	MILP	MO	a,b,c,d
E	Jolai et al. (2012)	D	B	F	OFLP	B	-	MINLP	MO	a,b,d,e

Note: Planning approach: SFLP (static FLP), DFLP (dynamic FLP); planning phase: B (block layout), D (detailed layout); departments' dimensions: F (fixed), V (variable), M (mixed); Material handling configuration: MRLP (multirow layout problem), OFLP (open-field layout problem); P/D points location: C (on the centroid of departments), B (on the boundary of departments); Representation technique: SP (sequence-pair representation), FBS (flexible bay structure); Model type: MINLP (mixed-integer non-linear programming), MILP (mixed-integer linear programming); OF type: SO (single-objective), MO (multi-objective); OF description: a (minimise total material handling cost, TMHC), b (minimise total rearrangement cost, TRAC), c (minimise aspect ratio), d (maximise total closeness rating, TCR), e (maximise distance requests).

Meller et al. (2010) presented an MINLP model to address the unequal-area FLP by considering a sequence-pair representation to avoid overlapping departments in the continuous space. This model introduced a novel layout planning approach called the bottom-up approach, which addresses the two classic phases in layout planning, namely block layout (BL) and detailed layout (DL), in reverse to the traditional top-down approach, and in a more aligned way to how this process is conceived by layout planners in practice (Meller et al., 2004). However, one of the model's disadvantages is to assume that product demand is deterministic and known in advance. As product demands do not vary over time, a single layout consequently is obtained for the entire time planning horizon, which is known in the literature as the static facility layout problem (SFLP) (Moslemipour et al., 2017). These assumptions can be impractical in most industrial sectors, including the metal-mechanic, because the demand, and therefore, the flow of materials are often uncertain and time-varying. In an increasingly globalised business environment, it is more realistic to consider dynamic conditions (Bozorgi et al., 2015), mainly due to the constant need to readjust production capacity as a result of fluctuations in demand, shorter product life cycles, the adoption of technological changes in manufacturing systems, and disruptive events in supply chains, among other factors.

Another of the model's limitations is to consider the minimisation of the TMHC as a single objective function. It is common to use the cost of materials handling between each department or workstation as a single-objective function of a quantitative nature (Hosseini-Nasab et al., 2018). However, FLP is a multi-objective problem given the many quantitative and qualitative factors involved in the final decision (Bozorgi et al., 2015; Singh & Ingole, 2019). These include, in addition to the cost of materials handling, occupational health and safety, the handling of waste and hazardous substances, staff satisfaction, and flexibility for future layout changes, among others. Along the same line, another of the model's characteristics that limits its application to companies in the metal-mechanic sector is the consideration that P/D points are located at the centroid of departments, and not on their edges or borders, which is generally the case in reality. This assumption may generate suboptimal solutions with significantly lower TMHCs than those that incur in real situations.

McKendall & Hakobyan (2010) presented an MILP optimisation model that addresses only the BL phase, but considers dynamic demand conditions in line with the reality of many industrial sectors, such as the metal-mechanic industry. Based on this approach, and known in the literature as DFLP, an optimal layout for each time period that makes up the time planning horizon is sought so that the TMHC and total rearrangement cost (TRAC) are minimised (Erik & Kuvvetli, 2021; Pournaderi et al., 2019; Turanoğlu & Akkaya, 2018). This models' limitations include its single-objective nature and the sole consideration of the BL planning phase and P/D points located at the centroids of departments.

Mazinani et al. (2013) also presented an MILP model for BL planning in DFLP. It considers a flexible bay structure (FBS) as a technique to allocate departments on the continuous plant floor to avoid them overlapping. First introduced in (Tong, 1991), the FBS allows the placing of departments in parallel horizontal or vertical bands (called bays) of variable width along the available floor space. The width of each bay depends on the total area of the departments in the bay, and all departments located in each bay must have the same width, which limits the number of possible layout configurations (Kulturel-Konak & Konak, 2011).

Another restriction of the FBS is that the bays must be completely filled with departments. Therefore, each bay must include a feasible combination of departments concerning the shape constraints, which might be challenging to satisfy if the departments have very different sizes and shapes. As a result, the FBS generates solutions that may incur higher TMHC than other forms of continuous representation for highly constrained problems (Kulturel-Konak & Konak, 2011). However, the bay boundaries can form the basis of an aisle structure that makes it easier for the layout planner to transfer the design resulting from the BL to the detailed design of a real production system (Kulturel-Konak, 2017).

The latter model's limitations include its single-objective nature, the aforementioned limitations of the FBS, the sole consideration of the BL planning phase, not considering demand uncertainty and the location of P/D points at the centroids of departments.

The MILP model introduced by Abedzadeh et al. (2013) approaches the unequal-area DFLP through the FBS from a multi-objective perspective which, in addition to minimising TMHC and TRAC, seeks to minimise the aspect ratio of departments and to maximise TCR. The latter objective function is based on subjective criteria defined by the analyst that are difficult to quantify. In layout planning, these considerations, expressed on an ordinal qualitative rating scale, should be satisfied to the greatest extent possible. The TCR aims to bring the most relation-intensive departments closer together in the final allocation scheme by guaranteeing the principle of circulation; the safety and satisfaction of the workforce; the minimum distance covered by the flow of materials, transport means and personnel; among other factors. This feature would be very useful to consider when making layout decisions in metal-mechanic companies since, in addition to the costs associated with the material handling system, a more significant degree of flexibility for future changes is needed. Similarly, in metalworking plants, there are mechanical, physical and chemical safety risks that must be minimised when determining the best layout scheme for the departments.

Finally, the model presented by Jolai et al. (Jolai et al., 2012) approaches unequal-area DFLP from a multi-objective perspective. It implies the particularity of considering that the flow of materials occurs between the P/D points located on the edges of departments. In this way, the model better simulates the operating conditions of metal-mechanical companies and minimises the risk of generating solutions with far from real TMHC values.

5 Conclusions

This chapter addresses five mathematical optimisation models that can serve as a reference for determining a mathematical optimisation model, which best fits the actual context of the metal-mechanic industrial sector and facilitates facility layout decision making.

After the comparative analysis, it can be concluded that a mathematical optimisation model for facility layout decision making in the metal-mechanic sector must meet the following technical specifications at least: (i) be dynamic (i.e., by considering several time periods as part of the planning horizon in response to demand variability); (ii) start from demand forecasts under uncertainty conditions; (iii) consider regular and unequal-area departments; (iv) contemplate that the flow of materials occurs between the P/D points located on the edges of work cells, and not at their centroids; (v) consider in the layout design, the design of the aisles where materials, means of transport and personnel will circulate; (vi) consider a multi-objective optimisation approach that takes both qualitative and quantitative factors into account; and (vii) contemplate a bottom-up planning approach that firstly takes into account the detailed design of the departments making up the production system and then the BL or, alternatively, takes into account both phases concurrently. The forthcoming chapters will be oriented to formulate a new conceptual proposal and a bottom-up multi-objective optimisation approach to DFLP.

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CAPÍTULO V

A CONCEPTUAL FRAMEWORK FOR MULTI-OBJECTIVE FACILITY LAYOUT PLANNING BY A BOTTOM-UP APPROACH

Este capítulo está siendo revisado por la revista *International Journal of Operations & Production Management* para su eventual publicación con el título “A conceptual framework for multi-objective facility layout planning by a bottom-up approach”, siendo sus autores, Pablo Alberto Pérez Gosende, Josefa Mula y Manuel Díaz-Madroñero.

CAPÍTULO V

A CONCEPTUAL FRAMEWORK FOR MULTI-OBJECTIVE FACILITY LAYOUT PLANNING BY A BOTTOM-UP APPROACH

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 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 & 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 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 & Vieira, 2017; Hosseini-Nasab et al., 2018; la Scalia et al., 2019; Pérez-Gosende et al., 2020). 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 V-1, constructed from the taxonomy defined by (Pérez-Gosende et al., 2021).

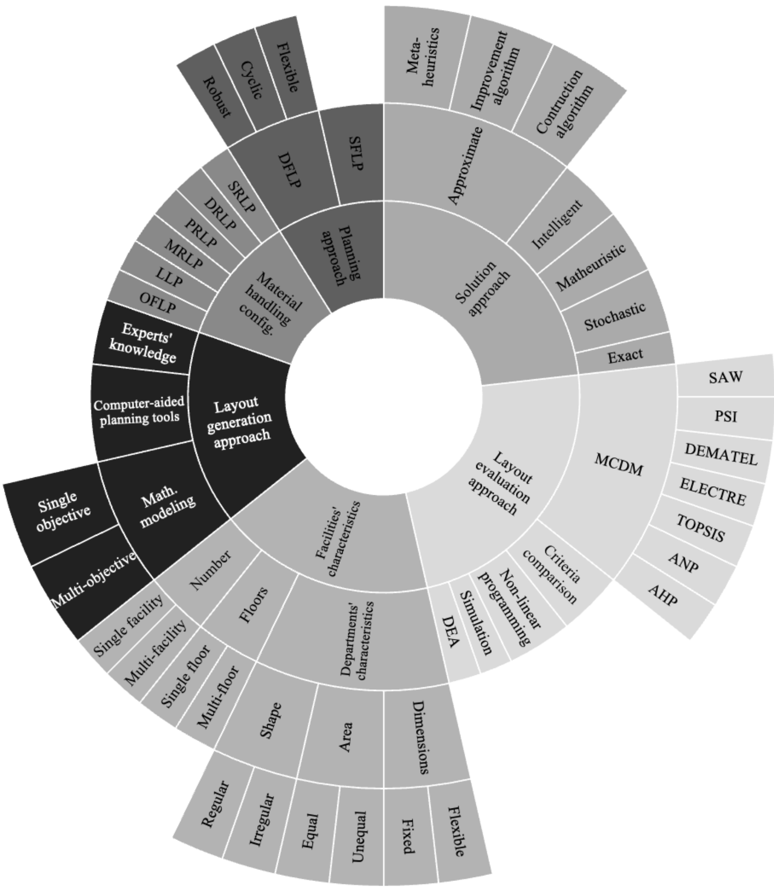

Figure V-1. A general framework for addressing FLP.

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 & 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 &

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 & 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 V-2.

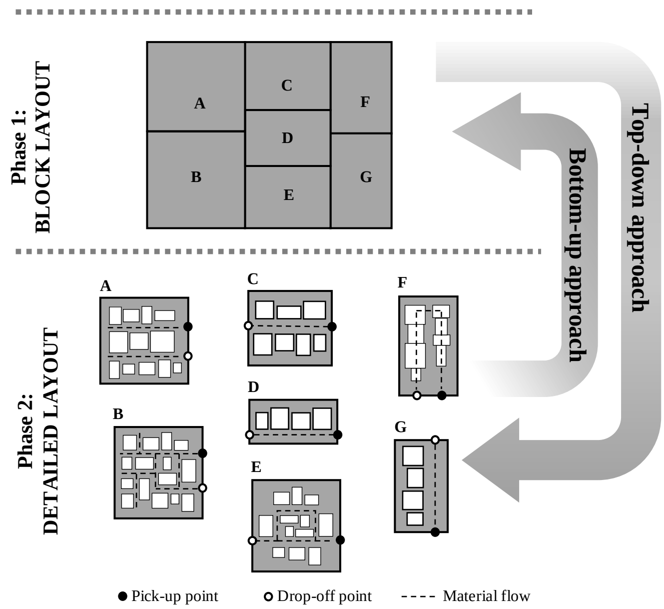

Figure V-2. Approaches to address FLP: top-down vs. bottom-up.

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 & Vieira, 2017).

In the industrial manufacturing systems context, the total material handling cost (MHC) is a key factor to obtain optimal layouts (G. Y.-H. Chen, 2013; D. Singh & Ingole, 2019) and also to reduce production wastes (Chiarini & 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.

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 V-1 shows the objectives that these papers proposed, as well as their resolution approaches, up to 2020.

Table V-1. Survey of papers addressing mFLP.

References	Planning phase		Objective function[a]		Case studies	Resolution approach[b]	Decision-support tools
	BL	DL	Minimise	Maximise			
Singh & 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 & Singh (2011)	√		7	20	Undefined	Three-level AHP-based heuristic approach	LINGO
Cheng & 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 & S. 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

References	Planning phase		Objective function[a]		Case studies	Resolution approach[b]	Decision-support tools
	BL	DL	Minimise	Maximise			
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 & Moshref-Javadi (2014)	√	√	1	25	Test problems	Multi-objective SSA, NSGA-II, ε-CM	CPLEX, MATLAB
Chen & 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
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 & Seifbarghy (2016)	√		1, 2, 12		Test problems	Multi-objective WFA	MATLAB
Che et al. (2017)	√		1, 9		Academic building	ε-CM	CPLEX, C++
Pourvaziri & Pierreval (2017)	√		1, 2, 12, 8		Hypothetical case study	Cloud-based multi-objective SA, simulation	Enterprise Dynamics
Azimi & Soofi (2017)		√	1, 15		Hypothetical case study	NSGA-II, simulation	MATLAB, Enterprise Dynamics
Tayal & 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 & 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 & Ingole (2019)	√		1	20	Test problems	BBO, non-dominated	MATLAB

References	Planning phase		Objective function[a]		Case studies	Resolution approach[b]	Decision-support tools
	BL	DL	Minimise	Maximise			
						sorting BBO, NSGA-II	
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.

Table V-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 V-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 V-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.

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

References	i	ii	iii	iv	v	vi	vii	viii	ix	x	xi
Singh & Singh (2010)	√	√	√		√	√	√	√		√	√
Ku et al. (2011)	√	√		√	√	√	√	√	√	√	√
Şahin (2011)	√	√	√		√	√	√	√	√	√	√
Singh & Singh (2011)	√	√	√		√	√	√	√		√	
Cheng & 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 & 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 & Moshref-Javadi (2014)	√	√			√	√	√	√	√	√	√
Chen & 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 & Seifbarghy (2016)		√	√		√	√	√	√	√	√	√
Che et al. (2017)	√	√			√		√	√	√	√	√
Pourvaziri & Pierreval (2017)			√		√	√	√	√	√	√	√
Azimi & Soofi (2017)	√	√	√		√	√	√	√	√	√	√
Tayal & Singh (2018)			√		√	√	√	√		√	√
Li et al. (2018)		√			√	√	√	√		√	√
Liu et al. (2018)	√	√			√	√	√	√	√	√	√

References	i	ii	iii	iv	v	vi	vii	viii	ix	x	xi
Nagarajan et al. (2018)	√	√			√	√	√	√	√	√	√
Chen et al. (2019)	√	√	√		√	√	√	√	√	√	√
Le et al. (2019)	√	√	√		√	√	√	√	√	√	√
Liu & Liu (2019)	√	√		√	√	√	√	√	√	√	√
Pournaderi et al. (2019)		√	√		√	√	√	√	√	√	√
Singh & 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.

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 & 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 & S. 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 V-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 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 V-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 & 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 & 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 (S. P. Singh & 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 V-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.

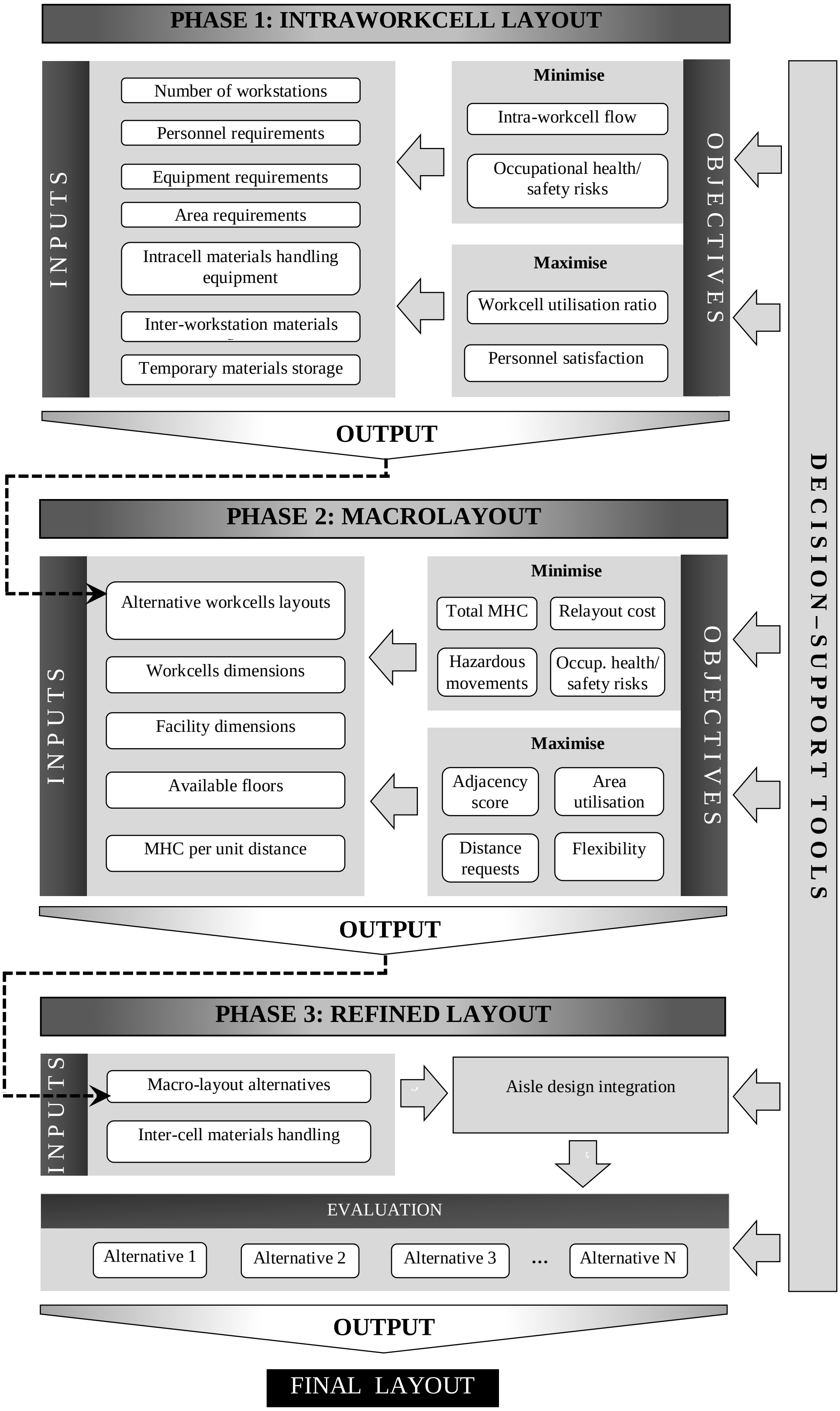

Figure V-3. Conceptual framework for mFLP.

3.1 Intraworkcell layout phase

As seen in Figure V-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 points. The inputs for this phase are defined in Table V-3.

Table V-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.

This phase should include the maximisation and minimisation objectives shown in Table V-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.

Table V-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.

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 V-5 and the objectives to be considered are shown in Table V-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.

Table V-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.

Table V-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.

Objectives	Description
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.

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 V-2, we find multicriteria decision methods (MCDM), simulation, non-linear programming, data envelopment analysis (DEA) or simply comparing technical and economic/financial criteria.

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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CAPÍTULO VI

A BOTTOM-UP MULTI-OBJECTIVE OPTIMIZATION APPROACH TO DYNAMIC FACILITY PLANNING

Este capítulo está siendo revisado por la revista *International Journal of Production Research* para su eventual publicación con el título "A bottom-up multi-objective optimization approach to dynamic facility planning", siendo sus autores, Pablo Alberto Pérez Gosende, Josefa Mula y Manuel Díaz-Madroñero.

CAPÍTULO VI

A BOTTOM-UP MULTI-OBJECTIVE OPTIMIZATION APPROACH TO DYNAMIC FACILITY PLANNING

1 Introduction

Planning the layout of production and service facilities (FLP) refers to the process of finding the best arrangement of all the elements making up the production system in the available physical space, and in such a way that certain relevant objectives are fulfilled (Pérez-Gosende et al., 2021). Of these objectives, better uses of space, equipment and workforce, improving the flow of information, materials and personnel, improving employee satisfaction, job security and the interaction with customers, and flexibility for future changes are prominent (Heizer et al., 2019).

Given its importance and its impact on organisations' productivity and competitiveness (Altuntas & Selim, 2012; Ku et al., 2011; Navidi et al., 2012), FLP is an important research area in the operations management field (Ahmadi et al., 2017; Al-Zubaidi et al., 2021; Anjos & Vieira, 2017; Burggraf et al., 2021; Hosseini-Nasab et al., 2018; Kikolski & Ko, 2018; la Scalia et al., 2019; Maganha et al., 2019; Pérez-Gosende et al., 2020a, 2020b, 2021).

When plant layout is planned in line with the assumption that demand will remain constant over the entire planning horizon, the problem is known as the static facility layout problem (SFLP) (Moslemipour et al., 2017). However in many production systems, the consideration of a single layout may be impractical, because the flow of materials is unlikely to remain constant over time. Instead when demand is seasonal, it is desirable to consider a different plant layout design for each period into which the time planning horizon is divided. In this case, it would be a dynamic facility layout problem (DFLP) in which an optimal layout is adopted for each time period to minimise the total material handling cost (TMHC) and the total rearrangement cost (TRAC) (Erik & Kuvvetli, 2021; Pournaderi et al., 2019; Turanoğlu & Akkaya, 2018). In line with this, Hosseini-Nasab et al. (2018), Pérez-Gosende, Mula, and Díaz-Madroñero (2020a) and Pérez-Gosende, Mula, and Díaz-Madroñero (2021) concluded that DFLP has been less addressed in the scientific literature than the SFLP approach.

Traditionally, FLP has been approached by the systematic layout planning (SLP) methodology, which consists of a set of phases that involve plant location to layout implementation (Muther, 1961). However, the most addressed phases in the literature about the mathematical optimisation of an FLP problem are the two intermediate phases, known as block layout (BL) and detailed layout (DL). As part of the first phase, the appropriate position of the departments or work centres that make up the production or service system in the available physical space is defined. Subsequently in the DL, the following are defined for each department: the best arrangement scheme for machinery, material depots and workstations; the location of the material pick-up and drop-off points (P/D); the structure of corridors through which materials, means of transport and personnel will circulate is integrated. This hierarchical planning process is traditionally carried out sequentially, and is known as the top-down approach (Meller et al., 2004). However, it has been shown that, in practice, layout managers prefer to start with the DL phase and then proceed to the BL, what has been formalised by Meller, Kirkizoglu, and Chen (2010) as the bottom-up approach. Figure VI-1 represents both approaches to FLP planning when FLP is formulated as a mathematical optimisation problem.

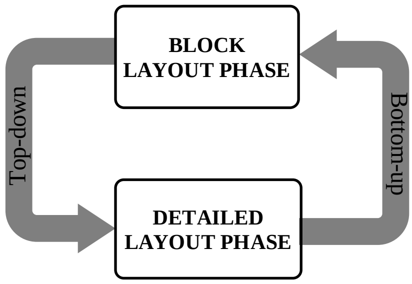

Figure VI-1. Top-down and bottom-up approaches to FLP.

It is important to highlight that developing optimisation models that address both the BL and DL phases simultaneously in the DFLP context has scarcely been addressed, with most contributions in this area mostly made in the modelling of one of these two phases (Pérez-Gosende et al., 2021). In doing so, the combined use of TMHC and TRAC over the entire planning horizon as a single-objective function of a quantitative nature is common (Hosseini-Nasab et al., 2018; Pérez-Gosende et al., 2020b). However in real production systems, FLP is a multi-objective problem due to the large number of factors involved in the final decision (Bozorgi et al., 2015; Matai, 2015; Singh & Ingole, 2019). In this context, the present paper contributes a new MOMINLP model to optimise DFLP with unequal area departments from a bottom-up approach, which considers the DL and BL phases concurrently and dynamically. This model has been dubbed bottom-up mDFLP and aims to bridge a research gap, that of DFLP optimisation integrating BL and DL, which has been identified in the literature, but is barely addressed.

The rest of the article is organised as follows. Section 2 describes the literature review that is relevant to the study topic. Section 3 describes the problem to be addressed. Section 4 formulates the MOMINLP model, dubbed as bottom-up mDFLP. Section 5 presents, as part of the model solution methodology, alternatives for its linearisation, and the reduction of the possible symmetry of solutions to reduce the computational effort. As part of this section, the multi-objective solution approach based on the lexicographic method is presented. Section 6 includes the computational results and the model's validation for a real case study. Finally, Section 7 describes the study conclusions and future research guidelines.

2 Literature review

In a globalised business environment, the need to consider dynamic conditions in the layout planning process is a requirement, mainly due to the need to readjust production capacity as a consequence of demand fluctuations, and to adopt technological changes in manufacturing systems, increasingly shorter product life cycles and disruptive events in supply chains, among other factors (Chen, 2013; Dolgui & Ivanov, 2021; Vitayasak et al., 2017). Based on this approach, called the multiperiod or DFLP, a layout is designed for each time period into which the planning horizon is divided to minimise the TMHC and TRAC (Al Hawarneh et al., 2019; Pournaderi et al., 2019; Turanoğlu & Akkaya, 2018). It should be noted that depending on the seasonality of the demand in the concerned industry sector, time periods may be expressed as months, quarters, years, among others.

When planning dynamic facility layouts, departments can be considered to be of equal or unequal area (Feng & Che, 2018). The selection of discrete or continuous optimisation models to generate plant layout alternatives is based on this assumption (Allahyari & Azab, 2018). The problem of equal-area departments is often addressed by using discrete optimisation models to optimally allocate N departments to a set of N predefined locations (Xiao et al., 2017). Rosenblatt (1986) was the first to formulate DFLP with these characteristics. To solve it, he developed optimal and heuristic procedures based on dynamic programming. However, planning the layout according to the assumption that departments have equal areas when they actually do not can generate suboptimal solutions with a significantly lower TMHC than what would actually be incurred. Hence the importance of considering the real dimensions of departments according to the operations that will be performed in them. In the cases in which DFLP is formulated by considering departments with different areas, optimisation models that allow the plant layout to be represented in continuous space are normally used (Mazinani et al., 2013; McKendall & Hakobyan, 2010), which facilitates the simulation of the operating conditions that come closer to reality. Pérez-Gosende, Mula, and Díaz-Madroñero (2020a) identified that approximately 64% of the reviewed literature works in the DFLP contex, and for a time window between 2010 and 2019, considered departments with equal areas, and only the remaining 36% proposed the unequal area approach. This denotes certain underrepresentation of the latter approach in the literature.

In the dynamic industrial manufacturing systems context, the TMHC and TRAC are key factors in obtaining feasible plant layouts (Balakrishnan et al., 2003; Chen, 2013; Singh & Ingole, 2019). Together they constitute the most widely used quantitative objective function to search for solutions to DFLP (Hosseini-Nasab et al., 2018; Pérez-Gosende, Mula, and Díaz-Madroñero, 2020a; Pérez-Gosende, Mula, and Díaz-Madroñero, 2021). However when solving any plant layout problem, it might not be necessary to consider quantitative factors with a single objective function to generate satisfactory solutions because, in some industrial and service contexts, qualitative factors like closeness ratings, flexibility or safety may have be of similar or more relevance.

Considering both types of factors simultaneously as part of a mathematical optimisation model usually entails having to find a compromise solution in accordance with the decision maker's preferences (Che et al., 2017; Le et al., 2019). This is because the objectives to be optimised often clash (Ripon et al., 2013), and it is necessary to adopt a multi-objective optimisation approach to tackle these problems (Aiello et al., 2013; Ripon et al., 2013). Previously Pérez-Gosende, Mula, and Díaz-Madroñero (2021) identified that only 22% of the articles published between 2010 and 2019 that addressed FLP with a mathematical optimisation model applied a multi-objective approach.

Table VI-1 shows a review of the scientific literature available in the Web of Science related to DFLP and formulated as a multi-objective optimisation problem, mDFLP, using a time window from 2010 to the present-day. As we can see in this table, none of the reviewed papers simultaneously considers either sequentially or concurrently modelling the BL and the DL as part of the same optimisation problem. The papers that consider departments of equal area employ the equivalent QAP model, while most of those that contemplate unequal areas use MILP models. Note also that only Li et al. (2018) apply their formulation to a real-life case study. All the other works opt to look for solutions to mDFLP in classic test problems from the literature or hypothetical case studies. What this shows is that the contributions made to the mDFLP solution have barely been applied in practice. This statement falls in line with Meller, Kirkizoglu, and Chen (2010) when analysing the applicability of FLP research in the industry in a broader context.

Table VI-1. Survey of papers addressing mDFLP through mathematical models.

References	Planning phase	Work cell's area	Type of multiobjective model[a]	Objective function[b]	Practical application	
					Numerical example	Case study
Jolai et al. (2012)	BL	Unequal	MINLP	i, ii, x, xi	x	
Abedzadeh et al. (2013)	BL	Unequal	MILP	i, ii, v, x	x	
Emami & Nookabadi (2013)	BL	Equal	QAP	i, ii, x	x	
Samarghandi et al. (2013)	BL	Unequal	NLP	i, ii, x	x	
Chen & Lo (2014)	BL	Equal	QAP	i, ii, x	x	
Bozorgi et al. (2015)	BL	Equal	QAP	i, ii, x, xi	x	
Kheirkhah et al. (2015)	BL	Equal	BLPM	i, ii, vi	x	
Pourvaziri & Pierreval (2017)	BL	Equal	QAP	i,ii, vi, iv	x	
Tayal & Singh (2018)	DL	Equal	QAP	i, ii, iii, vii, x	x	
Li et al. (2018)	DL	Unequal	MINLP	i, ii, viii, ix, xii		Metalworking company
Pournaderi et al. (2019)	BL	Equal	QAP	i, ii	x	
Wei et al. (2019)	DL	Unequal	NLP	i, ii, xii	x	
Erfani et al. (2020)	BL	Unequal	MINLP	i, ii, iii, x, xii	x	
Erik & Kuvvetli (2021)	BL	Unequal	MINLP	i, ii, vi	x	
Our model	DL/BL	Unequal	MINLP	i, ii, x, xii		Metalworking company

[a]Type of multiobjective model: MINLP (mixed-integer non-linear programming), MILP (mixed-integer linear programming), QAP (quadratic assignment problem), NPL (non-linear programming), BLPM (bi-level programming model).
[b]Objective functions: i) minimum total materials handling cost; ii) minimum total rearrangement cost); iii) minimum transport time; iv) minimum work in process; v) minimum aspect ratio; vi) minimum costs related to material handling equipment; vii) minimum risk level associated with the hazardous materials and waste path; viii) minimum lost opportunity costs; ix) minimum occupational health/safety risks; x) maximum closeness rating among departments; xi) maximum distance requests among departments; xii) maximum area utilisation ratio.

In the reviewed literature, both the TMHC and TRAC are common to any DFLP formulation as initially defined by Rosenblatt (1986). However in most cases, the TRAC is considered to be fixed, and related to only the TRAC incurred while interrupting production due to the layout reorganisation work at the beginning of each period. Only a few authors consider the variable rearrangement costs associated with the amount of displacement of a department in the space between one period and another (Abedzadeh et al., 2013; Erfani et al., 2020; Erik & Kuvvetli, 2021). None of these papers objectively describe procedures to follow to obtain these costs.

Table VI-1 also shows that the total closeness rating (TCR) is one of the most frequently used objective functions in mDFLP formulation, which is accepted in only in slightly over 57% of the consulted literature. The use of the TCR is based on the fact that the departments with the highest intensity of relationships (whether quantitative or subjective in nature) should be as close as possible in the final arrangement scheme to guarantee the principle of circulation, the workforce's safety and satisfaction, and the minimum distance covered by the flow of materials, means of transport and personnel, among other factors.

For a given spatial arrangement scheme, the TCR value can be calculated as a linear function of the length of the common boundary between each pair of contiguous departments (Ghassemi Tari & Neghabi, 2018); like the sum of the adjacency ratings between those cells with a common side (Salmani et al., 2015); by summing the product of the adjacency ratings by the distance between the centroids of the working cells (Le et al., 2019); by summing the product of the adjacency values by the length of the common boundary between them (Bozorgi et al., 2015; Liu et al., 2020); by summing the product of the adjacency values by a factor of adjacency (Emami & S. Nookabadi, 2013; Huo et al., 2021; Jolai et al., 2012; Liu et al., 2018). This last variant was selected in the herein presented model. It has the particularity that, unlike other authors, the adjacency factor is determined as the complement of the proportion representing the distance between the centroids of each department in the direction of the x- and y-axes in relation to the maximum possible distance, defined by the sum of the width and length of the floorspace available for the plant layout.

When planning layout, although achieving the maximum utilisation of the available floor area is particularly important, this objective is not covered very much by the literature in the mDFLP context because it is only considered in three of a total of 14 reviewed papers (Erfani et al., 2020; Li et al., 2018; Wei et al., 2019). The authors calculate an area utilisation ratio (AUR), which relates the total area of the departments to that of the smallest rectangle in which they are circumscribed in the final ordering scheme per period. This forces the model to generate more compact layouts. As the formulation of this approach does not, however, consider the total area available for the arrangement of departments, layouts can be generated with a lot of unused space. Unlike these authors, the proposed model seeks to maximise the average AUR of the entire planning horizon by considering that, during each time period, the ratio between the area occupied by departments and the total available floor area should be come close as possible to unity. This forces the model to generate solutions that make better use of the floor space.

3 Problem statement

The problem under study consists of determining the position, in the available physical space, of a set N of rectangular workcells of different areas required by a production system so that its operations are efficiently performed during a multi-period planning horizon $(t = 1, \dots, T)$ with no overlapping between them. The different departments in which production or support activities are carried out are called the work cell to group, under the same term, the various forms of work organisation according to the possible process flow structure to be considered in each case, be it job shop, batch shop, assembly line or continuous flow (Ivanov et al., 2017). Here a work cell is defined as a space delimited by a physical or imaginary boundary in which the activities necessary for manufacturing processes to normally operate are carried out.

As shown in Figure VI-2, for each cell there is a set Q of feasible detailed layout alternatives that consider the organisation of machinery, workstations and depots for the temporary storage of materials, tools and technological tooling, and space for the flow of the materials in it and the location of P/D points. Each alternative DL can adopt four possible orientations following a clockwise rotation from its standard orientation as shown in Figure VI-3.

For each cell design in its standard orientation (r=1), its dimensions in direction $s = x, y$ (l_{tiqr}^{s}), its area (a_{tiqr}), and the distances (δ_{tiqr}^{s}) from the lower left cell vertex (cv_{ti}^{s}) to its P/D point, are known (Figure VI-4). Subsequently from the relations described in Table VI-2, the equivalent of these measures can be obtained for all three remaining orientations.

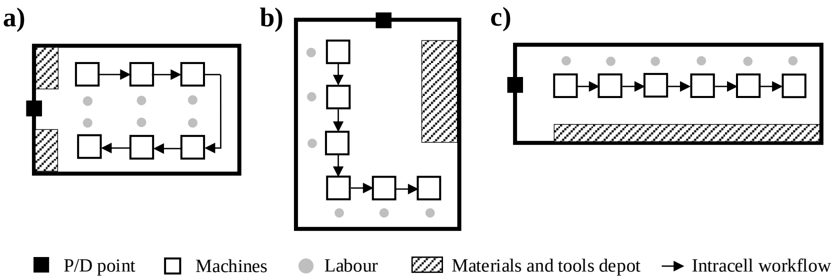

Figure VI-2. Representation of three alternative DL designs in standard orientation for a given work cell.

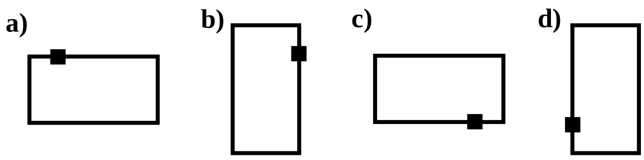

Figure VI-3. Possible work cell orientations based on clockwise rotation: a) *r* =1, b) *r* =2, c) *r* =3, d) *r* =4.

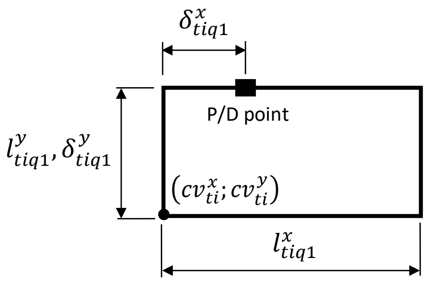

Figure VI-4. Relevant coordinates and parameters for a workcell *i* with design *q* in its standard orientation *r*=1 during time period *t*.

Table VI-2. Obtaining the values of l^{s}_{tiqr}, and δ^{s}_{tiqr} in direction $s = x, y$ for any work cell orientation from their value in the standard orientation *r*=1.

r = 1	*r* = 2	*r* = 3	*r* = 4
l^{x}_{tiq1}	$l^{x}_{tiq2} = l^{y}_{tiq1}$	$l^{x}_{tiq3} = l^{x}_{tiq1}$	$l^{x}_{tiq4} = l^{y}_{tiq1}$
l^{y}_{tiq1}	$l^{y}_{tiq2} = l^{x}_{tiq1}$	$l^{y}_{tiq3} = l^{y}_{tiq1}$	$l^{y}_{tiq4} = l^{x}_{tiq1}$
δ^{px}_{tiq1}	$\delta^{px}_{tiq2} = \delta^{py}_{tiq1}$	$\delta^{px}_{tiq3} = l^{x}_{tiq1} - \delta^{px}_{tiq1}$	$\delta^{px}_{tiq4} = l^{y}_{tiq1} - \delta^{py}_{tiq1}$
δ^{py}_{tiq1}	$\delta^{py}_{tiq2} = l^{x}_{tiq1} - \delta^{px}_{tiq1}$	$\delta^{py}_{tiq3} = l^{y}_{tiq1} - \delta^{py}_{tiq1}$	$\delta^{py}_{tiq4} = \delta^{px}_{tiq1}$

4 MOMINLP model formulation

The parameters characterising the different DL alternatives for each work cell are fed into the proposed model. The model selects the appropriate DL alternative for each work cell and optimises, according to certain objectives, their relative position in the available physical space in the plant for each time period making up the planning horizon. In this way, the model output simultaneously provides the DL of each work cell, as well as the BL of the facility. However, the fact that a set of alternative DLs for each work cell needs to be determined in advance to establish an appropriate BL implies that the planning approach considered by the model is, unlike the traditional top-down approach, more in line with a bottom-up approach. As far as we know, this is the first time that mDFLP has been formulated by this approach.

Of the model's objective functions, we find the work cell closeness rating, which is based a set of experts' assessment of the relevant qualitative factors that condition the adjacency requirements between each pair of work cells. Quantitative factors, such as the TMHC, the TRAC (considering its fixed and variable components) and the AUR of the plant, constitute the other considered objective functions. The notation applied in the model formulation is presented in Table VI-3.

Table VI-3. Notations used in the formulation.

Indices:	
i, j	Workcells ($i, j = 1, \dots, N$)
q	Alternative workcell designs ($q = 1, \dots, Q$)
r	Workcell orientation ($r = 1, \dots, R$)
t	Time periods ($t = 1, \dots, T$)
s	Direction in the *x* and *y*-axis ($s = x, y$)
Parameters:	
F_{tij}	Material flow (*t*/period) between workcells *i* and *j* in time period *t* (upper triangular matrix)
C_{tij}	Cost to transport materials a unit distance between workcells *i* and *j* in time period *t* ($/t·m)
FRC_{ti}	Fixed cost of rearranging workcell *i* at the beginning of time period *t* ($)
VRC_{ti}	Variable cost of rearranging workcell *i* at the beginning of time period *t* ($/m)
L^s	Length of the plant floor in direction *s* (m)
l^s_{tiqr}	Length of workcell *i* along direction *s* in time period *t* according to the design *q* in the orientation *r* (m)
δ^s_{tiqr}	Distance along direction *s* in time period *t* from the lower left vertex of workcell *i* with design *q* in orientation *r* to the P/D point (m)
a_{tiqr}	Area of workcell *i* according to the design *q* in the orientation *r* in time period *t* (m^2)
v_{tij}	Closeness value (0–5) between workcells *i* and *j* in time period *t*
ce	Cost per extra meter required in the *x*- and *y*-axis direction ($/m)
co	Cost per every underused metre in the *x*- and *y*-axis direction ($/m)
Decision variables:	
dp^s_{tij}	Distance along direction *s* in time period *t* between the P/D points of workcells *i* and *j* (m)
dc^s_{tij}	Distance along direction *s* in time period *t* between the centroids of workcells *i* and *j* (m)
l^s_{ti}	Length of workcell *i* along direction *s* in time period *t* (m)
lo^s_{ti}	Clearance distance from workcell *i* to the floorspace boundary along direction *s* in time period *t* (m)
le^s_{ti}	Extra length required for workcell *i* along direction *s* in time period *t* (m)
δ^s_{ti}	Distance along direction *s* in time period *t* from the lower left vertex of workcell *i* to its P/D point (m).
A_{ti}	Area of workcell *i* in time period *t* (m^2).

cv_{ti}^{s}	Lower-left-vertex coordinate of workcell *i* in direction *s* in time period *t*.
cp_{ti}^{s}	P/D point coordinate of workcell *i* in direction *s* in time period *t*.
p_{ti}^{s}	Displacement of workcell *i* in direction *s* from time period *t*-1 to *t* (m).
λ_{tij}	Closeness factor between workcells *i* and *j* in time period *t*
$\Delta_{tiqr} =$	$\begin{cases} 1 & \text{If design } q \text{ in orientation } r \text{ is selected for workcell } i \text{ at the beginning of time period } t \\ 0 & \text{Otherwise} \end{cases}$
$\varphi_{tij}^{s} =$	$\begin{cases} 1 & \text{If workcell } i \text{ precedes } j \text{ in direction } s \text{ in time period } t \\ 0 & \text{Otherwise} \end{cases}$
$\gamma_{ti} =$	$\begin{cases} 1 & \text{If workcell } i \text{ is rearranged at the beginning of time period } t \\ 0 & \text{Otherwise} \end{cases}$

The model, called bottom-up mDFLP, is based on the following assumptions:

- The firm operates in a dynamic environment where demand is known for each time period
- The material flow intensities between work cells are known for each time period
- The facility's dimensions are known and remain fixed over the entire planning horizon
- The number of work cells required for production processes to operate normally is known
- In each work cell, a finite set of ordering schemes can be generated according to the analyst's preference
- Each alternative ordering scheme for each work cell can adopt four different orientations (R=4) in clockwise rotation
- The work cells, for any arrangement scheme, are rectangular-shaped, have fixed dimensions and must fit in the available area of the plant without them overlapping
- Different alternative arrangement schemes for each work cell do not necessarily have the same area requirement. Consequently, work cells may have different areas
- Each work cell has a single point through which the receipt and dispatch of materials take place. This point is located at cell boundaries (not at the cell centroid)

The proposed optimisation model to address the bottom-up mDFLP is formulated as follows:

Objective functions:

$$\min f_1 = \sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{j>i}^{N}\sum_{s=\{x,y\}} C_{tij}F_{tij}dp_{tij}^{s} + \sum_{t=2}^{T}\sum_{i=1}^{N} FRC_{ti}\gamma_{ti} + \sum_{t=2}^{T}\sum_{i=1}^{N}\sum_{s=\{x,y\}} VRC_{ti}p_{ti}^{s} - co\sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{s=\{x,y\}} lo_{ti}^{s} + ce\sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{s=\{x,y\}} le_{ti}^{s} \quad \text{(VI-1)}$$

$$\max f_2 = \sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{j>i}^{N} v_{tij}\lambda_{tij} + co\sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{s=\{x,y\}} lo_{ti}^{s} - ce\sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{s=\{x,y\}} le_{ti}^{s} \quad \text{(VI-2)}$$

$$\max f_3 = \frac{1}{T}\sum_{t=1}^{T}\left(\frac{\sum_{i=1}^{N} A_{ti}}{\prod_{s=\{x,y\}} L^{s}}\right) + co\sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{s=\{x,y\}} lo_{ti}^{s} - ce\sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{s=\{x,y\}} le_{ti}^{s} \quad \text{(VI-3)}$$

Subject to:

$$cv_{ti}^{s} + l_{ti}^{s} + lo_{ti}^{s} = L^{s} + le_{ti}^{s} \qquad \forall s, \forall t, \forall i \qquad \text{(VI-4)}$$

$$cv_{ti}^{s} + l_{ti}^{s} \leq cv_{tj}^{s} + L^{s}\left(1 - \varphi_{tij}^{s}\right) \qquad \forall s, \forall t, \forall i \neq j \qquad \text{(VI-5)}$$

$$\varphi_{tij}^{x} + \varphi_{tji}^{x} + \varphi_{tij}^{y} + \varphi_{tji}^{y} = 1 \qquad \forall t, \forall i, \forall j > i \qquad \text{(VI-6)}$$

$$dp_{tij}^{s} = \left|cp_{ti}^{s} - cp_{tj}^{s}\right| \qquad \forall s, \forall t, \forall i, \forall j > i \qquad \text{(VI-7)}$$

$$dc_{tij}^{s} = \left|(cv_{ti}^{s} + \frac{l_{ti}^{s}}{2}) - (cv_{tj}^{s} + \frac{l_{tj}^{s}}{2})\right| \qquad \forall s, \forall t, \forall i, \forall j > i \qquad \text{(VI-8)}$$

$$\lambda_{tij} = 1 - \left(\frac{\sum_{s=\{x,y\}} d_{tij}^{cs}}{\sum_{s=\{x,y\}} L^{s}}\right) \qquad \forall t, \forall i, \forall j > i \qquad \text{(VI-9)}$$

$$\sum_{q=1}^{Q}\sum_{r=1}^{R} \Delta_{tiqr} = 1 \qquad \forall t, \forall i \qquad \text{(VI-10)}$$

$$l_{ti}^{s} = \sum_{q=1}^{Q}\sum_{r=1}^{R} l_{tiqr}^{s}\Delta_{tiqr} \qquad \forall s, \forall t, \forall i \qquad \text{(VI-11)}$$

$$\delta_{ti}^{s} = \sum_{q=1}^{Q}\sum_{r=1}^{R} \delta_{tiqr}^{s}\Delta_{tiqr} \qquad \forall s, \forall t, \forall i \qquad \text{(VI-12)}$$

$$A_{ti} = \sum_{q=1}^{Q}\sum_{r=1}^{R} a_{tiq}\,\Delta_{tiqr} \qquad \forall t, \forall i \qquad \text{(VI-13)}$$

$$cp_{ti}^{s} = cv_{ti}^{s} + \delta_{ti}^{s} \qquad \forall s, \forall t, \forall i \qquad \text{(VI-14)}$$

$$p_{ti}^{s} = \left|(cv_{ti}^{s} + \frac{l_{ti}^{s}}{2}) - (cv_{t-1,i}^{s} + \frac{l_{t-1,i}^{s}}{2})\right| \qquad \forall s, \forall i, \forall t > 1 \qquad \text{(VI-15)}$$

$$\gamma_{ti} = \begin{cases} 1 \text{ If } p_{ti}^{s} \neq 0 \quad \forall s, \forall i, \forall t > 1 \quad or \quad l_{t-1,i}^{x} \neq l_{ti}^{x} \quad \forall i, \forall t > 1 \\ 0 \text{ Otherwise} \end{cases} \qquad \text{(VI-16)}$$

$$dp_{tij}^{s}, dc_{tij}^{s} \geq 0 \qquad \forall s, \forall t, \forall i, \forall j \qquad \text{(VI-17)}$$

$$cv_{ti}^{s}, l_{ti}^{s}, cp_{ti}^{s}, \delta_{ti}^{s}, p_{ti}^{s} \geq 0 \qquad \forall s, \forall t, \forall i \qquad \text{(VI-18)}$$

$$A_{ti} \geq 0 \qquad \forall t, \forall i \qquad \text{(VI-19)}$$

$$\Delta_{tiqr} \in \{0,1\} \qquad \forall t, \forall i, \forall q, \forall r \qquad \text{(VI-20)}$$

$$\varphi_{tij}^{s} \in \{0,1\} \qquad \forall s, \forall t, \forall i, \forall j \qquad \text{(VI-21)}$$

$$\gamma_{ti} \in \{0,1\} \qquad \forall t, \forall i \qquad \text{(VI-22)}$$

The first term in Objective Function (VI-1) measures the TMHC, while the second and third terms allow to respectively obtain the fixed and variable components of the TRAC between the consecutive time periods over the entire planning horizon, namely the total fixed cost of rearranging workcells (TFRC) and the total variable cost of rearranging workcells (TVRC). The fourth and fifth terms of this first function respectively correspond to a penalty for the over- or underutilised length in the *x*- or *y*-axis direction while establishing departments in the available physical space. As we can see, these expressions are repeated in Objective Functions (VI-2) and (VI-3). The first term of Objective Function (VI-2) seeks to maximise the total closeness rating between the work cells making up the production system. The closeness ratings used in this work to characterise the adjacency requirements between work cells are presented in Table VI-4. The first term of Objective Function (VI-3) seeks to maximise the average AUR value among all the periods into which the planning time horizon is divided.

Constraint (VI-4) ensures that cells are located within the available floorspace limits of the plant. Constraints (VI-5) and (VI-6) prevent any overlap between work cells. The distance between the P/D points of each pair of cells is determined by Constraint (VI-7) and the distance between their centroids is obtained by Constraint (VI-8). The closeness factor required to fulfil Objective Function (VI-2) is calculated by Constraint (VI-9). Constraint (VI-10) ensures that, during each time period, for each work cell only a single design alternative is chosen in all its four possible orientations. Constraint (VI-11) defines, for each time period, the length of each work cell in the *x*- and *y*-axis direction.

Table VI-4. Closeness values assigned to closeness requirements.

Closeness requirement	Closeness value	Relation description
X	$v_{ij} = 0$	It is not desirable for work cells *i* and *j* to be near one another
U	$v_{ij} = 1$	It is unimportant for work cells *i* and *j* to be near one another
O	$v_{ij} = 2$	It is ordinary for work cells *i* and *j* to be near one another
I	$v_{ij} = 3$	It is important for work cells *i* and *j* to be near one another
E	$v_{ij} = 4$	It is especially important for work cells *i* and *j* to be near one another
A	$v_{ij} = 5$	It is absolutely necessary for work cells *i* and *j* to be near one another

Constraint (VI-12) allows, for each time period, to obtain the distance from the lower left vertex of each work cell to its respective P/D point in the x- and y-axes direction. Constraint (VI-13) allows the area of each department to be obtained for each time period.

The coordinates of the P/D points in the x- and y-axes direction for each time period are calculated by Constraint (VI-14). Constraint (VI-15) allows to determine the extent to which the work cell has changed position between two consecutive time periods. Constraint (VI-16) ensures that if a work cell has changed its position in the space or along its length in the *x*-axis direction between two consecutive time periods, then a rearrangement cost is incurred. This constraint can alternatively be expressed by Constraints (VI-23)-(VI-25). The non-negativity restrictions are shown in (VI-17)-(VI-19). Finally, Constraints (VI-20)-(VI-22) restrict the domain of the binary decision variables.

$$p_{ti}^{s} \leq L^{s}\gamma_{ti} \qquad \forall s, \forall i, \forall t > 1 \qquad \text{(VI-23)}$$

$$l_{ti}^{x} - l_{t-1,i}^{x} \leq L^{x}\gamma_{ti} \qquad \forall i, \forall t > 1 \qquad \text{(VI-24)}$$

$$l_{t-1,i}^{x} - l_{ti}^{x} \leq L^{x}\gamma_{ti} \qquad \forall i, \forall t > 1 \qquad \text{(VI-25)}$$

5 Solution methodology

5.1 Linearisation approach

The proposed model is non-linear because of the presence of absolute value functions in Constraints (VI-7), (VI-8) and (VI-15). These absolute value functions can be generally linearised in three ways, as shown below for Constraint (VI-7).

Linearisation form 1 (Sherali et al., 2003):

$$dp_{tij}^{s} \geq cp_{ti}^{s} - cp_{tj}^{s} \qquad \forall s, \forall t, \forall i, \forall j > i \qquad \text{(VI-26)}$$

$$dp_{tij}^{s} \geq cp_{tj}^{s} - cp_{ti}^{s} \qquad \forall s, \forall t, \forall i, \forall j > i \qquad \text{(VI-27)}$$

Linearisation form 2 (Abedzadeh et al., 2013):

$$dp_{tij}^{s} = dp_{tij}^{+s} + dp_{tij}^{-s} \qquad \forall s, \forall t, \forall i, \forall j > i \qquad \text{(VI-28)}$$

$$cp_{ti}^{s} - cp_{tj}^{s} = dp_{tij}^{+s} - dp_{tij}^{-s} \qquad \forall s, \forall t, \forall i, \forall j > i \qquad \text{(VI-29)}$$

$$dp_{tij}^{+s}, dp_{tij}^{-s} \geq 0 \qquad \forall s, \forall t, \forall i, \forall j > i \qquad \text{(VI-30)}$$

Linearisation form 3 (Poler et al., 2014):

$$dp_{tij}^{s} = cp_{ti}^{s} - cp_{tj}^{s} \qquad \forall s, \forall t, \forall i, \forall j > i \qquad \text{(VI-31)}$$

$$dp_{tij}^{s} \leq Dp_{tij}^{s} \qquad \forall s, \forall t, \forall i, \forall j > i \qquad \text{(VI-32)}$$

$$-dp_{tij}^{s} \leq Dp_{tij}^{s} \qquad \forall s, \forall t, \forall i, \forall j > i \qquad \text{(VI-33)}$$

Of these three forms of linearisation of the absolute value functions, that which results in the shortest computational time to a solution when testing a single-objective and single-period version of the model will be selected.

5.2 Reducing problem symmetry

The bottom-up mDFLP, like many other FLP variants formulated to search for solutions in a continuous space (i.e. when considering unequal-area FLP departments), can generate symmetric solutions. In these cases, for example, if the resulting ordering scheme is rotated 90, 180 or 270 sexagesimal degrees, it provides the same solution. The possibility of a model generating symmetric solutions can considerably increase computational efforts and resolution times (Sherali et al., 2003). To avoid this, if the analyst decides to not fix some department in space when running the model on a particular test problem, the inclusion of symmetry breaking constraints (SBC) can be useful (Anjos & Vieira, 2017; Meller et al., 2010; Sherali et al., 2003).

One of the ways to break symmetry in the FLP variants with a continuous representation is to require the centroid of some key department i' to be located in a specific quadrant of the facility (Meller et al., 1998), for instance, the lower left quadrant, as shown in Constraint (VI-34). This symmetry breaking method, called the q-position method in Sherali, Fraticelli, and Meller (2003), has the disadvantage of it losing functionality when the centroid of i' coincides with the centroid of the facility $\left(\frac{L^x}{2};\frac{L^y}{2}\right)$. To apply this method, key department i' can be that with the highest flow intensity to and from other work cells during the first period of the planning horizon ($max_{t=1,(i,j)\epsilon N} \sum_{i\neq j}^{N} F_{tij}$). Possible ties can be broken by considering the cell with the largest area (Meller et al., 1998) or the work cell with the largest average area if several detailed design alternatives q are considered per cell.

$$cv_{ti'}^{s} + \frac{l_{ti'}^{s}}{2} \leq \frac{L^{s}}{2} \qquad \forall s, \forall t, \forall i' \qquad \text{(VI-34)}$$

Another way to break the symmetry of solutions is by applying the p-q position method defined in Sherali, Fraticelli, and Meller (2003). According to this method, two key cells p and q (denoted in the bottom-up mDFLP model as i' and j') are previously selected by the analyst, which forces the first one to be located in a position to the left and below the second one, as shown in Constraints (VI-35)-(VI-36). In DFLP, as the layouts of later periods depend on that obtained for the first one, then the cells with the highest flow intensity between them during the first period of the planning horizon are normally selected ($F_{ti'j'} = max_{t=1,(i,j)\in N} F_{tij}$) (Abedzadeh et al., 2013). With a tie, the pair with the largest area can be chosen (Sherali et al., 2003), or the largest average area if more than one detailed design alternative is considered per cell. Another way to break the tie is to select the pair of cells that includes that with the smallest index number (Meller et al., 2010).

$$cv_{ti'}^{s} + \frac{l_{ti'}^{s}}{2} \leq cv_{tj'}^{s} + \frac{l_{tj'}^{s}}{2} \qquad \forall s, \forall t, \forall i' \neq j' \qquad \text{(VI-35)}$$

$$\varphi_{tj'i'}^{s} = 0 \qquad \forall s, \forall t, \forall i' \neq j' \qquad \text{(VI-36)}$$

Of both these methods for reducing the possible symmetry of solutions, that which results in the shortest computational time to the solution when testing a single-objective and single-period version of the model will be selected.

5.3 Balancing multi-objectives

In solving multi-objective optimisation problems, there is generally no single solution that simultaneously optimises all the objective functions considered when they clash by nature (Rodrigues et al., 2017). In these cases, decision makers look for a preferred solution as opposed to the optimal solution (Mavrotas, 2009). In multi-objective problems, the optimality concept is replaced with Pareto optimality. Pareto optimal solutions, which form the so-called Pareto optimal set, are those that cannot improve the value of an objective function without deteriorating the performance of at least one of the others (Mavrotas, 2009). Thus when faced with a multi-objective problem, the decision maker aims to search for a preferred solution among Pareto optimal solutions (Aiello et al., 2013; Ripon et al., 2013). According to Wang, Olhofer, and Jin (2017), setting up a decision maker's preferences is vitally important because it allows optimisation algorithms to be oriented towards the search for preferred solutions instead of the whole Pareto front.

One of the methods that, *a priori*, allows a decision maker's preference to be set up in the optimisation process is the lexicographic (LO) method (Jee et al., 2007; Romero, 2001). In this approach, the decision maker assigns a priority order to each optimisation objective according to its importance. Then in that order, a sequence of subproblems is solved that consider only one objective at a time. The optimal value obtained for each objective is then used as a reference to constrain the optimality of the solution in relation to that objective (Hathhorn et al., 2013; Jee et al., 2007). As each objective is optimised separately, the LO can handle multi-objectives with different unit scales without them having to be normalised. According to Arora (2017), the LO always provides a Pareto optimal solution. For all these reasons, in this paper LO is used as a strategy to search for an optimal solution to the proposed bottom-up mDFLP model.

6 Computational results

In this section, we firstly define the characteristics of the real case study to apply and validate the bottom-up mDFLP model. Then we select the form of linearisation of the absolute value functions and the method to generate SBC that has the strongest impact on reducing the computational resolution time in a simplified version of the model of a single-objective and single-period nature. Finally, once the final multi-objective model is adjusted, we then search for a Pareto optimal solution to a real case study (N=12/T=3) by applying a strategy based on the LO.

The multi-objective bottom-up mFDLP model, along with its single-objective and single-period variants, are coded in MPL 5.0.8.116 and solved using the Gurobi 9.1.2 optimisation solver on a computer with 32 Gb RAM and two Intel® Xeon® E5-2640 v2 microprocessors at a frequency of 2.0 GHz each.

6.1 Real-world case study

This section considers datasets from a real manufacturing system. The company under study belongs to the metal-mechanical sector and is engaged in the manufacture of axial flow pumps, turbines, compressors, belt conveyors and tooling. Table VI-5 shows the identified work cells and their relevant dimensions. Figure VI-5 presents the current plant layout. In the offices, support processes related to administrative management, logistics and human resources are carried out. Hence these three spaces are considered a single block, which is why they must remain together for safety and organisational reasons.

Table VI-5. Relevant dimensions of the work cells in the current layout.

i	Work cell description	cv_{ti}^{x}	cv_{ti}^{y}	l_{ti}^{x}	l_{ti}^{y}	A_{ti}	cp_{ti}^{x}	cp_{ti}^{y}	δ_{ti}^{x}	δ_{ti}^{y}
1	Press shop	4.00	11.00	5.00	6.00	30.00	9.00	14.00	5.00	3.00
2	Polishing area	8.50	5.00	3.00	6.00	18.00	8.50	8.00	0	3.00
3	Threading workshop	4.00	2.00	6.00	3.00	18.00	10.00	3.50	6.00	1.50
4	Sandblasting area	4.00	5.00	4.50	6.00	27.00	8.50	8.00	4.50	3.00
5	Milling workshop	9.00	11.00	6.00	6.00	36.00	13.00	11.00	4.00	0
6	Computer numerical control module	10.00	2.00	5.00	3.00	15.00	13.25	5.00	3.25	3.00
7	Lathe shop	11.50	5.00	3.50	6.00	21.00	13.25	5.00	1.75	0
8	Assembly area	15.00	7.00	4.00	10.00	40.00	15.00	14.00	0	7.00
9	Inspection/packaging area	15.00	2.00	4.00	5.00	20.00	17.00	7.00	2.00	5.00
10	Reception/dispatch area	19.00	17.00	10.00	4.20	42.00	24.00	21.20	5.00	4.20
11	Offices	4.00	17.00	15.00	4.20	63.00	4.00	18.00	0	1.00
12	Warehouse	19.00	2.00	10.00	15.00	150.00	24.00	17.00	5.00	15.00

The production system under study has a seasonal demand characterised by three temporary periods of differentiated demand throughout the calendar year. Thus an annual planning horizon is considered, consisting of three 4-month periods (T=3).

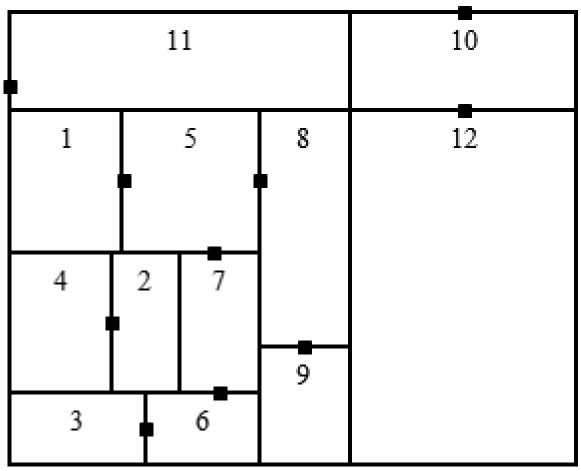

Figure VI-5. Current layout.

The detailed distribution alternatives proposed for each work cell and their relevant dimensions, are presented in Appendix V. Similarly, this appendix shows the flow intensities between each pair of work cells during each 4-month period, as well as the unit cost of material handling and the proximity ratings identified by a group of seven experts, including operators, supervisors and middle managers, reaching a consensus. So the minimisation of the TMHC and TRAC is considered a priority by the company. The total space available in the plant for spatial distribution is 45 m long x 30 m wide.

6.2 Tightening the model

Before moving on to solve the N=12/T=3 case study, it is necessary to adjust the model by selecting not only the form of linearisation of the absolute value functions, but also the symmetry breaking method with the strongest impact on reducing computational resolution times. To this end, nine variants of single-objective and single-period models are tested for each test problem, which seek to optimise exclusively the TMHC during a single time period for each alternative linearisation of the absolute value functions, without considering symmetry breaking constraints in each case, but they must be contemplated according to the q-position method and the p-q position method described in Section 5.2. These single-objective and single-period versions of the model are found in Table VI-6. The results obtained from both the TMHC and the computational resolution times are shown in Table VI-7.

Thus for small problems (N≤6), using the linearisation form 1 of the absolute value functions is recommended, while employing SBC is discouraged, which allows lower TMHC and shorter run times than other variants. However, utilising SBCs, especially those generated by the p-q position method, significantly reduce computational times for test instances of seven departments or more, with the best performance achieved when they are combined with linearisation form 2 of the absolute value functions.

Table VI-6. Single-objective and single-period test model alternatives.

	Linearization form 1	Linearization form 2	Linearization form 3
Without SBC	Min f_1 s.t.: (VI-4)-(VI-6), (VI-10)-(VI-12), (VI-14), (VI-17), (VI-18), (VI-20), (VI-21), (VI-26), and (VI-27)	Min f_1 s.t.: (VI-4)-(VI-6), (VI-10)-(VI-12), (VI-14), (VI-17), (VI-18), (VI-20), (VI-21), and (VI-28)-(VI-30)	Min f_1 s.t.: (VI-4)-(VI-6), (VI-10)-(VI-12), (VI-14), (VI-17), (VI-18), (VI-20), (VI-21), and (VI-31)-(VI-33)
q method	Min f_1 s.t.: (VI-4)-(VI-6), (VI-10)-(VI-12), (VI-14), (VI-17), (VI-18), (VI-20), (VI-21), (VI-26), (VI-27), and (VI-34)	Min f_1 s.t.: (VI-4)-(VI-6), (VI-10)-(VI-12), (VI-14), (VI-17), (VI-18), (VI-20), (VI-21), (VI-28)-(VI-30), and (VI-34)	Min f_1 s.t.: (VI-4)-(VI-6), (VI-10)-(VI-12), (VI-14), (VI-17), (VI-18), (VI-20), (VI-21), (VI-31)-(VI-33), and (VI-34)
p-q method	Min f_1 s.t.: (VI-4)-(VI-6), (VI-10)-(VI-12), (VI-14), (VI-17), (VI-18), (VI-20), (VI-21), (VI-26), (VI-27), (VI-35), and (VI-36)	Min f_1 s.t.: (VI-4)-(VI-6), (VI-10)-(VI-12), (VI-14), (VI-17), (VI-18), (VI-20), (VI-21), (VI-28)-(VI-30), (VI-35), and (VI-36)	Min f_1 s.t.: (VI-4)-(VI-6), (VI-10)-(VI-12), (VI-14), (VI-17), (VI-18), (VI-20), (VI-21), (VI-31)-(VI-33), (VI-35), and (VI-36)

Table VI-7. The TMHC values and computational runtime for the single-objective and single-period test model alternatives.

		Linearisation form 1			Linearisation form 2			Linearisation form 3		
N	SBC	TMHC	Runtime (s)	Gap (%)	TMHC	Runtime (s)	Gap (%)	TMHC	Runtime (s)	Gap (%)
5	No	26,88	0.89[a]	0	32.89	3.85	0	32.89	3.13	0
	q	26.88	3.88	0	32.89	3.64	0	32.89	5.12	0
	p-q	26.88	2.30	0	32.89	1.80	0	32.89	3.66	0
6	No	283.81	3.78[a]	0	352.77	16.78	0	352.77	15.20	0
	q	283.81	13.58	0	352.77	13.38	0	352.77	26.68	0
	p-q	283.81	14.33	0	352.77	10.48	0	352.77	12.94	0
7	No	1331.48	261	0	1507.65	64	0	1507.65	206	0
	q	1331.48	282	0	1507.65	148	0	1507.65	99	0
	p-q	1346.39	62	0	1507.65	19.61[a]	0	1507.65	41.25	0
8	No	2014.32	8711	0	2215.29	4355	0	2215.29	1075	0
	q	2014.32	10429	0	2215.29	691	0	2215.29	1423	0
	p-q	2014.32	2142	0	2215.29	60[a]	0	2215.29	396	0
9	No	1535.42	86400[b]	34.7	1728.35	86400[b]	33.2	1953.16	86400[b]	24.5
	q	1951.14	86400[b]	17	2137.25	86400[b]	17.4	2096.69	86400[b]	18.9
	p-q	2349.87	44935	0	2586.53	843[a]	0	2586.53	1481	0
10	*p-q*	1771.90	86400[b]	24.6	2586.53	2683[a]	0	2586.53	16243	0
11	*p-q*	-	-	-	2586.53	1357[a]	0	2586.53	9684	0
12	*p-q*	-	-	-	8344.60	4239[a]	0	8344.60	14337	0

[a]Best computational runtime for each test instance.
[b]Prematurely terminated after 24 hours of computation.

It is highlighted how using linearisation form 1 provides lower TMHC values than the other alternatives, but leads to longer computational resolution times, which makes the model unsolvable (runtime is longer than 24 hours) for 10 work cells, even when considering SBC by the p-q position method.

Accordingly, the recommended bottom-up mDFLP model includes the SBC generated by the p-q position method and considers linearisation form 2 for the absolute value functions in (VI-7), (VI-8) and (VI-15). In particular, the last two would be linearised as illustrated in (VI-37)-(VI-42).

$$d_{tij}^{cs} = d_{tij}^{+cs} + d_{tij}^{-cs} \qquad \forall s, \forall t, \forall i, \forall j > i \qquad \text{(VI-37)}$$

$$\left(c_{ti}^{vs} + \frac{l_{ti}^{s}}{2}\right) - \left(c_{tj}^{vs} + \frac{l_{tj}^{s}}{2}\right) = d_{tij}^{+cs} - d_{tij}^{-cs} \qquad \forall s, \forall t, \forall i, \forall j > i \qquad \text{(VI-38)}$$

$$d_{tij}^{+cs}, d_{tij}^{-cs} \geq 0 \qquad \forall s, \forall t, \forall i, \forall j > i \qquad \text{(VI-39)}$$

$$p_{ti}^{s} = p_{ti}^{+s} + p_{ti}^{-s} \qquad \forall s, \forall i, \forall t > 1 \qquad \text{(VI-40)}$$

$$\left(c_{ti}^{vs} + \frac{l_{ti}^{s}}{2}\right) - \left(c_{t-1,i}^{vs} + \frac{l_{t-1,i}^{s}}{2}\right) = p_{ti}^{+s} - p_{ti}^{-s} \qquad \forall s, \forall i, \forall t > 1 \qquad \text{(VI-41)}$$

$$p_{ti}^{+s}, p_{ti}^{-s} \geq 0 \qquad \forall s, \forall i, \forall t > 1 \qquad \text{(VI-42)}$$

In summary, the equivalent MOMILP model of the bottom-up mDFLP considers the optimisation of Objective Functions (VI-1)-(VI-3), subject to Constraints (VI-4)-(VI-6), (VI-9)-(VI-14), (VI-17)-(VI-25), (VI-28)-(VI-30), and (VI-35)-(VI-42).

6.3 Bottom-up mDFLP solution

Given the proposed model's multi-objective nature, this paper uses the LO as a strategy to search for a Pareto optimal solution to the N=12/T=3 case study. Firstly, according to the characteristics of the manufacturing system and the preference of the company's top management, as part of the LO, the TMHC and TRAC are simultaneously optimised (*f1*). Secondly, the TCR (*f2*) and, finally, the average AUR (*f3*) for the three time periods making up the planning horizon are considered. This order of priority coincides with the frequency of use of these objective functions in the reviewed literature (Table VI-1). So the following sequence of subproblems is considered in the application of the LO:

Subproblem 1: Optimise the highest priority Objective Function (f_1):

$$\min f_1 = Z_1^*$$

subject to:

Constraints (VI-4)-(VI-6), (VI-9)-(VI-14), (VI-17)-(VI-25), (VI-28)-(VI-30), (VI-35)-(VI-42).

Subproblem 2: Optimise the Objective Function with the second order of priority (f_2):

$$\max f_2 = Z_2^*$$

subject to:

$f_1 \leq Z_1^*$ (VI-43)

and Constraints (VI-4)-(VI-6), (VI-9)-(VI-14), (VI-17)-(VI-25), (VI-28)-(VI-30), (VI-35)-(VI-42).

Subproblem 3: Optimising the Objective Function with the third order of priority (f_3):

$\max f_3 = Z_3^*$

subject to:

$f_2 \geq Z_2^*$ (VI-44)

and Constraints (VI-4)-(VI-6), (VI-9)-(VI-14), (VI-17)-(VI-25), (VI-28)-(VI-30), (VI-35)-(VI-43).

Once the previous subproblems are successively solved, a dynamic plant layout is obtained. It involves an ordering scheme for each considered time period. The results of the most relevant decision variables for this solution are shown in Appendix VI. The total computational time is 5 hours, 44 minutes and 32 seconds, which is considered acceptable (Sherali et al., 2003). The representation of the plant layout obtained for each time period is presented in Figure VI-6.

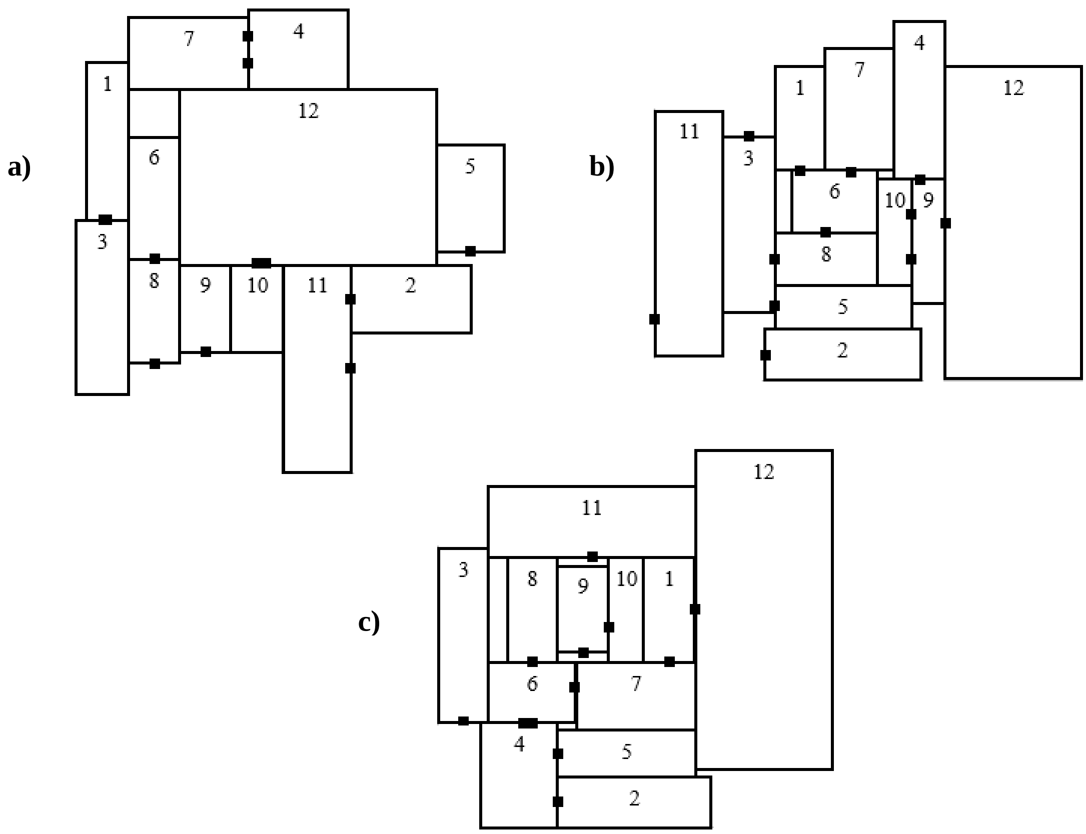

Figure VI-6. Dynamic layout for each time period: a) *t*=1, b) *t*=2 and c) *t*=3.

Similarly, and for comparative purposes, the model is run by fixing the position of the lower left vertex of each work cell, as well as its orientation, over the three time periods by adding Constraints (VI-45) and (VI-46).

$$cv_{ti}^{s} = cv_{t+1,i}^{s} \qquad \forall s, \forall t, \forall i \qquad \text{(VI-45)}$$

$$\Delta_{tiqr} = \Delta_{t+1,iqr} \qquad \forall t, \forall i, \forall q, \forall r > 1 \qquad \text{(VI-46)}$$

Once the LO-based sequential optimisation strategy is applied in line with these new constraints, an SFLP solution is obtained; i.e. a single solution for the entire planning horizon. The detailed results of the most relevant variables of this static solution are presented in Appendix VII, while the resulting layout representation is shown in Figure VI-7.

Table VI-8 offers the results of the model's objective functions for the three specific cases: a) the current plant layout; b) the solution corresponding to the dynamic plant layout; c) the solution corresponding to the static plant layout. As we can see, both the current layout and the static layout proposal do not incur rearrangement costs, Both the TFRC and TVRC provide a single ordering scheme for the entire planning horizon. Although the dynamic layout solution incurs rearrangement costs, it has lower overall costs than the other alternatives, which represents a 13.59% improvement over the current layout and one of 8.07% over the static proposal. This distribution represents a 3.65% improvement over the TCR of the current distribution and one of 2.58% for the static proposal.

On the contrary, the current layout is that with the best AUR, which can be justified by the lower level of priority assigned to this objective function in the LO-based model resolution strategy. It is important to note that a lower AUR solution does not represent any technical or economic operational constraints for the considered planning horizon, but only a lower level of flexibility for future changes.

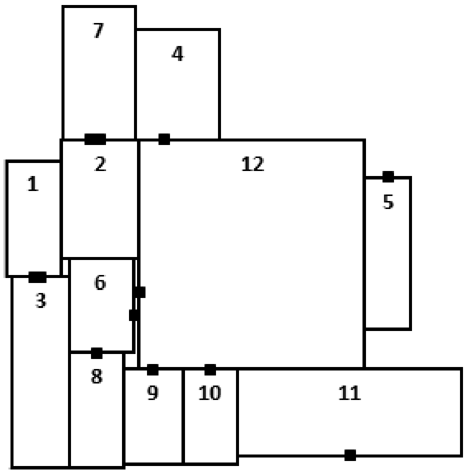

Figure VI-7. Representation of the static layout for the whole planning horizon.

Finally, it is worth noting that the dynamic bottom-up mDFLP performs better than the static one in all its indicators; i.e., total costs, TCR and AUR. However, if the company's top management considers that savings in the TMHC represented by the implementation of the dynamic layout solution do not compensate for the possible management effort involved in making changes to both the BL and DL at the beginning of each time period, it can consider the static layout solution to be viable because it does not incur rearrangement costs and guarantees a 5.52% improvement in the TMHC and of 1.07% in the TCR in relation to the current plant layout.

Table VI-8. Objective functions results.

OF	OF description	Current layout	bottom-up mDFLP solutions			
			Dynamic	Improve-ment (%)	Static	Improve-ment (%)
Min f_1	a) TMHC ($/year)	126984.33	108895.66	14.24%	119972.03	5.52%
	b) TFRC ($/year)	0.00	600.00	-	0.00	-
	c) TVRC ($/year)	0.00	231.34	-	0.00	-
	Total costs (a+b+c)	126984.33	109727.00	13.59%	119972.03	5.52%
Max f_2	TCR	306.84	318.035	3.65%	310.123	1.07%
Max f_3	AUR (%)	35.56	30.63	-13.86%	30.05	-15.49%

7 Conclusions

This paper presents an MOMINLP model, called bottom-up mDFLP, which allows the dynamic facility layout problem to be addressed with a bottom-up multi-objective planning approach by considering both quantitative and qualitative objective functions. As far as the authors of this article know, this is the first time that mDFLP is formulated with a bottom-up approach.

The model considers three objective functions: (VI-1) minimising both the TMHC and TRAC; (VI-2) maximising the TCR; (VI-3) maximising the AUR. The model is applied to the case study of a company in the metal-mechanical sector, with 12 departments and a planning horizon composed of three time periods of differentiated demand and material handling costs.

In addition to the bottom-up multi-objective approach that is considered in the model's formulation, other novel elements are proposed to address mDFLP, such as the estimation of both the TCR and AUR. On the one hand, the TCR is obtained by summing the product of the closeness ratings by an adjacency factor that can be interpreted as the complement of the ratio representing the distance between the centroids of each department in the x- and y-axes direction in relation to the maximum possible distance, defined by the sum of the width and length of the surface available for the plant layout. On the other hand, maximising the average AUR of the entire planning horizon is considered to be an objective function by assuming, during each time period, that the ratio between the area occupied by work cells and the total available area of the plant should come as close as possible to unity. This forces the model to generate solutions that better use the available space. This is possible thanks to considering several DL alternatives that do not necessarily have equal areas for each work cell during each time period into which the planning horizon is divided.

Additionally to adjust the original multi-objective model, nine simplified versions of the same model are tested, but they have a single-objective and single-period nature, to determine which formulation strategy generates the least computational effort among three linearisation forms of the absolute value functions and two SBC generation forms. As a result of this experimentation, for problems of six departments or fewer, not using SBC, but employing linearisation form 1 of the absolute value functions in (VI-26)-(VI-27) yields lower TMHC values and shorter computational times than in other variants. However, for instances of seven departments or more, using the SBCs generated by applying the p-q position method combined with linearisation form 2 of the absolute value functions in (VI-28)-(VI-29) significantly reduces the computational time.

Once the proposed model is adjusted, the MOMILP equivalent is obtained, whose resolution employs the LO method as a strategy to balance the three considered objective functions, which allow two pareto optimal solutions to be obtained for the proposed real case study: (VI-1) a dynamic layout (proposing a different plant layout for each time period); (VI-2) a static layout (proposing a single ordering scheme for the entire planning horizon). The results of the objective functions in each case are compared to the values of the current layout, which leads the dynamic solution to better perform in terms of total costs and the TCR in relation to not only the current layout of the case under study, but also to the AUR for the static layout proposal.

Managerial implications are oriented to provide facility layout planners with a new optimisation model in two versions (dynamic and static), whose solutions in both approaches constitute improvement opportunities in relation to the plant layout to plan or reconfigure. Based on the results of both proposals, companies can assess the costs and benefits of each alternative solution and choose that which best aligns with their strategic planning and favours the performance of their operations.

Future research could run the proposed MOMINLP, bottom-up mDFLP model, by considering production systems with more work cells, and resort to other resolution strategies based on deep reinforcement learning. Along the same lines, the use of metaheuristic or matheuristic algorithms is recommended as possible resolution approaches. Additionally, the proposed model can be applied to case studies from other industrial sectors apart from the metal-mechanical sector herein contemplated. Other future research works could consider uncertainty conditions when estimating the material flow intensity for each time period, and could integrate the system of corridors through which it could circulate throughout the production system. In addition, a larger number of objectives can be incorporated into the model, including the minimisation of occupational health and safety risks, among others.

8 References

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CAPÍTULO VII

CONCLUSIONES Y LÍNEAS FUTURAS DE INVESTIGACIÓN

CAPÍTULO VII

CONCLUSIONES Y LÍNEAS FUTURAS DE INVESTIGACIÓN

1 Introducción

En esta tesis doctoral se ha abordado la problemática de la distribución espacial de plantas industriales en entornos de demanda dinámicos. La distribución en planta (FLP) se define como el proceso que involucra la disposición, en el espacio físico disponible, de los elementos que conforman el sistema de producción de manera que se cumplan adecuada y eficazmente los objetivos estratégicos de la organización (Pérez-Gosende et al., 2021). Se considera una decisión estratégica dentro de la planificación de las operaciones empresariales, ya que su elevado coste impide a menudo que se tome como una opción viable durante periodos de tiempo cortos, y de ella dependen en gran medida la eficiencia, la productividad y la competitividad de los sistemas de fabricación. Para abordar el problema, en esta tesis doctoral se ha propuesto un modelo de optimización matemática multi-objetivo basado en un enfoque de planificación ascendente o *bottom-up*, teniendo en cuenta criterios cuantitativos y cualitativos.

En primer lugar, en el capítulo II se ha desarrollado una revisión bibliográfica sobre el problema de FLP en su contexto más amplio. Para analizar los 232 artículos seleccionados se ha propuesto una taxonomía que permite clasificar el problema en función de su tipo (nuevas instalaciones o redistribución); el enfoque de planificación (estático o dinámico); la fase de planificación (distribución de conjunto o detallada); las características de las instalaciones (número de edificios, número de plantas, consideración del espacio desde el punto de vista bidimensional o tridimensional, la forma y el área de los departamentos); la configuración del sistema de manipulación de materiales (configuraciones de una fila, de dos filas, de varias filas, de filas paralelas, de bucle cerrado y de campo abierto); así como el enfoque para la generación y evaluación de alternativas de distribución en planta.

La generación de alternativas de distribución en planta se ha abordado, principalmente, mediante modelos matemáticos de optimización, concretamente, con modelos de programación cuadrática discreta para departamentos de igual tamaño, o mediante modelos de programación entera mixta lineales o no lineales para departamentos con áreas desiguales. Otros enfoques para generar alternativas de distribución implican recurrir al conocimiento de expertos y a herramientas de planificación asistida por computadoras.

Los artículos que abordaron el FLP como un problema de optimización matemática fueron caracterizados de acuerdo al tipo de modelo matemático (discreto, continuo); la naturaleza de la función objetivo (monobjetivo, multiobjetivo); el tipo de datos (deterministas, no deterministas); la consideración de la demanda cierta o incierta; las métricas de distancia empleadas (rectilínea, euclidiana, euclidiana cuadrada, Chebychev, basada en el contorno y basada en la trayectoria del flujo de materiales); y el enfoque de solución adoptado (exacto, aproximado, estocástico, matemático, inteligente e híbrido). En general, los algoritmos de solución más utilizados fueron los metaheurísticos: algoritmos genéticos, recocido simulado, enjambre de partículas, búsqueda tabú, colonia de hormigas y búsqueda de vecindad variable.

En el contexto industrial actual, en el que la transición de la cadena de suministro tradicional orientada a los costes a la cadena de suministro sostenible es casi obligatoria, la consideración de condiciones de producción estáticas, como la demanda constante a lo largo del horizonte temporal de planificación, no es un supuesto realista, pero ha sido la estrategia de planificación más frecuentemente abordada en la literatura científica relacionada con el FLP. Para ayudar a cubrir este vacío, en el capítulo III se ha profundizado en la distribución en planta en entornos dinámicos (DFLP) mediante una revisión bibliográfica adicional para ofrecer las tendencias actuales y algunas directrices para investigación futuras en este contexto.

En la bibliografía revisada se pudo observar que las decisiones de DFLP se centraban, exclusivamente, en dos de las tres dimensiones de la sostenibilidad: la económica y la social, dejando a un lado la dimensión ambiental, que sería un ámbito a investigar. Se identificó, además, que la mayor parte de la bibliografía científica en el contexto del DFLP no aborda el problema en entornos industriales concretos sino aplicado a casos de estudio hipotéticos o ejemplos numéricos, lo que sustenta la limitada aplicación de la investigación sobre el FLP en la práctica, como ya había sido señalado en Meller et al. (2010). Por otro lado, es común el tratamiento de la distribución en bloque y la distribución detallada por separado cuando en la práctica sería más útil para los directores de operaciones considerar ambas fases como parte del mismo problema. Asimismo, la mayoría de los modelos de optimización buscan minimizar una única función objetivo de carácter cuantitativo. Lo anterior, sustenta la necesidad de abordar el FLP en entornos de aplicación concretos, abordando tanto la distribución de bloque como la distribución detallada como parte del mismo problema, y considerando un enfoque de modelación multi-objetivo que involucre tanto criterios cualitativos como cuantitativos.

En el capítulo IV se ha desarrollado un análisis comparativo de las características y limitaciones de cinco modelos matemáticos de optimización seleccionados como referencia para formular un nuevo modelo optimización que se adapte mejor al contexto real de las operaciones industriales y facilite la toma de decisiones de planificación de la distribución en planta. Como resultado de este análisis se han identificado ciertas características técnicas que se sugiere que sean consideradas al formular el FLP como un modelo de optimización matemática, siendo éstas: (i) ser dinámico, o sea, considerar varios periodos temporales como parte del horizonte de planificación en respuesta a la variabilidad de la demanda; (ii) partir de previsiones de demanda en condiciones de incertidumbre; (iii) considerar departamentos regulares y de áreas diferentes; (iv) contemplar que el flujo de materiales se produce entre los puntos de recepción y despacho situados en los bordes o fronteras de los departamentos, y no en sus centroides; (v) considerar en el diseño del *layout* el diseño de los pasillos por donde circularán los materiales, los medios de transporte y el personal; (vi) considerar un enfoque de optimización multiobjetivo que tenga en cuenta factores cualitativos y cuantitativos; y (vii) contemplar un enfoque de planificación *bottom-up* que tenga en cuenta primero la distribución detallada en el interior de cada uno de los departamentos que componen el sistema de producción y, posteriormente, la disposición de estos departamentos en el espacio físico disponible o, alternativamente, que tenga en cuenta ambas fases de forma concurrente.

En este sentido, el capítulo V presenta un marco conceptual para facilitar a académicos y profesionales la toma de decisiones sobre la planificación multiobjetivo del FLP. En lugar de considerar las fases de diseño en bloque y de diseño detallado de forma consecutiva mediante el enfoque tradicional descendente o *top-down*, el marco conceptual formaliza el FLP como un problema multiobjetivo (mFLP) siguiendo estas fases en sentido inverso mediante un enfoque ascendente o *bottom-up*, e integrando también una tercera fase, denominada fase de diseño refinado, que no se había contemplado anteriormente en la literatura. Además de identificar las entradas y salidas de cada fase, el marco conceptual agrupa varios objetivos relacionados con el mFLP que han sido considerados recientemente en la literatura, y los formaliza y contextualiza según la fase de planificación en la que están involucrados.

En línea con el marco de trabajo conceptual desarrollado, el capítulo VI presenta un modelo multiobjetivo no lineal entero mixto (MOMINLP), denominado bottom-up mDFLP, que permite abordar el problema de la distribución en planta de instalaciones industriales en contextos de demanda dinámica con un enfoque de planificación multiobjetivo *bottom-up* y considerando funciones objetivo de naturaleza cuantitativa y cualitativa. El modelo considera tres funciones objetivo que persiguen: (1) minimizar el coste total de manejo de materiales (TMHC) y el coste total de reordenamiento (TRC); (2) maximizar el *rating* total de cercanía entre departamentos (TCR); y (3) maximizar el ratio de utilización de área (AUR). El modelo se aplica a un caso de estudio de una empresa del sector metalmecánico con 12 departamentos y un horizonte de planificación compuesto por tres periodos de tiempo de demanda y costes de manejo de materiales diferenciados.

Además del enfoque multiobjetivo *bottom-up* que se considera en la formulación del modelo, se proponen otros elementos novedosos para abordar el mDFLP, como la estimación tanto del TCR como del AUR. Adicionalmente, para ajustar el modelo multiobjetivo original, se experimentaron nueve versiones simplificadas del mismo modelo, pero de carácter monobjetivo y monoperíodo, para determinar qué estrategia de formulación generaba el menor esfuerzo computacional entre tres formas de linealización de las funciones de valor absoluto y dos formas de generación de restricciones de ruptura de simetría.

Una vez ajustado el modelo propuesto se obtuvo el equivalente modelo lineal entero mixto multiobjetivo (MOMILP), cuya resolución emplea el método lexicográfico como estrategia para equilibrar las tres funciones objetivo consideradas, lo que permitió obtener dos soluciones pareto-óptimas para el caso de estudio real propuesto: (a) una solución dinámica que propone un esquema de ordenamiento diferente para cada periodo de tiempo; y (b) una disposición estática que propone un único esquema de distribución para todo el horizonte de planificación temporal. Los resultados de las funciones objetivo en cada caso se comparan con los valores del *layout* actual, lo que ha validado que la solución dinámica ha tenido un mejor comportamiento en términos de costes totales y del TCR en relación no sólo con el layout actual del caso en estudio, sino también con el AUR para la propuesta de layout estático.

La aplicación del modelo de optimización propuesto en el contexto de una empresa real del sector metalmecánico abre un conjunto de lineas de investigación. Éstas están vinculadas de un modo u otro con el problema inicialmente planteado en esta tesis doctoral aunque escapan a la delimitación de su alcance. Estas líneas de investigación futuras se presentan en el siguiente apartado.

2 Líneas futuras de investigación

Como parte de la investigación desarrollada en esta tesis doctoral se han identificado varias vías de trabajo que pueden representar líneas de investigación para futuras investigaciones en el contexto de la planificación de la distribución espacial de plantas industriales. En este apartado se describen, sucintamente, las más relevantes.

Tradicionalmente, el FLP se ha abordado a través de la metodología de planificación sistemática de la distribución (*systematic layout planning*, SLP), a través de un conjunto de fases que involucran desde la localización de la planta hasta la implementación del layout (Muther, 1961). Sin embargo, las fases más abordadas en la literatura relacionada al FLP formulado como un problema de optimización matemática, son las dos fases intermedias, denominadas fase de distribución de conjunto (*block layout*, BL) y fase de distribución detallada (*detailed layout*, DL). Este proceso de planificación jerárquico, tradicionalmente se realiza de forma secuencial, y es conocido en la literatura como enfoque *top-down* (Meller et al., 2004). No obstante, se ha demostrado que, en la práctica, los analistas de *layout* prefieren comenzar por la fase DL y luego proseguir con la BL, en lo que ha sido formalizado por (Meller et al., 2010) como un enfoque *bottom-up*. Esta tesis doctoral ha considerado este último enfoque para abordar el FLP en entornos de demanda dinámicos, siendo la primera vez que el enfoque *bottom-up* es empleado en este contexto mediante un modelo de optimización matemática multiobjetivo. Sin embargo, es poco común en la literatura el desarrollo de modelos matemáticos que aborden tanto la fase BL como la fase DL de forma simultánea. Es mucho más frecuente que las contribuciones en este ámbito se realicen en el modelado de una de estas dos fases (Pérez-Gosende et al., 2021). En tal sentido, investigaciones futuras deben considerar el modelado de ambas fases de manera secuencial o concurrente para facilitar a los directores de operaciones la toma de decisiones de planificación de la distribución en planta.

Al formular el FLP como un problema de optimización matemática es común el uso combinado del TMHC y el TRAC a lo largo de todo el horizonte de planificación como una función monoobjetivo de naturaleza cuantitativa (Hosseini-Nasab et al., 2018; Pérez-Gosende et al., 2020a). Sin embargo, en la vida real, el FLP es un problema de carácter multiobjetivo, debido a la gran cantidad de factores que intervienen en la decisión final (Bozorgi et al., 2015; Matai, 2015; Singh & Ingole, 2019). En este contexto, las investigaciones futuras que aborden el FLP en cualquiera de sus variantes, deberían considerar, además del coste del manejo de materiales, la seguridad y salud en el trabajo, el manejo de desperdicios y sustancias peligrosas, la satisfacción del personal, y la flexibilidad para futuras distribuciones, entre otras.

En Pérez-Gosende (2021) se demostró que casi el 80% de los trabajos revisados (183 de 232 artículos) optó por buscar soluciones al FLP en problemas de prueba clásicos de la literatura o casos de estudio hipotéticos, lo que demuestra que las contribuciones a la solución del FLP han tenido poca aplicación en la práctica tal como ya se había indicado en (Meller et al., 2010). De acuerdo con ello se espera que investigaciones futuras aborden el FLP en casos de estudio de la vida real, para contribuir, tal como fue una de las motivaciones de esta tesis doctoral, a cerrar esta brecha de investigación.

Cuando en la toma de decisiones relativas al FLP se parte del supuesto que la demanda de productos se mantendrá constante durante todo el horizonte de planificación, el proceso se focaliza, básicamente, hacia la obtención de un diseño de *layout* único. En este caso, al considerar que las condiciones productivas son estáticas, el problema es conocido como de distribución en planta estática o uniperíodo (SFLP) (Vitayasak et al., 2017). Sin embargo, esta asunción puede resultar impráctica en la mayoría de los sectores industriales pues es poco probable que la demanda y, por tanto, el flujo de materiales en el interior de la planta se mantenga constante en el tiempo. En un entorno empresarial cada vez más globalizado es más realista considerar condiciones dinámicas (Bozorgi et al., 2015; Defersha & Hodiya, 2017), debido, principalmente, a la necesidad constante de reajustar la capacidad productiva como consecuencia de las fluctuaciones de la demanda, los ciclos de vida de productos cada vez más cortos, la adopción de cambios tecnológicos de los sistemas de fabricación, y a los eventos disruptivos de las cadenas de suministro, entre otros factores (Emami & S. Nookabadi, 2013; Vitayasak et al., 2017). A partir de este enfoque, denominado dinámico o multiperíodo (DFLP), se diseña un *layout* para cada período de tiempo de modo que se minimicen los costes totales de transporte de materiales y los relacionados con la redistribución de las instalaciones (Pournaderi et al., 2019). Entre la literatura revisada, como puede observarse en el capítulo V, menos de la tercera parte de los trabajos que abordaron el FLP desde una perspectiva multiobjetivo consideraron un enfoque de planificación dinámico.

En el capítulo III se promovió la planificación de la distribución de las instalaciones considerando los entornos dinámicos como una estrategia alternativa para contribuir a la sostenibilidad de las cadenas de suministro. Sin embargo, a pesar de la popularidad de este tema entre los investigadores del campo de la dirección de operaciones, se identificó que todavía existen brechas de conocimiento en lo que respecta a la inclusión equilibrada de las dimensiones que componen la sostenibilidad (Pérez-Gosende et al., 2020b). Hasta la fecha, las contribuciones de la comunidad científica a la toma de decisiones en el contexto del DFLP se han concentrado, principalmente, en la dimensión económica de la sostenibilidad, y en la dimensión social en menor medida. No se encontró ninguna mención explícita a la dimensión medioambiental en la literatura revisada.

Por otra parte, los resultados de esta tesis doctoral podrían animar a los profesionales o practicantes a facilitar su toma de decisiones de distribución en planta desde una perspectiva holística, no sólo considerando el factor económico sino también elementos de carácter medioambiental y social, para de esta forma contribuir a una gestión sostenible de la cadena de suministro. Esto también podría ayudar a mejorar la reputación de la empresa entre los clientes actuales y potenciales, los inversores, los proveedores, las entidades gubernamentales y otras partes interesadas ya comprometidas con el desarrollo sostenible.

También es importante subrayar que, a pesar de los intentos que se han hecho para considerar la dimensión social de la sostenibilidad en la planificación dinámica de la distribución de las instalaciones, éstos aún son escasos (Pérez-Gosende et al., 2020b). Es necesario realizar más esfuerzos para incluir un análisis de los riesgos físicos, químicos, biológicos y ergonómicos a la hora de determinar las prioridades de proximidad entre las máquinas y los puestos de trabajo de los departamentos. En la misma línea, cabe analizar en qué medida la distribución en el espacio industrial de los elementos que componen el sistema de producción/servicio podría contribuir a la humanización del trabajo y a favorecer el bienestar, la realización personal y la autoestima de los trabajadores (y de los clientes); aumentar la motivación intrínseca; reducir el estrés físico y mental; y evitar la exposición a riesgos psicosociales. Sin duda, se trata de una brecha que investigaciones futuras deberán contribuir a cerrar.

El estudio de revisión de Pérez-Gosende et al. (2020b) demostró que aproximadamente el 64% de la literatura revisada en el contexto del DFLP consideraba los departamentos de áreas iguales, y solo el 36% restante elegía el enfoque de áreas desiguales, lo que demuestra una cierta subrepresentatividad de este último enfoque en la literatura científica. La planificación del *layout* en un caso de estudio de la realidad bajo la asunción de que los departamentos tienen áreas iguales cuando en realidad no lo son, puede generar soluciones subóptimas con un TMHC significativamente inferior al que se incurriría en la realidad, de ahí la importancia de considerar las dimensiones reales de los departamentos de acuerdo con las operaciones que en ellos se desarrollarán. En estos casos donde el DFLP se formula considerando departamentos con áreas diferentes suelen emplearse modelos de optimización que permiten la representación de la distribución en planta en el espacio continuo (Mazinani et al., 2013; McKendall & Hakobyan, 2010), lo que facilita la simulación de condiciones de operación más cercanas a la realidad.

A pesar de que uno de los principios clásicos del FLP es obtener el máximo aprovechamiento posible del espacio en el interior de la planta industrial, la mayoría de artículos revisados consideró el espacio desde el punto de vista bidimensional, enfocándose, únicamente, en obtener el máximo aprovechamiento de la superficie del suelo de la planta. Al ser poco común la consideración del espacio tridimensional en el contexto del FLP, las investigaciones futuras deberían poner una especial atención en este aspecto para la optimización del problema de la distribución en planta, aunque esto represente un desafío adicional en su resolución.

De igual forma, la mayoría de las investigaciones han considerado el diseño de la distribución en planta en el contexto de un único piso. Sin embargo, es común que los sistemas de fabricación consideren más de un piso para el desarrollo de sus operaciones. En este contexto, en la literatura revisada solo tres trabajos (6%) consideraron varios pisos en la formulación del mFLP (Che et al., 2017; Cheng & Lien, 2012; Hathhorn et al., 2013).

Al ser la minimización del MHC una de las funciones objetivo más usadas en los modelos de optimización del FLP (Hosseini-Nasab et al., 2018; Pérez-Gosende et al., 2020b, 2021), la ubicación de los puntos de recepción y despacho en cada centro de actividad es determinante. Es común que al modelar el FLP se asuma que los puntos de recepción y despacho de materiales (P/D) se encuentran en el centroide de cada departamento y la distancia entre estos centroides determina la distancia recorrida por el flujo de trabajo. Estas suposiciones pudieran funcionar bien en sistemas de fabricación donde el transporte de materiales se realiza mediante grúas de pórtico (Asef-Vaziri et al., 2017), pero son incompatibles con la mayoría de los diseños de *layout* de la vida real, donde los puntos P/D están ubicados, generalmente, en los bordes de los departamentos, y el flujo de trabajo circula a través de los pasillos que los interconecta. De ahí que los modelos que consideran distancias intercentroides rectangulares o euclideas puedan generar soluciones pseudo-óptimas con TMHC significativamente inferiores a los que se incurrirían en situaciones reales.

En los sistemas de fabricación, los pasillos son caminos que permiten el movimiento del personal, así como de los medios de transporte y los materiales entre las distintas áreas de trabajo. La estructura de los pasillos contribuye a la eficiencia de la distribución en planta por su incidencia en la reducción de la distancia recorrida por el flujo de materiales, el tiempo medio de flujo y los costes de manipulación de materiales (Pourvaziri et al., 2021). Sin embargo, a pesar de la importancia de este aspecto, sólo unos pocos artículos en la literatura han abordado el diseño de la estructura de pasillos de forma integrada en el diseño de la distribución en planta de los sistemas de fabricación (Chang et al., 2006; Gómez et al., 2003; Klausnitzer & Lasch, 2016, 2019; Lee et al., 2005; Pourvaziri et al., 2021). Por lo tanto, las investigaciones futuras deberían prestar una mayor atención a la integración del sistema de pasillos al abordar el FLP en sistemas de producción de la realidad.

En la literatura revisada, pudo constatarse que el TMHC y el TRAC son comunes a cualquier formulación del DFLP tal como fue definido inicialmente por Rosenblatt (1986). Sin embargo, en la mayoría de los casos se considera que el TRAC es fijo, relacionándolo, únicamente, con aquel en el que se incurre durante la interrupción de la producción por las labores de reorganización del *layout* al inicio de cada período temporal. Solo unos pocos autores han considerado los costes variables de reorganización asociados a la cantidad de desplazamiento de un departamento en el espacio entre un período temporal y otro (Abedzadeh et al., 2013; Erfani et al., 2020; Erik & Kuvvetli, 2021). Ninguno de estos trabajos describe de forma objetiva procedimientos para la obtención de estos costes. De tal forma, es recomendable que las investigaciones que puedan desarrollarse en el futuro consideren la deficinión de procedimientos para la estimación del coste de manipulación de materiales, así como de los costes fijos y variables de reorganización, pues de la magnitud de éstos dependen en gran medida los esquemas de ordenamiento finales generados por el modelo. Una estimación muy subjetiva de estos costes puede generar soluciones factibles desde el punto de vista matemático, pero inviables desde el punto de vista técnico-económico en entornos industriales concretos.

La utilización de proyecciones de la demanda de los productos es fundamental para cuantificar el flujo de materiales entre los departamentos de producción, que es uno de los parámetros fundamentales al modelar el FLP. En este contexto, aproximadamente 9 de cada 10 trabajos que abordaron el FLP como un problema de optimización multiobjetivo parten del supuesto de que la demanda es conocida de antemano, lo que pudiera ser una asunción poco realista al diseñar plantas completamente nuevas, donde, generalmente, no se dispone de información histórica sobre el comportamiento de la demanda. Esta razón, unida a la volatilidad de la demanda en un mundo cada vez más globalizado, sustenta la necesidad de considerar su estimación bajo condiciones de incertidumbre.

La planificación de la capacidad de producción como respuesta a la variabilidad de la demanda, la toma de decisiones para lidiar con eventos disruptivos en las cadenas de suministro y la adopción de nuevas tecnologías y procesos, entre otros factores, pueden implicar la necesidad de realizar ajustes a la distribución en planta, por ello, al planificarla es conveniente considerar el mayor grado de flexibilidad posible para permitir cambios futuros con el mínimo esfuerzo, la mayor rapidez y el menor gasto de recursos. Entre la literatura consultada solo un artículo consideró la flexibilidad al abordar el mFLP (Singh & Singh, 2011).

Los modelos de optimización matemática han sido, tradicionalmente, abordados en profundidad como un enfoque para lograr una distribución óptima o un conjunto de soluciones aceptables ante diferentes variantes de FLP. No obstante, en la revisión bibliográfica realizada como parte de esta tesis doctoral se identificaron trabajos de investigación que abordaban otros enfoques para el mismo objetivo, como el conocimientos de expertos o las herramientas de planificación asistida por ordenador. Debido a la complejidad de la formulación, interpretación y resolución de los modelos de optimización matemática, las herramientas de planificación de *layout* asistidas por computador son preferidas por los tomadores de decisiones de distribución en planta a nivel empresarial ya que éstas pueden desempeñar un papel fundamental en la mejora de su capacidad para evaluar y decidir la idoneidad de las diferentes alternativas de solución con respecto a los objetivos o criterios preestablecidos (Taticchi et al., 2015). Sin embargo, tal como se demostró en el capítulo II de esta tesis, la mayoría de las herramientas de planificación asistida por computadora utilizadas en la literatura revisada para generar alternativas de diseño no están disponibles para su uso comercial. Por ello, las investigaciones futuras deben proyectarse hacia el desarrollo de nuevas herramientas de software basadas en el *cloud computing* y, por tanto, accesibles desde internet para facilitar a académicos y profesionales la toma de decisiones efectivas en cuanto a la planificación de la distribución espacial de plantas industriales.

Investigaciones futuras podrían ejecutar el modelo MOMINLP bottom-up mDFLP propuesto en esta tesis doctoral considerando sistemas de producción con un mayor número de departamentos, y recurrir a otras estrategias de resolución basadas en el aprendizaje por refuerzo o la programación dinámica para la propuesta automática de alternativas de distribución iniciales. En la misma línea, se podría investigar el empleo de algoritmos metaheurísticos o matheurísticos o incluso de contextos de supercomputación o cuánticos como posibles enfoques de resolución para reducir los tiempos computacionales en problemas de gran tamaño. De igual forma, sería relevante que el modelo propuesto pudiese aplicarse a casos de estudio de otros sectores industriales además del sector metalmecánico.

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ANEXO I

CHARACTERISTICS OF THE MATHEMATICAL MODELS USED IN THE FORMULATION OF THE SFLP

ANEXO I

CHARACTERISTICS OF THE MATHEMATICAL MODELS USED IN THE FORMULATION OF THE SFLP

References	Problem representation	Type of objective function	Objective function	Constraints	Demand	Type of data	Distance metric	Solution approach
Samarghandi et al. (2010)	C	Q	d	4,7	C	D	R	A(MH)
Díaz-Ovalle et al. (2010)	C	Q	n,o	4,23	C	D	E	E
Drezner (2010)	C	Q	d	4	C	D	R	E
Hernández Gress et al. (2011)	C	Q	a	2,4	C	D	R	A(MH)
Jithavech and Krishnan (2010)	D	Q	a	2	U	ND	R,E	A(MH)
Jung et al. (2010)	D	Q	n,o,p	2,4	C	D,ND	E	H(E,S)
Komarudin and Wong (2010)	C	Q	a	2,4,13	C	D	R	A(MH)
Meller et al. (2010)	C	Q	a	2,4,5,6	C	D	R	E
Samarghandi and Eshghi (2010)	C	Q	a	2,4	C	D	R	A(MH)
Sanjeevi and Kianfar (2010)	C	Q	d	2,4	C	D	R	E
Scholz et al. (2010)	C	Q	a	2,4	C	D	R	A(MH)
Singh and Singh (2010)	D	MO	g,f,A,D	2	C	D	R	A
Yew Wong and Chiak See (2010)	D	Q	a	2	C	D	R	A(MH)
Kulturel-Konak and Konak (2011a)	C	Q	a	2,4	C	D	R	A(MH)
Datta et al. (2011)	C	Q	a	2,4,7	C	D	R	A(MH)
González-Cruz & Gómez-Senent (2011)	D	Q	y	-	C	D	-	A(IA)
Jankovits et al. (2011)	C	Q	a	2,4	C	D	R	E
Ku et al. (2011)	D	MO	a,j,m	2	C	D	R	A(MH)
Kulturel-Konak and Konak (2011b)	C	Q	a	2,4	C	D	R,E	A(MH)
Kumar et al. (2011)	C	Q	d	3,16	C	D	R	A(IA)
Park et al. (2011)	C	Q	o,n,c,p	2,10,11,12	C	D	R	E
Şahin (2011)	D	MO	a,A	2	C	D	R	A(MH)
Singh and Singh (2011)	D	MO	g,A	2	C	D	R	A
Taghavi and Murat (2011)	C	Q	a	2,3,4	C	D	R	A(IA)
Tuzkaya et al. (2013)	D	Q	a	2	C	D	R	A(MH)
Cheng and Lien (2012a)	D	MO	H,J	2,4	C	D	R	A(MH)
Lee and Tseng (2012)	C	Q	f	2	U	ND	R	H(MH,S)
Aiello et al. (2012)	C	MO	a,d,m,A	2,4,13	C	D	R	A(MH)
Altuntas & Selim (2012)	D	Q	g	-	C	ND	-	A(CA)
Amaral and Letchford (2013)	C	Q	a	2,4	C	D	R	E,A(IA)
Bernardi and Anjos (2013)	C	Q	a	2,4,13	C	D	SE	E

References	Problem representation	Type of objective function	Objective function	Constraints	Demand	Type of data	Distance metric	Solution approach
Bozer and Wang (2012)	C	Q	a	2,4,13	C	D	R	A(IA)
Cheng and Lien (2012b)	D	C	H,J	2	C	D	R	A(MH)
Ulutas and Kulturel-Konak (2012)	C	Q	a	2,4,13	C	D	R,E	A(MH)
Hale et al. (2012)	D	Q	d	-	C	D	R	A(CA)
Hungerländer and Rendl (2013)	C	Q	a	4	C	D	R	E
Kaveh et al. (2012)	D	Q	a	2	C	D	R	A(MH)
Krishnan et al. (2012)	D	Q	a,g	2	C	D	R	A(MH)
Kulturel-Konak (2012)	C	Q	a	2,4	C	D	R	A(MH)
Lee (2012)	C	Q	f	2	C	D,ND	R	H(S,MH)
Liu and Sun (2012)	C	Q	a	2,4,6	C	D	R	A(MH)
Navidi et al. (2012)	D	MO	a,o	2	U	D	R	A(MH)
Palubeckis (2012)	D	Q	a	2	C	D	R	E,A(MH)
Yang et al. (2013a)	C	MO	t,d,k	2	C	D	E	A(MH)
García-Hernández et al. (2013)	C	MO	a,m,B,C	2,4	C	D	R	A(MH)
Kothari and Ghosh (2013a)	C	Q	d	2	C	D	R	A(MH)
Matai et al. (2013a)	D	Q	a	2,4	C	D	R	A(IA)
Aiello et al. (2013)	C	MO	a,d,m,A	2,4	C	D	R	A(MH)
Amaral (2013)	C	Q	d	2,4	C	D	R	E
Kothari and Ghosh (2014a)	C	Q	d	2,4	C	D	R	A(MH)
Kothari and Ghosh (2014b)	C	Q	d	2,4	C	D	R	A(MH)
Chang and Ku (2013)	C	Q	a	2,4,13	C	D	R	A(MH)
García-Hernández et al. (2015)	C	MO	a,B	2,13	C	D	E	A(MH)
Garcia-Hernandez et al. (2013)	C	MO	g,B	2	C	D	R	A(MH)
Hathhorn et al. (2013)	C	MO	a,c	2,4,10,12,14	C	D	R	A
Jabal-Ameli and Moshref-Javadi (2014)	D	MO	a,G	2	C	D	R	A(MH)
Javadi et al. (2013)	C	Q	q,a,c,b	2,3,4,5,6	C	D	R	E
Leno et al. (2012)	C	MO	a,A	2,4,5	C	D	R	A(MH)
Jia et al. (2013)	C	Q	a	4	C	D,ND	R	H(A,S)
Jiang and Nee (2013)	C	Q	a,h,l	6,10,15	C	D	R,E	A(MH)
Khaksar-Haghani et al. (2013)	D	Q	a,q	2,3	C	D	R	A(MH)
Kothari and Ghosh (2013b)	C	Q	d	2,4	C	D	R	A(IA)
Kulturel-Konak and Konak (2013)	C	Q	a	2,4	C	D	R	M
Lenin et al. (2013)	C	MO	d,x,q	3,16	C	D	R	A(MH)
Matai et al. (2013b)	D	MO	g,A	2	C	D	R	A(MH)
Ou-Yang and Utamima (2013)	C	Q	d	2,4	C	D	R	H(S,MH)

References	Problem representation	Type of objective function	Objective function	Constraints	Demand	Type of data	Distance metric	Solution approach
Ripon et al. (2013)	C	MO	a,A	2,4,13	C	D	E	A(MH)
Ulutas and Kulturel-Konak (2013)	C	Q	a	2,4,13	C	D	R	A(MH)
Xiao et al. (2013)	C	Q	d	2,4	C	D	R	A(CA,MH)
Moatari-Kazerouni et al. (2015a)	C	MO	a,w	2	C	D	R	H (CA,IA)
Altuntas et al. (2014)	C	C	A	-	C	D,ND	-	A(CA)
Bukchin and Tzur (2014)	C	Q	a	2,4,13	C	D	R	E
Hong et al. (2014)	C	Q	d	2,4	C	D	R	E,A(IA)
Hungerländer (2014)	D	Q	d	2	C	D	R	E
Jiang et al. (2014)	C	MO	a,d,k,w	2,6,16	C	D	R,E	A(CA)
Kaveh and Safari (2014)	C	Q	d	3,16	C	D	R	A(MH)
Moatari-Kazerouni et al. (2015b)	C	MO	a,w	2	C	D	R	H (CA,IA)
Neghabi et al. (2014)	C	Q	a	2,4	C	D	R	E
Raja & Anbumalar (2014)	D	Q	a	-	C	D	R	A(CA)
Zhao and Wallace (2014)	D	Q	a	2,3,16,17	U	D	R	E,A(IA)
Zheng (2014)	C	Q	a	2,4,5	C	D	R	A(CA)
Palubeckis (2015a)	C	Q	d	2,4,7	C	D	R	A(MH)
Caputo et al. (2015)	C	Q	n,o,p	2,4,16	C	D	R	A(MH)
Garcia-Hernandez et al. (2013)	C	MO	g,B	2,4	C	D	R	A(MH)
Ghassemi and Neghabi (2015)	C	Q	A	2,4,10	C	D	R,CH	E
Gonçalves and Resende (2015)	C	Q	d	2,4,10	C	D	R	E,A(MH)
Helber et al. (2016)	D	Q	f	2	C	D	R	A(IA)
Hungerländer and Anjos (2015)	D	Q	d	2,4,7	C	D	R	E
Lee (2015)	C	Q	n,o,b	2,4,6	C	D	R	A(MH)
Matai (2015)	D	MO	a,f,r,A	2	C	D	R	A(MH)
Palubeckis (2015b)	D	Q	d	2	C	D	R	A(MH)
Qudeiri et al. (2015)	C	Q	a	4	C	D	R	H(MH,S,I)
Salmani et al. (2015)	C	MO	j,A	2,4	C	D	R	A
Saraswat et al. (2015)	C	MO	d,i,o	2,4,13,19,20	C	D,ND	R	A(MH)
Tasadduq et al. (2015)	C	Q	a	4	C	D	R,E,SE	A(CA,IA)
Zhao and Wallace (2016)	D	Q	a	2,3,16,17	U	D	R	A(IA)
Ahmadi and Akbari (2016)	C	Q	a	2,4,13	C	D	R	E
Alves et al. (2016)	C	Q	j	2,4	C	D,ND	-	H(IA,S)
Anjos and Vieira (2016)	C	Q	a	2,4,13	C	D	R,SE	E
Chae and Regan (2016)	C	Q	d	2,4,13	C	D	R	E
Che et al. (2017)	C	MO	a,j	2,4	C	D	R	A

References	Problem representation	Type of objective function	Objective function	Constraints	Demand	Type of data	Distance metric	Solution approach
Choi et al. (2017)	C	Q	a,j,m	2,4,8,18	C	D,ND	E	A(MH)
Glenn and Vergara (2016)	C	Q	d	2,4	C	D	R	A(IA)
Guan and Lin (2016)	C	Q	d	2,4	C	D	R	A(MH)
Horta et al. (2016)	D	Q	d	3	C	D	R	E
Hou et al. (2016)	C	Q	j	-	C	D	-	A(CA)
Huang and Wong (2017)	D	Q	a	2,5,6,11	C	D	R	E
Ingole and Singh (2017)	C	Q	a	2	C	D	R	A(MH)
Kim et al. (2016)	D	Q	d	15,17,21	C	ND	R	A(IA)
Neghabi and Ghassemi (2016)	C	C	A	2,4,8,10	C	D	CH	E
Paes et al. (2017)	C	Q	d	2,4,13	C	D	R,E,SE	A(MH)
Palubeckis (2017)	C	Q	d	2,4	C	D	R	A(MH)
Rubio-Sánchez et al. (2016)	C	Q	d	2,4	C	D	R	A(MH)
Sikaroudi & Shahanaghi (2016)	C	C	A	-	C	D	E	A(IA)
Xiao et al. (2016)	C	Q	d	2,4	C	D	R	A(CA,MH)
Leno et al. (2016)	C	Q	a	2,4,5	C	D	CB	A(MH)
Zhou et al. (2017)	D	Q	a	2	C	D	R	A(MH)
Asef-Vaziri et al. (2017)	C	Q	d	2,4,5,13	C	D	FB	A(MH)
Asef-Vaziri and Kazemi (2018)	C	Q	d	27	C	D	R	E
Azimi and Soofi (2017)	D	MO	a,s	16,19	C	ND	R	H(MH,S,I)
Defersha and Hodiya (2017)	D	Q	a	2,3,10,17	C	D	R	A(MH)
Gai and Ji (2019)	C	Q	a	2,4	C	D,ND	R	E
Ghassemi and Neghabi (2018)	C	Q	A	2,4,8	C	D	R	E
Grobelny and Michalski (2017)	D	Q	a	2,4	C	D	R,E	A(MH)
Kang and Chae (2017)	C	Q	a	2,4	C	D	R	A(MH)
Latifi et al. (2017)	C	Q	n,b,o,p	4,6,10,11,15, 22,23,24	C	D	R	A(MH)
Ning and Li (2018)	C	Q	d	2,4	C	D	R	A(MH)
Palomo-Romero et al. (2017)	C	Q	a	2,4,13	C	D	R,E	A(MH)
Safarzadeh and Koosha (2017)	C	Q	a,v	2,4	C	D,ND	R	A(MH)
Tubaileh and Siam (2017)	C	Q	a	2,4,5	C	D	R	A(CA,IA)
Xie et al. (2018)	C	Q	a	2,4,10,13,25	C	D	R,E,CH	E
Park and Seo (2019)	C	Q	a	2,4,5,6	C	D	R	A(CA,IA)
Feng et al. (2018)	C	Q	a,q	2,3,4,16	C	D	R	M
Allahyari and Azab (2018)	C	Q	a	2,4,26	C	D	R	A(CA,IA)
Brunoro Ahumada et al. (2018)	D	Q	o,p	11	C	D,ND	R	H(S,E)

References	Problem representation	Type of objective function	Objective function	Constraints	Demand	Type of data	Distance metric	Solution approach
Ejeh et al. (2018)	C	Q	c,o	2,4,10,11,12	C	D	R	E
Feng and Che (2018)	D	Q	E	2,4,8	C	D	R	E
Friedrich et al. (2018)	C	Q	d	2,13	C	D	CB	A(CA,IA)
Jeong and Seo (2018)	C	Q	d	4,6	C	D	R	A(CA,MH)
Kalita and Datta (2018)	C	Q	d	1,9	C	D	R	A(MH)
Kang et al. (2018)	C	Q	d	4,5,6	C	D	BR	A(MH)
Leno et al. (2018)	C	Q	a	2,4,5	C	D	CB	A(MH)
Liu et al. (2018)	C	MO	a,A,F	2,4	C	D	R	A(MH)
Nagarajan et al. (2018)	C	MO	d,e	3,4	C	D	R	A(MH)
Park et al. (2018)	C	Q	o,p,c	4,6,10,11	C	D	R	E
Sun et al. (2018)	C	Q	a	2,4	C	D	R,E	A(MH)
Wang et al. (2018)	C	Q	o,n,c	4,6,15,28,29	C	D	R	A(MH)
Wu et al. (2018)	C	Q	j	2,4,8,13	C	D	R	A(CA,IA)
Hu and Yang (2019)	D	Q	d	2,10,21	C	D	R	A(MH)
Vázquez-Román et al. (2019)	C	Q	n,o	2,4,7	C	D	R,E	E
Chen et al. (2019)	D	MO	s,G	2,3	C	D	R	A(MH)
Cravo and Amaral (2019)	C	Q	d	3,16	C	D	R	A(MH)
De Lira-Flores et al. (2019)	C	Q	n,o,u,p	2,4,6,10,30	C	D	R,E	E
Gulsen et al. (2019)	D	Q	d	3,7,16,17,21	C	D	R	A(IA)
Kim and Chae (2019)	C	Q	d	2,4	C	D	FB	A(MH)
Klausnitzer and Lasch (2019)	C	Q	d	2,4,13	C	D	FB	E
Kovacs (2019)	D	Q	d	2	C	D	R	A(CA)
La Scalia et al. (2019)	C	Q	a	2,4	C	D	R	A(MH)
Le et al. (2019)	D	MO	a,b,A	2	C	D	R	A(MH)
Liu and Liu (2019)	C	MO	a,A	2,4,13	C	D	R	A(MH)
Ramirez Drada et al. (2019)	D	Q	a	2	C	D	R	A
Singh and Ingole (2019)	D	MO	a,A	2	C	D	R	A(MH)
Yang et al. (2019)	C	Q	d	4,25	C	D	R	E,A(IA)
Zhang et al. (2019)	D	Q	d	2	C	D	R	A(IA)
Garcia-Hernandez et al. (2019)	C	Q	a	2	C	D	R,E	A(MH)

Note: Problem representation: D (discrete), C (continuous); Type of objective function: Q (single-objective quantitative), C (single-objective qualitative), MO (multi-objective); Objective function description (lowercase letters indicate minimization objectives and capital letters represents maximization objectives): 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 the 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), A (closeness rating among departments), B (decision maker's level of satisfaction), C (distance requests among departments), D (level of risk related to materials flow path and hazardous waste), E (total material flow among adjancent departments), F (area utilization ratio), G (work stations utilization ratio), H (level of preference for assigning facilities to spaces), J (level of preference in relation to interactivity among departments); Model constraints: 1 (budget), 2 (area), 3 (capacity), 4 (non overlapping), 5 (pick up and drop off points location), 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 elevators), 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); Demand: C (certain), U (uncertain); Type of data: D (deterministic); ND (non deterministic); Distance metric: R (rectilinear), E (euclidean), SE (squared euclidean), CH (chebyshev), CB (contour-based), FB (flow path-based); Solution approach: E (exact), A (approximate), S (stochastic), I (intelligent), M (matheuristic), H (hybrid), CA (construction algorithm, IA (improvement algorithm), MH (metaheuristic).

ANEXO II

CHARACTERISTICS OF THE MATHEMATICAL MODELS USED IN THE FORMULATION OF THE DFLP

ANEXO II

CHARACTERISTICS OF THE MATHEMATICAL MODELS USED IN THE FORMULATION OF THE DFLP

References	**Problem representation**	**Type of objective function**	**Objective function**	**Constraints**	**Demand**	**Type of data**	**Distance metric**	**Solution approach**
McKendall and Hakobyan (2010)	C	Q	a,b	2,4,6	C	D	R	A(CA,IA)
Madhusudanan, Hunagund and Krishnan (2011)	D	Q	a,b	2	C	D	R	A(MH)
Yang, Chuang and Hsu (2011)	D	Q	a,b	2	C	D	R	A(MH)
Abedzadeh *et al.* (2013)	C	MO	a,b,m,A	2,4	C	D,ND	R	A(MH)
Guan *et al.* (2012)	D	Q	a,b	2	C	D	FB	A(MH)
Jolai, Tavakkoli and Taghipour (2012)	C	MO	a,b,A,C	2,4,5,6	C	D	R	A(MH)
Kia *et al.* (2012)	D	Q	a,b,q	2,3	C	D	R	E,A(MH)
McKendall and Liu (2012)	D	Q	a,b	2	C	D	R	A(MH)
Azimi and Saberi (2013)	D	Q	a,b	2	C	D	R	A(MH)
Emami and S. Nookabadi (2013)	D	MO	a,b,A	2	C	D	R	A(MH)
Hosseini-Nasab and Emami (2013)	D	Q	a,b	2	C	D	R	A(MH)
Kaveh, Dalfard and Amiri (2014)	D	Q	a,b	2	U	D,ND	R	H(S,MH)
Kia *et al.* (2013)	D	Q	a,b,q	2,3,16,31	C	D	R	E,A(MH)
Mazinani, Abedzadeh and Mohebali (2013)	C	Q	a,b	2,4,6,16	C	D	R	A(MH)
Samarghandi, Taabayan and Behroozi (2013)	D	MO	a,b,A	2	U	D,ND	R	A(MH)
Chen (2013)	D	Q	a,b	2	C	D	R	A(MH)
Bozorgi, Abedzadeh and Zeinali (2015)	D	MO	a,b,A,C	2	C	D	E	A(MH)
Chen and Lo (2014)	D	MO	a,b,A	2	C	D	R	A(MH)
Hosseini, Khaled and Vadlamani (2014)	D	Q	a,b	2	C	D	R	A(MH)
Kia *et al.* (2014)	D	Q	a,b,q	2,3,16,17, 21,31	C	D	R	A(MH)
Kulturel-Konak and Konak (2015)	C	Q	a,b	2,4	C	D	R	M
Nematian (2014)	C	Q	a	2,4,7	C	ND	R	H(E,S)
Pourvaziri and Naderi(2014)	D	Q	a,b	2	C	D	R	A(MH)
Derakhshan Asl and Wong (2017)	C	Q	a,b	2,4	C	D	R	A(MH)
Kheirkhah, Navidi and Messi Bidgoli (2015)	C	MO	a,b,o	2,19,33	C	D	R	A(MH)
Li *et al*. (2015)	D	Q	a,b	1,2	C	D	R	A(MH)
Ulutas and Islier (2015)	D	Q	a,b	2	C	D	R	A(MH)
Zarea Fazlelahi *et al.* (2016)	D	Q	a,b	2	U	D	R	A(MH)
Hosseini and Seifbarghy (2016)	D	MO	a,b,o	2,19,33	C	D	R	A(MH)
Pourvaziri and Pierreval (2017)	D	MO	a,b,o,i	2,5,19,20	U	D,ND	R	A(MH)
Tayal and Singh (2018)	D	MO	a,b,f,r,A	2	U	ND	R	A(MH)

References	Problem representation	Type of objective function	Objective function	Constraints	Demand	Type of data	Distance metric	Solution approach
Kumar and Singh (2017)	D	Q	a,b	32	C	D	R	A(IA)
Liu *et al.* (2017)	C	Q	a,b	2,4	C	D	R	H(S,IA)
Moslemipour, Lee and Loong (2017)	D	Q	a	2	U	D	R	E,A(MH)
Vitayasak, Pongcharoen and Hicks (2017)	C	Q	a,b	2,4,7	U	D,ND	R	A(MH)
Xiao *et al.* (2017)	C	Q	a,b	2,4,10,25	C	D	R	A(MH)
Kulturel-Konak (2017)	C	Q	a,b	2,4,5,10	C	D	R	M
Li, Tan and Li (2018)	C	MO	a,b,v,w,F	1,2,4	C	D	R	A(MH)
Peng *et al.* (2018)	D	Q	a,b	19	U	ND	R	H(S,MH)
Turanoğlu and Akkaya (2018)	D	Q	a,b	2	C	D	R	A(MH)
Vitayasak and Pongcharoen, (2018)	C	Q	D	2,4	U	D	R	A(MH)
Al Hawarneh, Bendak and Ghanim (2019)	D	Q	a,b	2,4	C	D	E	A(IA)
Pournaderi, Ghezavati and Mozafari (2019)	D	MO	a,b	1,19	C	D	R	A(MH)
Wei, Yuan and Ye (2019)	C	MO	a,b,F	2,4,7	C	D	R	A(MH)

Note: Problem representation: D (discrete), C (continuous); Type of objective function: Q (single-objective quantitative), C (single-objective qualitative), MO (multi-objective); Objective function description (lowercase letters indicate minimization objectives and capital letters represents maximization objectives): 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 the 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), A (closeness rating among departments), B (decision maker's level of satisfaction, C (distance requests among departments), D (level of risk related to materials flow path and hazardous waste), E (total material flow among adjancent departments), F (area utilization ratio), G (work stations utilization ratio), H (level of preference for assigning facilities to spaces), J (level of preference in relation to interactivity among departments); Model constraints: 1 (budget), 2 (area), 3 (capacity), 4 (non overlapping), 5 (pick up and drop off points location), 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 elevators), 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); Demand: C (certain), U (uncertain); Type of data: D (deterministic); ND (non deterministic); Distance metric: R (rectilinear), E (euclidean), SE (squared euclidean), CH (chebyshev), CB (contour-based), FB (flow path-based); Solution approach: E (exact), A (approximate), S (stochastic), I (intelligent), M (matheuristic), H (hybrid), CA (construction algorithm, IA (improvement algorithm), MH (metaheuristic).

ANEXO III

METAHEURISTICS USED TO FIND SUBOPTIMUM SOLUTIONS TO SFLP AND DFLP

ANEXO III

METAHEURISTICS USED TO FIND SUBOPTIMUM SOLUTIONS TO SFLP AND DFLP

Metaheuristic	SFLP	DFLP
GA	Hernández Gress et al. (2011); Jithavech and Krishnan (2010); Yew Wong and Chiak See (2010); Datta et al. (2011); Ku et al. (2011); Tuzkaya et al. (2013); Aiello et al. (2012); Krishnan et al. (2012); Liu and Sun (2012); Yang et al. (2013a); García-Hernández et al. (2013); Aiello et al. (2013); Kothari and Ghosh (2014b); García-Hernández et al. (2015); Garcia-Hernandez et al. (2013); Jabal-Ameli and Moshref-Javadi (2014); Leno et al. (2012); Jiang and Nee (2013); Khaksar-Haghani et al. (2013); Kulturel-Konak and Konak (2013); Lenin et al. (2013); Caputo et al. (2015); Garcia-Hernandez et al. (2013); Gonçalves and Resende (2015); Qudeiri et al. (2015); Leno et al. (2016); Choi et al. (2017); Paes et al. (2017); Asef-Vaziri et al. (2017); Azimi and Soofi (2017); Palomo-Romero et al. (2017); Safarzadeh and Koosha (2017); Feng et al. (2018); Kalita and Datta (2018); Leno et al. (2018); Sun et al. (2018); Wang et al. (2018); Chen et al. (2019); Le et al. (2019); Singh and Ingole (2019)	Emami and S. Nookabadi (2013); Pournaderi, Ghezavati and Mozafari (2019); Peng *et al.* (2018); Yang, Chuang and Hsu (2011); Kaveh, Dalfard and Amiri (2014); Mazinani, Abedzadeh and Mohebali (2013); Samarghandi, Taabayan and Behroozi (2013); Kia *et al.* (2014); Pourvaziri and Naderi(2014); Zarea Fazlelahi *et al.* (2016); Vitayasak, Pongcharoen and Hicks (2017); Vitayasak and Pongcharoen, (2018); Wei, Yuan and Ye (2019)
SA	Ku et al. (2011); Şahin (2011); Tuzkaya et al. (2013); Khaksar-Haghani et al. (2013); Matai et al. (2013b); Xiao et al. (2013); Matai (2015); Palubeckis (2015b); Saraswat et al. (2015); Palubeckis (2017); Xiao et al. (2016); Leno et al. (2016); Defersha and Hodiya (2017); Grobelny and Michalski (2017); Feng et al. (2018); Jeong and Seo (2018); Leno et al. (2018)	Madhusudanan, Hunagund and Krishnan (2011); Kia *et al.* (2012); Kia *et al.* (2013); Hosseini-Nasab and Emami (2013); Emami and S. Nookabadi (2013); Hosseini, Khaled and Vadlamani (2014); Pourvaziri and Naderi(2014); Kaveh, Dalfard and Amiri (2014); Li *et al.* (2015); Kulturel-Konak and Konak (2015); Pourvaziri and Pierreval (2017); Moslemipour, Lee and Loong (2017); Kulturel-Konak (2017); Tayal and Singh (2018); Turanoğlu and Akkaya (2018); Pournaderi, Ghezavati and Mozafari (2019)
PSO	Samarghandi et al. (2010); Kulturel-Konak and Konak (2011[a]); Cheng and Lien (2012[a]); Cheng and Lien (2012b); Ou-Yang and Utamima (2013); Lee (2015); Liu et al. (2018); Hu and Yang (2019)	Kheirkhah, Navidi and Messi Bidgoli (2015); Jolai, Tavakkoli and Taghipour (2012); Azimi and Saberi (2013); Hosseini-Nasab and Emami (2013); Samarghandi, Taabayan and Behroozi (2013); Derakhshan Asl and Wong (2017)

Metaheuristic	SFLP	DFLP
TS	Samarghandi et al. (2010); Scholz et al. (2010); Kulturel-Konak (2012); Palubeckis (2012); Kothari and Ghosh (2013b); Ou-Yang and Utamima (2013); Jeong and Seo (2018)	McKendall and Hakobyan (2010); McKendall and Liu (2012); Samarghandi, Taabayan and Behroozi (2013); Bozorgi, Abedzadeh and Zeinali (2015)
ACO	Komarudin and Wong (2010); Yew Wong and Chiak See (2010); Kulturel-Konak and Konak (2011b); Lee and Tseng (2012); Lee (2012); Guan and Lin (2016); Liu et al. (2018)	Chen (2013); Chen and Lo (2014)
VNS	Ripon et al. (2013); Palubeckis (2015[a]); Guan and Lin (2016)	Abedzadeh *et al.* (2013); Guan *et al.* (2012); Samarghandi, Taabayan and Behroozi (2013); Hosseini, Khaled and Vadlamani (2014); Kulturel-Konak (2017)
ABC	Cheng and Lien (2012a); Cheng and Lien (2012b); Nagarajan et al. (2018)	Li, Tan and Li (2018)
AIS	Ulutas and Kulturel-Konak (2012); Ulutas and Kulturel-Konak (2013)	Ulutas and Islier (2015)
BSA	Zhou et al. (2017)	Vitayasak, Pongcharoen and Hicks (2017)
FA	Ingole and Singh (2017); La Scalia et al. (2019)	Tayal and Singh (2018)
GRASP	Rubio-Sánchez et al. (2016); Cravo and Amaral (2019)	-
SSA	Kothari and Ghosh (2014b); Jabal-Ameli and Moshref-Javadi (2014)	-
HSA	Kaveh et al. (2012); Chang and Ku (2013); Kang and Chae (2017)	-
EM	-	Guan *et al.* (2012)
DE	-	Emami and S. Nookabadi (2013)
ICA	-	Hosseini, Khaled and Vadlamani (2014)
CSS	Kaveh and Safari (2014)	-
PR	Rubio-Sánchez et al. (2016)	-
WFA	-	Hosseini and Seifbarghy (2016)
PEA	-	Xiao *et al.* (2017)
BA	Latifi et al. (2017)	-
CE	Ning and Li (2018)	-
TLBO	-	Vitayasak and Pongcharoen, (2018)
CSA	Kang et al. (2018)	-
BFO	-	Turanoğlu and Akkaya (2018)

Metaheuristic	SFLP	DFLP
MBO	Kim and Chae (2019)	-
BBO	Singh and Ingole (2019)	-
CRO	Garcia-Hernandez et al. (2019)	-

[1]GA (genetic algorithms); SA (simulated annealing); PSO (particle swarm optimization); TS (tabu search); ACO (ant colony optimization); VNS (variable neighbourhood search); ABC (artificial bee colony algorithm); AIS (artificial immune system); BSA (backtracking search algorithm); FA (firefly algorithm); GRASP (greedy randomized adaptive search procedure); SSA (scatter search algorithm); HSA (harmony search algorithm); EM (electromagnetism-like mechanism); DE (differential evolution); ICA (imperialist competitive algorithm); CSS (charged system search); PR (path relinking); WFA (water flow-like algorithm); PEA (problem evolution algorithm); BA (bat algorithm); CE (cross-entropy method); TLBO (teaching-learning-based optimization); CSA (cuckoo search algorithm); BFO (bacterial foraging optimization); MBO (monarch butterfly optimization); BBO (biogeography-based optimization); CRO (Coral Reefs Optimization).

ANEXO IV

REAL-WORLD FLP APPLICATIONS

REAL-WORLD FLP APPLICATIONS

References	Industrial sector	Country	Number of case studies	Problem type	Planning phase	Planning approach	Number of entities (n)	Material handling configuration	Layout generation approach	Number of layout candidates	Layout evaluation approach	Mathematical model	Mathematical model solution approach	Decision-support tools	Obtained results
Alsyouf et al. (2012)	services	Sweden	1	R	B	SFLP	n=14	OFLP	EK	3	SAW				A MCDM framework was used for assessing the quality and cost of facility layout alternatives.
Eben-Chaime et al. (2011)	agrifood	Israel	1	G	B	SFLP	$376 \leq n \leq 410$	MRLP	EK	4	CC				The selected layout allowed an increase of up to 40% in annual profits.
Park et al. (2011)	chemical	Korea	2	G	D	SFLP	n=7,10	OFLP	MP	1		MILP	E	GAMS/ CPLEX	An optimal multi-floor plant layout with consideration of safety factors was obtained.
Tuzkaya et al. (2013)	metal-working	Turkey	1	G	B	SFLP	n=19	MRLP	MP			QAP	A(MH)		SA performed better than GA and a GA/SA-based hybrid approach in terms of the fitness values and the time requirements when solving a QAP.
Vasudevan and Son (2011)	automotive	USA	1	R	B	SFLP	n=6	OFLP	EK	4	SM				Among the 4 layout alternatives, the most favourable in terms of productivity and safety was chosen.
Yang et al. (2012)	micro electronics	Taiwan	1	G	B	SFLP	$1 \leq n \leq 4$	MRLP	EK	10	MCDM				A moderate-sized independent cell was selected as the most suitable layout design concept for a 300mm semiconductor foundry.
Lee and Tseng (2012)	services	Taiwan	1	R	B	SFLP	n=32	OFLP	MP			LP	H(MH,S)	VISSIM	The proposed system could save pedestrians' walking time and improve the operation and service efficiency in an airport terminal.
Cheng and Lien (2012a)	services	Taiwan	1	G	B	SFLP	n=28	MRLP	MP			QAP	A(MH)		The introduced optimization hybrid swarm algorithm outperformed BA and PSO in solving a QAP model.
Cheng and Lien (2012b)	services	Taiwan	1	G	B	SFLP	n=28	MRLP	MP			QAP	A(MH)		The introduced optimization hybrid swarm algorithm was able to efficiently solve a practical FLP case sudy at a hospital.
Lee (2012)	services	Taiwan	1	R	B	SFLP	n=16	OFLP	MP			QAP	H(S,MH)	VISSIM	The proposed model could effectively save passengers time and improve the service efficiency in a railway station.

References	Industrial sector	Country	Number of case studies	Problem type	Planning phase	Planning approach	Number of entities (n)	Material handling configuration	Layout generation approach	Number of layout candidates	Layout evaluation approach	Mathematical model	Mathematical model solution approach	Decision-support tools	Obtained results
McDowell and Huang (2012)	services	USA	1	R	D	SFLP	n=15	OFLP	EK	4	SAW				The selected layout for a hospital pharmacy outperformed other alternatives in terms of transportation distances and materials handling, employee utilization, and ergonomics.
García-Hernández et al. (2013)	meat-processing; recycling	Spain	2	G	B	SFLP	n=11,12	MRLP	MP	11,8		MILP	A(MH)		The novel multi-objective interactive GA allowed to find good layout solutions to the analysed case studies considering decision maker's preferences.
Garcia-Hernandez et al. (2013)	recycling	Spain	2	G	B	SFLP	n=10,11	MRLP	MP	9		MILP	A(MH)		The interactive GA introduced was able to capture the designer preferences in evaluating the layout solutions in a reasonable number of iterations.
Hadi-Vencheh and Mohamadghasemi (2013)	micro-electronics	Taiwan	1	G	B	SFLP	n=10	OFLP	SP	18	NLP			SPIRAL, MS Excel Solver	The methodological framework incorporated qualitative criteria as well as quantitative criteria to evaluate facility layout designs.
Jia et al. (2013)	metal-working	China	1	R	D	SFLP	n=12	SRLP, MRLP	MP	3	SM	NLP	H(A,S)	C++/ SQL Server	The obtained lean facility layout for a cylinder production line proved to increase equipment utilization ratio, reduce waste of personnel and equipment and improve production efficiency.
Lin et al. (2015)	services	China	1	G	B	SFLP	n=17	OFLP	EK	2	f-TOC				The best layout design for a hospital operating room, considering uncertainty analysis, was selected using an f-TOC
Azadeh and Moradi (2014)	micro-electronics	Iran	1	G	D	SFLP	n=10	OFLP	SP	21	SM,AHP, DEA			VIP-PLANOPT, Expert fit	A fuzzy SM-fuzzy AHP-fuzzy DEA algorithm was performed to select a suitable layout for a wafer foundry considering safety and ergonomics factors.

References	Industrial sector	Country	Number of case studies	Problem type	Planning phase	Planning approach	Number of entities (n)	Material handling configuration	Layout generation approach	Number of layout candidates	Layout evaluation approach	Mathematical model	Mathematical model solution approach	Decision-support tools	Obtained results
Al-Hawari et al. (2014)	woodworking	Jordan	1	R	B	SFLP	n=18	OFLP	EK	3	ANP, AHP				ANP method is applied for the first time in the FLP context as a strategic decision-making tool for the selection of the best facility layout plan for a wood furniture factory.
Azadeh et al. (2015)	chemical	Iran	1	R	B	SFLP	n=10	OFLP	EK	45	DEA, SM				The best layout design for a petrochemical company, considering stochastic outputs and safety and environmental factors, was selected through an integrated computer SM–stochastic DEA approach.
Hong et al. (2014)	micro-electronics	Korea	10	G	B	SFLP	5 ≤ n ≤ 30	MRLP	MP			MILP	E,A(IA)	C++/ CPLEX	The proposed algorithm showed being able to find optimal solutions to small-sized problems and to solve large-sized problems within an acceptable time.
Moatari-Kazerouni et al. (2015b)	services	Canada	1	R	B	SFLP	n=12	OFLP	MP			LP	H(CA,IA)		The implemented methodology considered transportation cost as well as safety issues in the re-layout of a hospital kitchen.
Ulutas and Islier (2015)	footwear	Turkey	1	G	B	DFLP	n = 54	MRLP	MP	4		QAP	A(MH)		The proposed re-layout scenario for a shoe manufacturing plant, considering a dynamic planning approach, reduced the total MHC by 5,69% over the current static layout.
Helber et al. (2016)	services	Germany	1	G	B	SFLP	n=28	MRLP	MP			QAP	A(IA)	GAMS/ CPLEX	A hierarchical layout planning approach was developed based on organizational and operational data from a large and complex university hospital.
Lee (2015)	chemical	Korea	2	G	D	SFLP	n=7	OFLP	MP			MINLP	A(MH)		A multi-floor FLP was solved in two case studies of ethylene oxide plants through an MINLP model considering safety distances between equipment for preventing dangerous accidents.

References	Industrial sector	Country	Number of case studies	Problem type	Planning phase	Planning approach	Number of entities (n)	Material handling configuration	Layout generation approach	Number of layout candidates	Layout evaluation approach	Mathematical model	Mathematical model solution approach	Decision-support tools	Obtained results
Choi et al. (2017)	shipbuilding	Korea	1	G	B	SFLP	n=20	OFLP	MP			NLP	A(MH)		A layout design that guarantees a minimum MHC during the construction of ships was obtained for a shipyard.
Glenn and Vergara (2016)	services	USA	2	R	B	SFLP	n=24,33	OFLP	MP			LP	A(IA)	VBA/ Excel	The proposed algorithm was applied to two equine facilities and was able to improve the flow distance by 7% and 6%, respectively.
Horta et al. (2016)	services	Portugal	1	G	B	SFLP	Not mentioned	MRLP	MP	3		LIP	E	GAMS/ CPLEX	The optimal layout obtained for a cross-docking warehouse that feeds a just-in-time distribution operation in a food retail company, reduced the flow distance in 23%.
Hou et al. (2016)	metal-working	China	41	G	B	SFLP	$14 \leq n \leq 200$	OFLP	MP			MILP	A(CA)	MATLAB	The proposed CA based on plane segmentation proved to be suitable for FLP instances of a limited number of facilities.
Huang and Wong (2017)	construction	China	1	G	B	SFLP	n=11	OFLP	MP	1		BMILP	E	Python/ GUROBI	An optimal layout solution for a toolkit manufacturer was found in 7.8 hours through B&B method applied to a mathematical model that utilizes small unit cells to
Kim et al. (2016)	micro-electronics	Korea	1	G	B	SFLP	n=16	MRLP	MP	18	SM	MINLP	A(IA)	AutoMod	The minimum flow distance layout configuration proved to be ineffective for a wafer foundry due to congestion of overhead hoist transport vehicles when the volume of materials flow was high.
Neghabi and Ghassemi (2016)	chemical	Iran	1	G	B	SFLP	n=6	OFLP	MP	9		MINLP	E	CPLEX	The proposed model introduced a novel approach for closeness rating assignment between departments and was used to find the optimal layout design for an ethylene oxide plant, considering economic feasibility and safety aspects.

References	Industrial sector	Country	Number of case studies	Problem type	Planning phase	Planning approach	Number of entities (n)	Material handling configuration	Layout generation approach	Number of layout candidates	Layout evaluation approach	Mathematical model	Mathematical model solution approach	Decision-support tools	Obtained results
Park et al. (2018)	chemical	Korea	1	G	D	SFLP	n=24	OFLP	MP	2		MINLP	E	GAMS/ DICOPT	A model for solving three-dimensional and multi-floor FLPs with safety considerations was proposed and validated in a natural gas liquefaction plant.
Wang et al. (2018)	chemical	China	1	G	B	SFLP	n=217	OFLP	MP	3		NLP	A(MH)	MATLAB	The approach used to attain an oil refinery layout under 3 different scenarios of the single, double and triple floor, proved the important role of floor number in the trade-off among investment cost, energy consumption, and land cost.
Wu et al. (2018)	construction	China	18	G	B	SFLP	$5 \leq n \leq 154$	OFLP	MP			MIQP	A(CA,IA)	C++/ GUROBI	A novel method for interior layout design proved to be faster by multiple orders of magnitude than previous works using stochastic optimization.
Li, Tan and Li (2018)	metalworking	China	1	G	D	DFLP	n = 12	OFLP	MP	2		NLP	A(MH)		The introduced mathematical model proved to be effective in finding the best layout solution for a machinery manufacturer combining safety, sustainability, high efficiency, and low cost.
Hu and Yang (2019)	micro-electronics	China	1	G	B	SFLP	n=18	MRLP	MP	5		NLP	A(MH)		PSO algorithm proved to be an effective approach for obtaining near-optimal solutions for the multi-row FLP in practical applications.
Abdollahi et al. (2019)	micro-electronics	Taiwan	1	G	B	SFLP	n=10	OFLP	SP	18	NLP			ALDEP, GAMS	An NLP model proved been able to choose the best layout among 18 alternatives for an integrated circuits packaging factory with more accuracy and shorter resolution time than previous studies.

References	Industrial sector	Country	Number of case studies	Problem type	Planning phase	Planning approach	Number of entities (n)	Material handling configuration	Layout generation approach	Number of layout candidates	Layout evaluation approach	Mathematical model	Mathematical model solution approach	Decision-support tools	Obtained results
De Lira-Flores et al. (2019)	chemical	Mexico	1	G	B,D	SFLP	n=9	OFLP	MP	6		MINLP	E	GAMS/ DICOPT	The introduced model allowed to determine the optimal location of the equipment and facilities, and the design of the safety instrumented system in an ethylene oxide plant.
Fogliatto et al. (2019)	services	Brazil	1	R	D	SFLP	n=18	OFLP	EK	5	AHP				The layout design selected for the sterilization unit of a large hospital, considering lean health care practices, made it possible to increase work productivity and reduce the number of monthly overtime hours by an average of 75%.
Kovacs (2019)	electronics assembly	Hungary	1	R	D	SFLP	n=11	OFLP	MP	8	CC	LP	A(CA)		The selected re-layout design for an assembly plant considering lean methods resulted in a significant reduction of total workflow, MHC, flow distance, space used for assembly, number of workers, labour cost and number of kanban stops.
Le et al. (2019)	construction	Canada	1	G	B	SFLP	n=25	OFLP	MP	3		QAP	A(MH)	MS Excel Solver	The introduced model met the requirements of project managers in terms of cost savings and preference for temporary facility relationships.
Lin and Wang (2019)	services	China	1	G	B	SFLP	n=8	OFLP	EK	2	AHP				The implemented methodology integrating fuzzy AHP and human reliability assessment, allowed to design and select the best layout plan for an operating theatre.
Ramirez Drada et al. (2019)	metal-working	Colombia	1	G,R	B	SFLP	n=17	OFLP	MP	14	TOPSIS	QAP	A		The introduced FLP resolution framework allows addressing both continuous and discrete representation problems in greenfield-layout or re-layout planning.
Al Hawarneh, Bendak and Ghanim (2019)	construction	UAE	1	G	B	DFLP	n=12	MRLP	MP	4		BILP	A(IA)	MATLAB	The enhanced optimisation model provided a layout design with the least possible cost considering relocation, dismantling and setup cost of temporary facilities for a large scale construction project.

ANEXO V

RELEVANT DATA FOR THE PRESENTED N=12/T=3 CASE STUDY

Table AV-1. Relevant dimensions for every detailed work cell design alternative in its standard orientation (*r*=1).

i	q	l^x_{tiq1}	l^y_{tiq1}	a_{tiqr}	δ^x_{tiq1}	δ^y_{tiq1}	i	q	l^x_{tiq1}	l^y_{tiq1}	a_{tiqr}	δ^x_{tiq1}	δ^y_{tiq1}
1	1	3	6	18	1.5	6	7	1	9	3.5	31.5	0	1.75
1	2	2.5	9	22.5	1.25	0	7	2	10	3	30	10	1.5
1	3	4	5	20	1.5	0	7	3	4	7	28	1.5	0
2	1	4.2	6.2	26.04	2.1	6.2	7	4	3	9	27	1.5	9
2	2	3	9	27	1.5	0	8	1	3	6	18	1.5	6
2	3	4	7	28	2	7	8	2	5	4	20	2	0
2	4	5	5	25	5	2.5	9	1	3	5	15	1.5	5
3	1	5	6	30	2.5	0	9	2	7	2	14	2.5	2
3	2	3	10	30	1.5	10	9	3	4	4	16	2	4
4	1	5.8	4.5	26.1	0	3	10	1	7	2	14	3.5	2
4	2	3	9	27	1.5	0	10	2	3	5	15	1.5	5
4	3	8	4	32	8	2	10	3	2	6	12	0	2
5	1	5	4	20	0	2	11	1	12	4	48	6	0
5	2	2.5	8	20	1.25	8	11	2	4	14	56	0	2
5	3	6	4	24	0	2	12	1	10	15	150	10	5
6	1	4	5	20	0	3	12	2	12	12	144	4	12
6	2	3	7	21	1.5	7	12	3	8	18	144	0	9
6	3	5	3.5	17.5	2	0	12	4	12.5	12.5	156.25	12.5	6.25

Table AV-2. Flow of materials (in tons per time period) between work cells during the first period.

	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	10.2	0	0	0	15.7	0	0	0	0	0
2	0	0	0	0	0	0	0	31.6	12.8	0	0	0
3	0	0	0	0	0	13.5	0	5.9	2.3	0	0	0
4	0	0	0	0	0	23.1	26.5	0	0	0	0	0
5	0	2.5	1.6	0	0	0	0	4.1	0	0	0	0
6	0	18.2	0	0	0	0	3.4	12.2	0	0	0	0
7	0	19.8	8.9	0	6.4	0	0	0	0	0	0	0

8	0	0	0	0	0	0	0	0	30.2	0	0	0
9	0	1.2	0.1	0	0	0	0	0	0	0	0	39.3
10	0	0	0	0	0	0	0	0	0	0	0	43.4
11	0	0	0	0	0	0	0	0	0	0	0	0
12	12.3	0	0	10.8	22.1	33.4	38.7	0	0	0	0.01	0

Table AV-3. Flow of materials (in tons per period) between work cells during the second period.

	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	0.68	14.51	17.56	2.51	22.32	0	0	0	0	0
2	0	0	0	9.87	0	0	0	36.23	18	0	0	3.25
3	0	5.23	0	0	2.54	4.2	0	2.64	0	0	0	0
4	0	0	0	0	5.23	3.12	0	5.25	4.56	0	0	0
5	0	12.37	7.32	0	0	12.45	3.5	7.18	2.05	0	0	0
6	0	2.87	9.54	2.35	0	0	0	16.25	4.55	0	0	0
7	0	1.2	12.71	1.75	18.42	11.87	0	24.98	0	0	0	0
8	0	0	0	12.76	0	0.52	0	0	45.24	0	0	8.75
9	1.25	1.03	0.08	1.02	0	3.75	0	0.02	0	0	0	45.6
10	0	0	0	0	0	0	0	0	0	0	0	82.52
11	0	0	0	0	0	0	0	0	0	0	0	0
12	18.7	1.02	1.22	14.78	32.47	38.41	0.71	1.56	0.97	0	0.025	0

Table AV-4. Flow of materials (in tons per period) between work cells during the third period.

	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	8.12	0	8.56	0	13.6	0	0	0	0	0
2	0	0	0	5.4	0	0	0	18.3	9.12	0	0	0
3	0	1.15	0	0	0	11.5	0	3.5	8.3	0	0	0
4	0	0	0	0	1.25	15.45	13.65	0	0	0	0	0
5	0	5.6	4.7	0	0	0	0	2.3	0	0	0	0
6	0	14.5	0	1.25	0	0	2.6	8.9	0	0	0	0
7	0	13.7	4.68	0	3.5	6.3	0	0	0	0	0	0
8	0	0	0	4.82	0	0	0	8.12	19.54	0	0	2.46
9	3.4	1.2	0.1	0	2	0	0	0	0	0	0	34.85

10	0	0	0	0	0	0	0	0	0	0	0	39.68
11	0	0	0	0	0	0	0	0	0	0	0	0
12	9.8	0.85	0.05	6.75	19.23	25.33	32.64	2.5	0	0	0.06	0

Table AV-5. Material handling cost per unit distance ($/t·m) during the first period.

	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	1.50	0	0	0	4.50	0	0	0	0	8.40
2	0	0	0	0	2.65	3.50	4.56	5.45	5.50	0	0	0
3	1.50	0	0	0	7.75	11.70	8.35	6.32	1.50	0	0	0
4	0	0	0	0	0	3.50	4.50	0	0	0	0	6
5	0	2.65	7.75	0	0	0	7.75	3.50	0	0	0	2.60
6	0	3.50	11.70	3.50	0	0	2.35	6.75	0	0	0	2.45
7	4.50	4.56	8.35	4.50	7.75	2.35	0	0	0	0	0	5.50
8	0	5.45	6.32	0	3.5	6.75	0	0	4.50	0	0	0
9	0	5.50	1.50	0	0	0	0	4.50	0	0	0	6.75
10	0	0	0	0	0	0	0	0	0	0	0	3.45
11	0	0.00	0	0	0	0	0	0	0	0	0	0
12	8.40	0	0	6	2.60	2.45	5.50	0	6.75	3.45	0	0

Table AV-6. Material handling cost per unit distance ($/t·m) during the second period.

	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	0.78	13.5	18.23	3.4	12	0	7.15	0	0	8.40
2	0	0	4.25	12.35	12.37	6.75	11.35	12.5	8.55	0	0	5.85
3	0.78	4.25	0	0	3.450	5.200	8.200	8.75	5.60	0	0	2.65
4	13.5	12.35	0	0	2.5	12.35	7	12.6	6.35	0	0	7.50
5	18.2	12.37	3.45	2.5	0	15.25	2.45	5.10	5.45	0	0	2.50
6	3.4	6.75	5.2	12.35	15.25	0	3.56	12.2	2.75	0	0	13.34
7	12	11.35	8.2	7	2.45	3.56	0	3.75	0	0	0	5.45
8	0	12.5	8.75	12.6	5.1	12.2	3.75	0	12.25	0	0	8.12
9	7.15	8.55	5.6	6.35	5.45	2.75	0	12.25	0	0	0	12.25
10	0	0	0	0	0	0	0	0	0	0	0	25.45
11	0	0	0	0	0	0	0	0	0	0	0	0.10
12	8.4	5.85	2.65	7.5	2.5	13.34	5.45	8.12	12.25	25.45	0.10	0

Table AV-7. Material handling cost per unit distance ($/t·m) during the third period.

	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	1.12	0	16.25	0	4.55	0	7.15	0	0	6.50
2	0	0	2.40	10.25	10.35	3.75	8.15	8.75	6.25	0	0	4.36
3	1.12	2.40	0	0	2.50	4.20	4.20	5.40	4.12	0	0	2.65
4	0	10.25	0	0	3.45	14.35	7.00	8.60	0	0	0	5.50
5	16.25	10.35	2.50	3.45	0	0	2.45	3.25	4.24	0	0	2.50
6	0	3.75	4.20	14.35	0	0	1.45	8.40	0	0	0	8.45
7	4.55	8.15	4.20	7.00	2.45	1.45	0	0	0	0	0	3.65
8	0	8.75	5.40	8.60	3.25	8.4	0	0	9.35	0	0	5.20
9	7.15	6.25	4.12	0	4.24	0	0	9.35	0	0	0	8.25
10	0	0	0	0	0	0	0	0	0	0	0	6.30
11	0	0	0	0	0	0	0	0	0	0	0	1.50
12	6.50	4.36	2.65	5.50	2.50	8.45	3.65	5.20	8.25	6.30	1.50	0

Table AV-8. Closeness requirements between work cells for the entire planning horizon.

1	2	3	4	5	6	7	8	9	10	11	12	
	U	E	U	U	U	E	U	U	U	X	I	1
		U	U	I	U	U	U	U	U	X	U	2
			U	U	E	U	I	U	U	U	U	3
				U	E	E	U	U	U	X	O	4
					O	U	U	U	U	X	E	5
						A	E	U	U	I	E	6
							U	U	U	X	E	7
								A	U	U	U	8
									A	O	A	9
										E	A	10
											O	11
												12

ANEXO VI

DYNAMIC LAYOUT SOLUTION FOR THE CASE STUDY *N*=12/*T*=3

ANEXO VI

DYNAMIC LAYOUT SOLUTION FOR THE CASE STUDY N=12/T=3

t	i	q	r	cv_{ti}^{x}	cv_{ti}^{y}	l_{ti}^{x}	l_{ti}^{y}	A_{ti}	cp_{ti}^{x}	cp_{ti}^{y}	δ_{ti}^{x}	δ_{ti}^{y}
1	1	2	1	3.49	14.50	2.50	9.00	22.50	4.74	14.50	1.25	0
1	2	3	4	18.99	8.00	7.00	4.00	28.00	18.99	10.00	0.00	2.00
1	3	2	1	3.00	4.50	3.00	10.00	30.00	4.49	14.50	1.50	10.00
1	4	1	1	12.99	22.00	5.80	4.50	26.10	12.99	24.99	0.00	3.00
1	5	3	4	23.99	12.76	4.00	6.00	24.00	25.99	12.76	2.00	0.00
1	6	2	3	5.99	12.26	3.00	7.00	21.00	7.49	12.26	1.50	0.00
1	7	3	4	5.99	22.00	7.00	4.00	28.00	12.99	23.50	7.00	1.50
1	8	1	3	6.00	6.26	3.00	6.00	18.00	7.50	6.26	1.50	0.00
1	9	1	3	8.99	7.00	3.00	5.00	15.00	10.49	7.00	1.50	0.00
1	10	2	1	11.99	7.00	3.00	5.00	15.00	13.49	12.00	1.50	5.00
1	11	1	4	14.99	0.00	4.00	12.00	48.00	18.99	6.00	4.00	6.00
1	12	1	2	8.99	12.00	15.00	10.00	150.00	13.99	12.00	5.00	0.00
2	1	1	3	6.99	11.99	3.00	6.00	18.00	8.49	12.00	1.50	0.00
2	2	2	2	6.49	0.00	9.00	3.00	27.00	6.49	1.49	0.00	1.50
2	3	2	1	4.00	3.99	3.00	10.00	30.00	5.49	13.99	1.50	10.00
2	4	2	1	13.99	11.50	3.00	9.00	27.00	15.49	11.50	1.50	0.00
2	5	2	4	7.00	3.00	8.00	2.50	20.00	6.99	4.25	0.00	1.25
2	6	3	1	7.99	8.49	5.00	3.50	17.50	10.00	8.49	2.00	0.00
2	7	3	1	9.99	11.99	4.00	7.00	28.00	11.49	11.99	1.50	0.00
2	8	1	4	7.00	5.49	6.00	3.00	18.00	7.00	7.00	0.00	1.50
2	9	2	4	15.00	4.50	2.00	7.00	14.00	15.00	7.00	0.00	2.50
2	10	3	3	13.00	5.50	2.00	6.00	12.00	15.00	9.50	2.00	4.00
2	11	2	1	0.00	1.49	4.00	14.00	56.00	0.00	3.49	0.00	2.00
2	12	3	1	16.99	0.00	8.00	18.00	144.00	16.99	9.00	0.00	9.00
3	1	1	3	12.00	9.50	3.00	6.00	18.00	13.50	9.50	1.50	0.00
3	2	2	2	7.00	0.00	9.00	3.00	27.00	7.00	1.50	0.00	1.50
3	3	2	3	0.00	6.00	3.00	10.00	30.00	1.49	6.00	1.50	0.00
3	4	1	2	2.50	0.20	4.50	5.80	26.10	5.50	5.99	3.00	5.80
3	5	2	4	7.00	3.00	8.00	2.50	20.00	7.00	4.25	0.00	1.25
3	6	3	1	3.00	6.00	5.00	3.50	17.50	5.00	5.99	2.00	0.00
3	7	3	2	8.00	5.50	7.00	4.00	28.00	7.99	8.00	0.00	2.50

t	i	q	r	cv_{ti}^{x}	cv_{ti}^{y}	l_{ti}^{x}	l_{ti}^{y}	A_{ti}	cp_{ti}^{x}	cp_{ti}^{y}	δ_{ti}^{x}	δ_{ti}^{y}
3	8	1	3	4.00	9.49	3.00	6.00	18.00	5.50	9.49	1.50	0.00
3	9	1	3	7.00	10.00	3.00	5.00	15.00	8.50	10.00	1.50	0.00
3	10	3	1	10.00	9.49	2.00	6.00	12.00	10.00	11.49	0.00	2.00
3	11	1	1	2.99	15.49	12.00	4.00	48.00	8.99	15.49	6.00	0.00
3	12	3	1	15.00	3.49	8.00	18.00	144.00	15.00	12.49	0.00	9.00

ANEXO VII

STATIC LAYOUT SOLUTION FOR THE CASE STUDY *N*=12/*T*=3

STATIC LAYOUT SOLUTION FOR THE CASE STUDY *N*=12/*T*=3

i	q	r	cv_{ti}^{x}	cv_{ti}^{y}	l_{ti}^{x}	l_{ti}^{y}	A_{ti}	cp_{ti}^{x}	cp_{ti}^{y}	δ_{ti}^{x}	δ_{ti}^{y}
1	1	3	0	10.00	3.00	6.00	18.00	1.50	10.00	1.50	0.00
2	1	1	3.00	11.00	4.20	6.20	26.04	5.10	17.20	2.10	6.20
3	2	1	0.42	0	3.00	10.00	30.00	1.92	10.00	1.50	10.00
4	1	4	7.00	17.20	4.50	5.80	26.10	8.50	17.20	1.50	0.00
5	2	1	19.20	7.20	2.50	8.00	20.00	20.45	15.20	1.25	8.00
6	3	4	3.42	6.00	3.50	5.00	17.50	6.92	8.00	3.50	2.00
7	3	1	3.00	17.20	4.00	7.00	28.00	4.50	17.20	1.50	0.00
8	1	1	3.42	0.00	3.00	6.00	18.00	4.92	6.00	1.50	6.00
9	1	1	6.42	0.19	3.00	5.00	15.00	7.92	5.20	1.50	5.00
10	2	1	9.42	0.19	3.00	5.00	15.00	10.92	5.20	1.50	5.00
11	1	1	12.42	0.69	12.00	4.00	48.00	18.42	0.69	6.00	0.00
12	2	4	7.20	5.20	12.00	12.00	144.00	7.20	9.20	0.00	4.00