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DEPARTAMENTO DE INGENIERÍA RURAL

TESIS DOCTORAL

GENETIC APPROACHES FOR THE UNEQUAL AREA FACILITY LAYOUT PROBLEM

Directores:
Lorenzo Salas Morera
Antonio Araúzo Azofra
Henri Pierreval

Autora:
Laura García Hernández

Córdoba, Junio de 2011

TITULO: *Genetic approaches for the unequal area facility layout problem*

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GENETIC APPROACHES FOR THE UNEQUAL AREA FACILITY LAYOUT PROBLEM

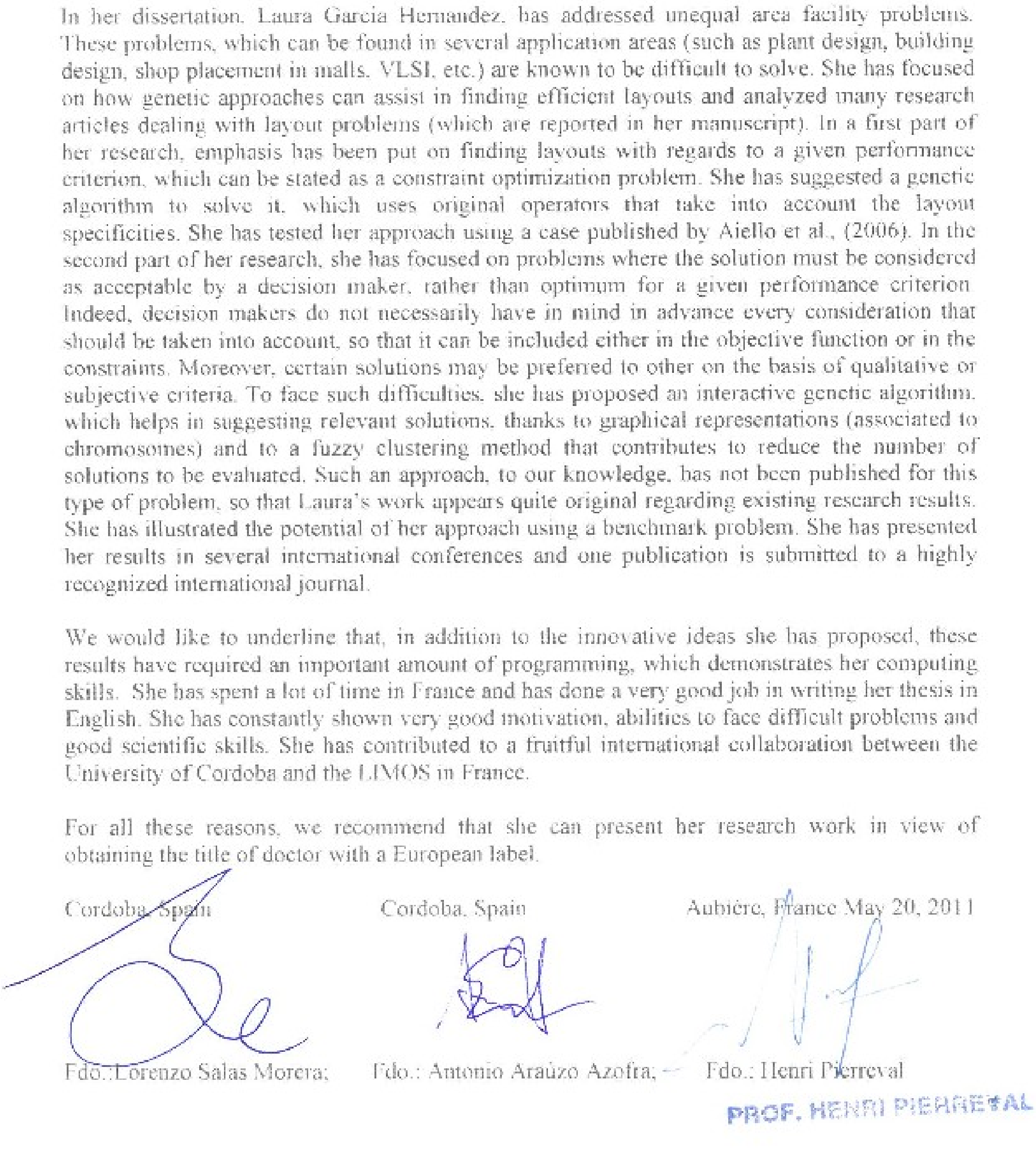
Tesis Doctoral presentada por Laura García Hernández, en satisfacción de los requisitos necesarios para optar al grado de Doctor, y dirigida por los Doctores: Lorenzo Salas Morera y Antonio Araúzo Azofra, de la Universidad de Córdoba, España; y Henri Pierreval, de LIMOS UMR CNRS 6158 IFMA, Clermont-Ferrand, Francia.

Firma del interesado,

Fdo.: Laura García Hernández

Córdoba, Junio de 2011

Justified report of the Directors of the Thesis:



In her dissertation, Laura Garcia Hernandez, has addressed unequal area facility problems. These problems, which can be found in several application areas (such as plant design, building design, shop placement in malls, VLSI, etc.) are known to be difficult to solve. She has focused on how genetic approaches can assist in finding efficient layouts and analyzed many research articles dealing with layout problems (which are reported in her manuscript). In a first part of her research, emphasis has been put on finding layouts with regards to a given performance criterion, which can be stated as a constraint optimization problem. She has suggested a genetic algorithm to solve it, which uses original operators that take into account the layout specificities. She has tested her approach using a case published by Aiello et al., (2006). In the second part of her research, she has focused on problems where the solution must be considered as acceptable by a decision maker, rather than optimum for a given performance criterion. Indeed, decision makers do not necessarily have in mind in advance every consideration that should be taken into account, so that it can be included either in the objective function or in the constraints. Moreover, certain solutions may be preferred to other on the basis of qualitative or subjective criteria. To face such difficulties, she has proposed an interactive genetic algorithm, which helps in suggesting relevant solutions, thanks to graphical representations (associated to chromosomes) and to a fuzzy clustering method that contributes to reduce the number of solutions to be evaluated. Such an approach, to our knowledge, has not been published for this type of problem, so that Laura's work appears quite original regarding existing research results. She has illustrated the potential of her approach using a benchmark problem. She has presented her results in several international conferences and one publication is submitted to a highly recognized international journal.

We would like to underline that, in addition to the innovative ideas she has proposed, these results have required an important amount of programming, which demonstrates her computing skills. She has spent a lot of time in France and has done a very good job in writing her thesis in English. She has constantly shown very good motivation, abilities to face difficult problems and good scientific skills. She has contributed to a fruitful international collaboration between the University of Cordoba and the LIMOS in France.

For all these reasons, we recommend that she can present her research work in view of obtaining the title of doctor with a European label.

Cordoba, Spain	Cordoba, Spain	Aubiére, France May 20, 2011
Fdo.:Lorenzo Salas Morera;	Fdo.: Antonio Araúzo Azofra;	Fdo.: Henri Pierreval

PROF. HENRI PIERREVAL

Informe justificado de los Directores de la Tesis:

En su tesis, Laura García Hernández, ha abordado los problemas de distribución en planta de instalaciones de área desigual. Estos problemas, que se pueden encontrar en varias áreas de aplicación (tales como diseño en planta, el diseño de edificios, la ubicación de tiendas en centros comerciales, VLSI, etc) se sabe que son difíciles de resolver. Ella se ha centrado en cómo las propuestas genéticas pueden ayudar a encontrar diseños eficientes y ha analizado numerosos artículos de investigación sobre los problemas de distribución en planta (que son presentados en su manuscrito). En una primera parte de su investigación, ha hecho hincapié en la búsqueda de la disposición de estas instalaciones con respecto a un criterio de comportamiento determinado, que puede expresarse como un problema de optimización con restricciones. Para resolverlo, ha propuesto un Algoritmo Genético que utiliza nuevos operadores para tener en cuenta las especificaciones del problema. Su enfoque ha sido probado mediante casos reportados en la bibliografía. En la segunda parte de su investigación, se ha centrado en problemas donde la solución final debe ser considerada como aceptable por el diseñador, en lugar de óptima para un criterio determinado. De hecho, los diseñadores no necesariamente tienen la obligación de tener en mente de antemano todas las consideraciones que puedan tenerse en cuenta para incluirlas en la función objetivo o en las restricciones. Por otra parte, puede ocurrir que ciertas soluciones sean preferibles a otras sobre una base de criterios cualitativos o subjetivos. Para hacer frente a esas dificultades, ella ha propuesto un Algoritmo Genético Interactivo, que ayuda a sugerir soluciones relevantes gracias a las representaciones gráficas (asociadas a los cromosomas) y a un método de agrupamiento difuso, que contribuye a reducir el número de soluciones a evaluar en cada iteración. Este enfoque, a nuestro mejor leal saber y entender, no ha sido publicado para este tipo de problemas, por lo que el trabajo de Laura parece bastante original con respecto a los resultados de investigación existentes. Ella ha puesto de manifiesto el potencial de su enfoque mediante problemas de referencia. Presentando sus resultados en varias conferencias internacionales, así como el envío de una publicación a una conocida revista internacional.

Nos gustaría subrayar que, además de las ideas innovadoras que ella ha propuesto, sus resultados han requerido una cantidad importante de programación, lo que demuestra sus habilidades en computación.

Ha pasado mucho tiempo en Francia y ha hecho un trabajo muy bueno por escribir su tesis en Inglés. Ella siempre ha demostrado mucha motivación, la capacidad para hacer frente a problemas difíciles y buenas habilidades científicas. Laura ha contribuido en una fructífera colaboración internacional entre la Universidad de Córdoba y la institución LIMOS en Francia.

Por todas estas razones, se le autoriza a que pueda presentar su trabajo con el objetivo de obtener el título de Doctor con Mención Europea.

En Córdoba, 23 de Mayo de 2011.

Cordoba, Spain
Fdo.:Lorenzo Salas Morera;

Cordoba, Spain
Fdo.: Antonio Araúzo Azofra;

Aubière, France May 20, 2011
Fdo.: Henri Pierreval
PROF. HENRI PIERREVAL

A mis padres y mi hermano.

Agradecimientos

En primer lugar deseo expresar mi más sincero agradecimiento a los directores de esta tesis doctoral. Gracias a Lorenzo Salas, por sacarme una sonrisa en mis momentos de desesperación, por apoyarme y confiar siempre en mí, y por que sin él, este punto de mi vida simplemente no hubiera sido una realidad. Gracias a Antonio Araúzo, por su dedicación, por sus desvelos y su paciencia inagotable. Gracias por estar siempre disponible para mi. A Henri Pierreval, por brindarme sus sabias palabras, por su rigor en el trabajo, por ayudarme siempre que lo he necesitado. *Je vous remercie beaucoup.*

Asimismo, agradezco a mi compañera y amiga, Amanda García, por su amabilidad; por ofrecerme su tiempo, su ayuda y consejos; y por facilitarme el camino con todo lo que estaba a su disposición. Gracias por ser una compañera de verdad, por ser para mí, un referente como profesional y persona. Gracias a mi también compañero y amigo, Javier Estévez, por darme esa chispa cada mañana, con esas divertidas palabras que no paran de hacerme reír y me llenan de vida.

Gracias a mis amigos y a todas aquellas personas que han hecho posible que llegue este momento. A Desirée, por escucharme, comprenderme y crear momentos inolvidables. A José, por su apoyo ilimitado, por consentirme, cuidar de mí e intentar verme siempre feliz.

A mis padres, por dármelo todo en esta vida, por quererme tanto, por sus enseñanzas, por esperarme siempre llegar, por los besos de cada día. Gracias de todo corazón.

Pero sobretodo, quiero dar las gracias a mi hermano, por confiar de forma incondicional en mí, por apoyarme cada segundo, por hacerme creer que todos los sueños pueden alcanzarse, y por un millón de cosas más. Gracias por ser mi alquimista particular y el mejor hermano del mundo.

A todos ellos, mil gracias.

“Nunca te das cuenta de lo que ya has hecho.
Sólo puedes ver lo que te queda por hacer”

Marie Curie

Carta a su hermano, 18 de Marzo de 1884.

Resumen

Esta tesis doctoral aborda el problema de distribución en planta, el cuál en líneas generales, pretende asignar o distribuir instalaciones en una planta industrial. Existen muchos problemas diferentes dependiendo de las características que sean consideradas de la planta industrial, como por ejemplo, la forma de las instalaciones, el número de plantas, la flexibilidad requerida en los sistemas de producción, el tipo de producto que se fabrica, etcétera. Uno de los problemas más abordados, ha sido el problema de distribución en planta con instalaciones de área desigual. Para solucionar este tipo problemas existen muchas técnicas que pretenden alcanzar un diseño eficiente de la planta industrial. Entre ellas, una de las estrategias más usadas por los investigadores ha sido la de los Algoritmos Genéticos (AGs). Los AGs requieren definir un esquema de codificación para representar el diseño de la planta industrial como una estructura de datos. Esta estructura determina el tipo de soluciones que pueden ser obtenidas, e influencia la capacidad del AG para encontrar buenas soluciones. Aunque existen varios trabajos que revisan el estado del arte de los problemas de distribución en planta, no hay ninguno que centre su revisión en los esquemas de codificación y los operadores evolutivos usados por los AGs. Así, una de las contribuciones de la tesis que se presenta, es el estudio de los esquemas de codificación y los operadores evolutivos empleados por los AGs en problemas de distribución en planta. Además, este estudio se completa con una clasificación de las diferentes estructuras de codificación utilizadas por los autores, un estudio de sus características y objetivos, y finalmente, la identificación de los operadores de cruce y mutación que pueden ser aplicados dependiendo de la estructura de codificación.

Por otro lado, en esta tesis se propone un AG para el problema de distribución en planta de instalaciones de área desigual, teniendo en cuenta aspectos que pueden ser cuantificados, tales como: el de flujo de material, las relaciones lógicas entre las actividades que se realizan en los centros de producción (comúnmente, instalaciones) y la forma de cada uno. Para ello, se sugiere una nueva forma de representar las plantas industriales. Este algoritmo se ha integrado en una aplicación informática que permite a los usuarios introducir los datos y configurar los parámetros del algoritmo, así como mostrar las soluciones propuestas de una manera sencilla y amigable. Finalmente, el algoritmo ha sido probado con varios problemas y sus resultados comparados con los obtenidos en otros trabajos citados en la bibliografía.

Aunque el problema de distribución en planta de instalaciones de área desigual ha sido resuelto con muchas estrategias, siempre ha sido abordado teniendo en cuenta criterios cuantificables. Sin embargo, existen características subjetivas que resultan muy interesantes para este problema. Dicha características son muy difíciles de tener en cuenta mediante los métodos clásicos de optimización. Por esta razón, se propone un Algoritmo Genético Interactivo (AGI) para el problema de distribución en planta de instalaciones de área desigual, el cuál permite la interacción entre el algoritmo y el diseñador. Con la implicación del conocimiento del diseñador en la propuesta, el proceso de búsqueda es guiado y ajustado a las preferencias de aquél en cada iteración del algoritmo. Para evitar sobrecargar al diseñador, la población de soluciones es clasificada en grupos mediante un método de *clustering*. Así, sólo un elemento de cada grupo es evaluado. Durante todo este proceso, aquellas soluciones que resulten interesantes para el diseñador son almacenadas en memoria. Las pruebas realizadas muestran que el AGI propuesto es capaz de captar las preferencias del diseñador, y que además, progresa hacia una buena solución en un número de iteraciones razonable.

Abstract

This thesis addresses the Facility Layout Problem (FLP), which broadly tries to assign or distribute facilities into an industrial plant layout. There are many different problems depending on the feaures that are considered from the industrial plant, as for example, the way of facilities, the number of plants, the flexibility required in the production systems, the type of product that manufactured, and so on. One of the most discussed of them has been the Unequal Area Facility Layout Problem (UA-FLP). To solve such problems exist many techniques that aim to achieve and efficcient design of the plant layout, among them, one of the most commonly used has been Genetic Algoritms (GAs). To represent the plant layout design as a data structure, GAs require a defined encoding scheme. Such structure defines the types of solutions that can be obtained, and influences the GA's ability to find good solutions. There are a few surveys on facility layout problems, but they have not addressed evolutionary issues in depth. Thus, in this thesis, one of the contributions that is presented is a study that focuses on the encoding schemes and the related operators used in GAs for solving FLPs. Moreover, this study is completed with a method of classifying the different encoding structures described in the bibliography, a revision of their main characteristics and objectives; and finally, the identification of the crossover and mutation operators that could be applied depending on the type of encoding scheme that has been employed.

Additionally, in this thesis a Genetic Algorithm (GA) for the UA-FLP is proposed. This approach takes into account aspects that can be quantified, such as: material handling costs, logical relations between spaces and the shape of each area. For that purpose, a new encoding representation for these problems is suggested. This algorithm has been integrated into a software application that allows users to enter data, configure the algorithm parameters, as well as, show the solutions proposed in a simple and user-friendly manner. Finally, the algorithm has been tested with various problems and the results compared with those reported in the bibliography.

Although the UA-FLP has been addressed using several methods, it has only been solved for criteria that can be quantified. However, there are subjective features that are interesting for this problem, which are difficult to take into account with a more classical heuristic optimisation. For that reason, an Interactive Genetic Algorithm (IGA) that allows an interaction between the algorithm and the Decision Maker (DM) is proposed. Involving the DM's knowledge in the approach guides the search process, adjusting it to the DM's preferences at each iteration of the algorithm. In order to avoid overload the DM, the whole population is classified into clusters by a clustering method, and only one representative element of each cluster is evaluated. A memory of the best solution is kept as a reference for the DM choices. The tests carried out show that the proposed IGA is capable of capturing DM preferences and that it can progress towards a good solution in a reasonable number of iterations.

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A - total area of the layout.

α_1, α_2 - weighting factors in the evaluation function of the proposed Genetic Algorithm.

α_{max} - is the maximum aspect ratio.

b - optimum aspect ratio.

c - number of clusters.

$c_{i,j}$ - cost associated to move a unit of material flow from facility i to facility j.

C - evaluation function to minimize in the proposed Genetic Algorithm.

$d_{i,j}$ - distance between facility i and facility j.

δ - Aspect ratio of the plant layout.

D_{ij} - the Manhattan distance between the facility centroids.

E_i - the mark assigned by the DM to the representative element of cluster i.

$f_{i,j}$ - quantity of material flow from facility i to facility j.

F_1 - function to evaluate the distance covered by materials.

F_2 - function to evaluate compliance with the logical ratios between facilities.

H - height of the layout.

L_i - the length of facility i.

m_{ij} - the membership grade of the individual j to the cluster i.

n - number of facilities.

N - number of individuals of the population.

REL_{ij} - triangular relational matrix that expressed the closeness ratios.

s_i - surface area of i facility.

$s.e._j$ - the estimated subjective evaluation of individual.

w_i - the width of facility i.

W - width of the layout.

x_1, y_1 - coordinates of the point 1.

x_2, y_2 - coordinates of the point 2.

x_i - aspect ratio of the facility *i* (largest side divided by the smallest side).

1. Introduction

1.1. Overview

Facility Layout Design (FLD) determines the placement of facilities in a manufacturing plant with the aim of determining the most effective arrangement in accordance with some criteria or objectives, under certain constraints. FLD is known to be very important for attaining production efficiency (Kouvelis et al., 1992) because it directly influences manufacturing costs, lead times, work in process and productivity. Well laid out facilities contribute to the overall efficiency of operations and can reduce between 20% and 50% of the total operating costs (Tompkins et al., 2003). There are many kinds of Facility Layout Problems (FLPs), which will be detailed in the next chapter. A classification of them is given in, for example, Drira et al. (2007), Kusiak et al. (1987) and Kulturel-Konak (2007).

Unequal Area Facility Layout Problem (UA-FLP) is one of the important

FLP which originally was formulated by Armour and Buffa (1963). In short, UA-FLP considers a fixed rectangular plant layout that is made up by unequal rectangular facilities with dimensions *H* (height) and *W* (width) that have to be placed effectively in the plant layout having into account the following criteria:

1. All the facilities must be located inside the plant layout.

2. All the facilities must not overlap with each other.

The goal of the UA-FLP is to divide the plant into facilities so as to optimise a target function, for example, to minimise the total material movement cost. Most researchers have addressed UA-FLP using quantitative performance criteria (e.g. material handling cost, closeness or distance relationships, adjacency requirements, aspect ratio), which are used in an optimization approach. This problem is a complete Non-deterministic Polynomial (NP) problem and thus, recent research using exact algorithms can only optimally solve up to 11 facilities (Meller et al., 2007). However, since optimal methods are limited by the number of facilities, other suboptimal have been developed to address more complex problems. In this respect, several Evolutionary Computation (EC) approaches have been applied to deal with UA-FLP. Among these, the Genetic Algorithms (GAs) (Holland, 1992) are commonly used. Genetic Algorithms (Gas) has been widely used because problems do not need to be modelled mathematically since only a fitness function is required which takes into account the limitations of the problem. In fact, the success of this type of algorithms depends partly on the consideration given to restrictions in the evaluation function (Michalewicz et al., 1996), as well as in the chosen coding of possible solutions (individuals) and in the selection and reproduction operators used. GAs can be applied successfully in problems in which the search space is large or not well understood or the evaluation function is complex, and if the problem does not require a global optimum but only a sufficiently satisfactory solution, as in the case of the facility layout design (Mitchell, 1998).

However, qualitative features have also to be taken into consideration, for instance: preferences about the location of specific facilities, distribution of the remaining spaces, relative placement preferences, or any other subjective preference that can be considered as important by the DM. An effective facility layout evaluation procedure necessitates the consideration of qualitative criteria, as well as quantitative criteria (Tuzkaya and Ertay, 2004). These qualitative features are complicated to take into account with a classical heuristic or meta-heuristic optimization (Brintup et al., 2007). Above all, it is very difficult to take into account of both quantitative and qualitative aspects at the same time, because it can not be easily formulated as an objective function. In this respect, the participation of the Decision Maker (DM) is essential to include qualitative considerations in the design. Besides, including the DM's experience into the algorithm provides additional advantages that will be detailed in Chapter 5. In this way, Brintup et al. (2006) have highlighted that Interactive Evolutionary Computation (IEC) can greatly contribute to improving optimized design by involving users in searching for a satisfactory solution (Brintup et al. 2007). Interactivity allows for more qualitative considerations, which can be more subjective, to be taken into account. In IEC the fitness function is replaced by a human's user evaluation (Takagi, 2001). Thus, intuition, emotion, and domain knowledge can be involved in the identification of good designs (Quiroz et al., 2007). To the best of our knowledge, there seems to have no article that proposes interactive approach for UA-FLP.

1.2. Objectives

The objectives of this thesis are to:

1. To study the encoding schemes and operators used in GAs for UA-FLP in order to discover the most adequate for each proposal and unexplored combinations to research.

2. To formulate and evaluate a novel GA for solving UA-FLP that improves the performance of the state of the art proposals.

3. To handle qualitative aspects in UA-FLP by the inclusion of expert knowledge into the approach and to adapt it to the Decision Maker (DM) preferences. For that purpose, an interactive algorithm to UA-FLP will be proposed.

1.3. Scope

This thesis covers the study, design, development, and evaluation of the proposed approaches for solving UA-FLPs. Also, this investigation makes conditional by the following limitations:

1. This research is only interested in solving UA-FLP which have a rectangular plant layout with fixed dimensions. Also, the

total facility area must not exceed the plant layout area.

2. All the facilities are considered rectangular and its areas are known in advance.

3. All the test problems are taken from the previous works that are related in the literature. The smallest problem contains 10 facilities whereas the largest one has 20 facilities.

4. This research is focused on evolutionary techniques for solving UA-FLP, particularly, using GAs.

1.4. Organization

The remainder of this thesis is detailed as follows. Chapter 2 gives the details of the related research of Layout Problems, and in particular, UA-FLP. It offers a review of the existing approaches to solve UA-FLP. In Chapter 3, a study focus on the encoding schemes and the operators used by GAs for solving UA-FLPs, is performed. Chapter 4 presents the suggested GA to deal with UA-FLP. In Chapter 5, an interactive approach to UA-FLP is proposed. Conclusions are stated in Chapter 6. Finally, the future lines of research are exposed in Chapter 7.

1.5. Conclusions

In this chapter, an introduction of the research, its objectives and its scope have been described. In this research it will review the existing approaches to solve FLPs and UA-FLPs. Moreover, it is expected to study the encoding schemes and operators used in GAs for FLPs and UA-FLPs in order to discover the most adequate for each proposal and the unexplored combinations to research.

Additionally, in this research is expected to produce a new GA and an IGA for solving UA-FLP. The first one, pretends to improve the performance of the results obtained by the proposals that are related in the literature. The second one, will allow to introduce qualitative considerations in the design using the expert knowledge from the DM. Besides, the idea of using an interactive approach for handling qualitative aspects in UA-FLP is a novel concept because from the best of our knowledge, there is no interactive approach applied to UA-FLP.

2. Facility Layout Problems and the Unequal Area Facility Layout Problem

2.1. Introduction

This chapter explains the basic concepts about Facility Layout Problems (FLPs). In Particular, the emphasis is put on the Unequal Area Facility Layout Problems (UA-FLP). An analysis of literature published in the area is performed in accordance with:

1. Workshop characteristics, such as: facility shapes and dimensions, material handling systems, multiple floor considerations, the planning horizon, the production characteristics, among others.

2. Layout representations. A distinction among the different ways to represent a layout is performed. Mainly, this breakdown is

done dividing into main categories, that is, continuous and discrete representations.

3. Resolution approaches. A revision of the approaches used to solve FLPs and UA-FLP has been realized, having into consideration the principal categories, that is to say, the exact procedures and the approximate approaches.

2.2. Facility Layout Problems

The problem of physical placement of the facilities in the plant area is referred to as FLP. A facility is any element that favours the benefit of any job. In this respect, a facility can be a department, a machine, a warehouse, a manufacturing cell, among others (Heragu, 2008). A facility layout is a physical distribution of the necessary elements that integrate the production process. This term implies not only a manufacturing but it also includes service systems (Meller and Gau, 1996).

The FLP is a well studied combinatorial optimization problem which arises in a variety of problems such as printed circuit board design; layout design of hospitals, schools, and airports; backboard wiring problems; typewriters; warehouses; hydraulic turbine design; among others (Singh and Sharma, 2006). Due to the fact that layout have tremendous impact on the overall operational efficiency of a facility, the FLP has been widely studied, and there are some surveys about it. Thus, Kusiak and Heragu (1987) offered various formulations of the FLP and the algorithms for solving it. Also, they compared twelve heuristic algorithms on the basis on their performance; Meller and Gau (1996) presented a stated of the art in FLP that includes new methodologies, objectives, algorithms and extensions to FLP; Singh and Sharma (2006) reviewed the different approaches that have been applied to FLPs; Drira et al. (2007) analysed the literature referred to FLPs using criteria as: the manufacturing system features, static/dynamic considerations, continual/discrete representation, problem formulation, and resolution approaches; and Kultutel-Konak (2007) presented a review of recent approaches in designing robust and flexible facilities under uncertainty.

A good distribution of facilities is crucial for attaining production efficiency (Kouvelis et al., 1992) because it directly influences manufacturing costs, lead times, work in process and productivity. In a traditional manufacturing, the type of material handling system used accounts for 25% of all employees, 55% of all space, and 87% of production time as stated by Frazelle (1986). Thus, it is estimated that between 20% and 50% of production costs can be attributed to material handling, although it is generally accepted that such costs can be reduced by at least between 10% and 30% through efficient design (Francis and White, 1974). Moreover, Tompkins et al. (2003) estimated that since 1955, approximately 8% of the gross national product, has been spent annually on new facilities in United States. Besides, contemporary facilities planning must include the concept of continuous improvement in the design approach. As a result, the authors estimated that over $250 billion are spent annually in United States alone on facilities that need to be planning or replanning.

The aim of FLP is to achieve the most effective arrangement in accordance with some criteria or objectives laid down, while also admitting some constraints. The most common objective is to minimize the material handling cost of the manufacturing plant layout, but it can also take into account others as to maximize the space utilization, flexibility, employee satisfaction and safety, among others (Muther, 1955). In this respect, Muther (1973) stated the following objectives for plant layout:

1. to reduce the travel distances of materials.
2. to have a regular flow of the parts and products avoiding bottleneck in the production.
3. to effectively utilize the space occupied by the facilities.
4. to enhance satisfaction and safety of workers.
5. to reduce lead time in the production.
6. to obtain flexibility that can be easily readjusted for changing conditions.

Different definitions of layout problems are in the literature because of the diversity of considerations that can exist. This way, Koopmans and Beckmann (1957) have introduced layout problem as a industrial problem in which the objective is to find an placement of all facilities to all locations with the intention of minimizing their associated cost of material flow. They modelled this problem as a *Quadratic Assignment Problem* (QAP), which will be described later. Meller et al. (1999) defined the FLP, as a non-overlapping planar orthogonal arrangement of *n* rectangular facilities within a given rectangular plant layout so as to minimize the product of material handling flow and the distance among facilities. Azadivar and Wang (2000) formulated the FLP as the determination of the relative locations for, and allocation of, the available space among a given number of facilities. Lee and Lee (2002) considered the FLP as the problem of arranging *n* unequal-area facilities of different sizes within a given total space, which can be bounded to the length or width of site area in a way to minimize the total material handling cost and slack area cost. Shayan and Chittilappilly (2004) reported the FLP as an optimization problem that tries to make layouts more efficient by taking into account various interactions among facilities and material handling systems while designing layouts.

Komarudin (2009) proposed a comparison between the main FLP categories: *Quadratic Assignment Problem* (QAP), *Unequal Area Facility Layout Problem* (UA-FLP) and *Machine Layout Problem* (MLP). For that purpose, he used the Table 1:

Table 1: Comparison of FLP categories

Problem Category	**Facility Size**	**Location candidate**	**Facility Area**
QAP	Equal, with fixed or ignored dimensions	Fixed location	Fixed or ignored
UA-FLP	Unequal, decision variables	Decision variables	Greater or equal than total facility areas
MLP	Unequal, with fixed dimensions	Decision variables	Greater or equal than total facility areas or free dimension

The QAP was originally introduced by Koopmans and Beckman (1957) who were trying to model a facilities location problem (Çela, 1998). The objective of QAP is to assign all the facilities to all locations such that the total assignment cost is minimized. Having into account that the facilities and locations have equal areas, which are fixed and known in advance.

The UA-FLP was originally introduced by Armour and Buffa (1963). The objective of UA-FLP problem is to partition the region into subregions, of appropriate area, having into account that the sum of the subregion area is equal to the area of global region, so as to minimize the total cost of the material flow. In this problem, the shape of the region (plant layout) and the subregions (facilities) are regular and unequal (Tate and Smith, 1995a).

The MLP is discussed in Heragu and Kusiak (1986). In this problem, the design involves the layout of machines and the work stations (Kusiak and the following criteria: Heragu, 1987). The objective to achieve in MLP is to allocate the machines in the plant layout minimizing the material handling costs (Tompkins et al., 2003). In this problem, the machines are different sizes and their locations depend on specific processes that are necessary to obtain the final products.

Several works have been published about FLP. In order to stress the essential features that can characterize the layout problems, some diagrams have been proposed (see Figure 1, Figure 6). They are based on the rough tree proposed by Drira et al. (2007). Thus, the problems related in the literature are distinguished between themselves, depending on specific factors as: the workshop characteristics, the problem addressed, and the approaches used to solve it.

2.2.1 Workshop characteristics

In the related literature, it is possible to find many factors and features that lead to different layout problems, this fact is displayed in Figure 1. Among others, these features can be: the facility shapes and dimensions, the material handling systems, the number of floors to consider, the layout evolution. These factors will be described as follows.

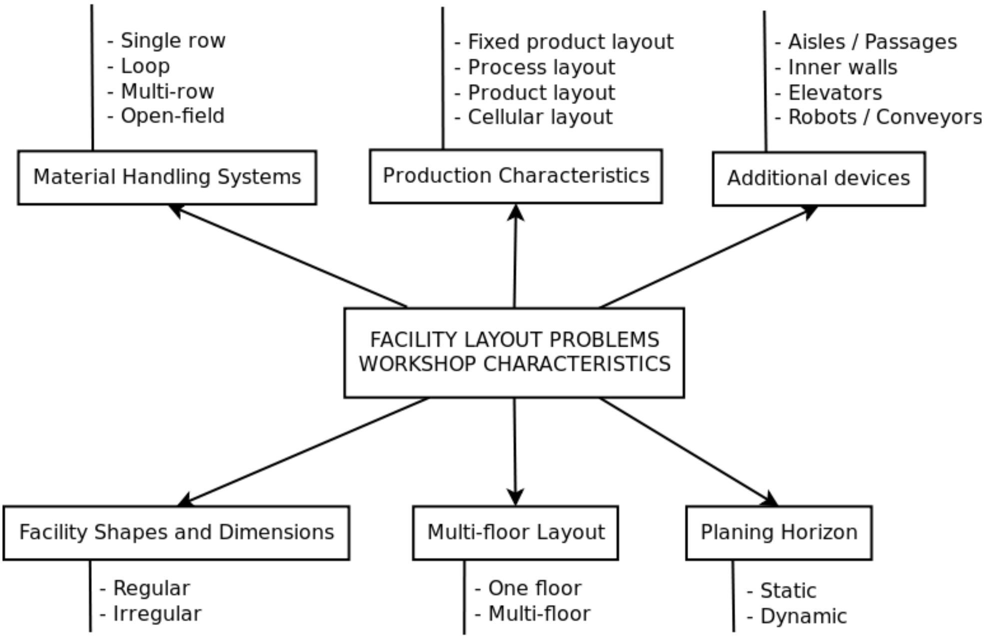


Figure 1: Workshop characteristics and its inherited FLPs

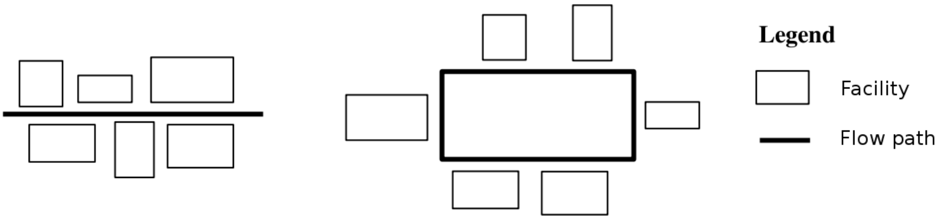
Facility shapes and dimensions

There are two common facility shapes. On the one hand, regular shape, which is usually a rectangular facility (Kim and Kim, 2000). On the other hand, irregular shape, which facilities are usually polygons that cover an angle of 270 degrees at least (Lee and Kim, 2000).

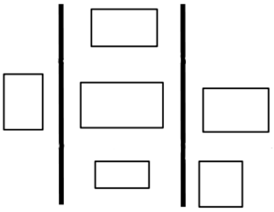
Concerning to the facility dimensions, as Chwif et al. (1998) refers in their work, a facility can be defined by means of: its fixed height and width dimensions, where a facility will be a fixed block layout; its area, its aspect ratio (described in Section 2.3. of this chapter), and a lower bound.

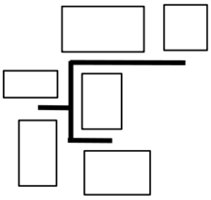
Material handling systems

The material handling system also determines different layout problems depending on the existing material handling path between facilities. Thus, Yang et al. (2005) offered a classification of layout arrangements having into account the type of material handling. They differed between single row layout, loop layout, multi-rows layout, and open field layout. These material handling systems are presented in Figure 2 which has been taken from Yang et al. (2005).



(a) Single row layout (b) Loop layout





(c) Multi-rows layout (d) Open-field layout

Figure 2: Layouts associated to material handling systems

In *single row layout problem*, the facilities are arranged along a line (no necessary a straight (Hassan, 1994) line), which determines the material handling path (Kumar et al., 1995; Kim et al., 1996; Djellab and Gourgand, 2001; Ficko et al., 2004). The *loop layout problem* assigns the facilities to the possible locations having into account that the material handling operates only in one direction and the loop is closed (Cheng et al., 1996; Cheng and Gen, 1998; Potts and Whitehead, 2001; Nearchou, 2006). The *multi-rows layout problem* deal with several rows of facilities (Hassan, 1994) taking into consideration that the material handling flow can be among facilities from the same row or from different rows (Cheng et al., 2001; Kim et al., 1996; Ficko et al., 2004). Finally, Yang et al. (2005) reported that the *open field layout problem* is attributed to problems where the facilities are arranged into layout without any restriction.

Multi-floor layout

In this problem, the aim is to allocate facilities in a manufacturing plant that has various floors or levels. In this type of configuration, not only the material flow can move horizontally on a given floor, but also from one floor to another ones, that is to say, in vertical direction. Because of vertical movement of material flow, it is necessary to include a device to transport it in the manufacturing layout, normally an elevator is used for that purpose. Considering the third dimension (vertical) obviously introduces additional complexity to FLP. For example, the distance between two facilities situated on different floors may be nonlinear (Heragu, 2008).

It seems that the earliest work on the multi-floor layout problem was performed by Johnson (1982). He investigated the problem of relative location of facilities in a multi-floor building. He offered an approach that is based on the well-known facility layout algorithm of CRAFT (Buffa et al., 1964). In order to solve multi-floor FLP many approaches have been proposed. Bozer et al. (1994) proposed MULTIPLE that extends CRAFT to a multiple floor problem, the only difference between them is in the exchange procedure and the layout formation (Zhang and Lai, 2006). Thus, Meller and Bozer (1996, 1997) developed SABLE, and Kochhar and Heragu (1998) suggested MULTI-HOPE for solving the multi-floor facility layout problem, they taken into consideration vertical movements of material flow from one floor to another.

The number and placement of elevators can be known in advance (Lee et al., 2005) or they must be obtained having into account the capacity of each elevator (Matsuzaki et al., 1999). Besides, the number of floors can also be known a priori (Lee et al., 2005), or they should be determined by the floor area and the dimensions of facilities (Patsiatzis and Papageorgiou, 2002).

Planning horizon: Static and Dynamic Facility Layout Problems

Currently, because of the demand of products and services changes in shorts periods of time, it is necessary that the manufacturing plant will be flexible and capable to adapt it quickly to this changing environment. In this context, Gupta and Seifoddini (1990) reported that every two years, the third part of USA manufacturing plants modifies their facility distribution deeply. Benjaafar and Sheikhzadeh (2000) stated that manufacturing facilities must be able to exhibit high levels of flexibility to react to significant changes in their operating requirements. Normally, most authors supposed a stable environment of production which the requirement of products and services are constants over a long period of time. Thus, they have considered a static plant layout when they deal with FLP and it is called *Static Facility Layout Problem.*

However, the are several works that take into account possible changes in the production environment where the manufacturing plant is designed to enable it adapt the plant to a changing environment (Rosenblatt, 1986; Balakrishnan et al., 1992; Kouvelis et al., 1992; Conway and Ventakaramanan, 1994; Balakrishnan et al., 2003; Braglia et al., 2003; Meng et al., 2004; Dunker et al., 2005). In this case, the problem is called *Dynamic Facility Layout Problem*. To solve this problem, the planning horizon is divided into periods with different material flow requirements, which can be weeks, months, seasons, years. Then, each period is associated to a static plant layout, this way, the plant layout for the *dynamic layout problem* is made up for the set of static layouts, each one is linked to each period.

In *Dynamic Facility Layout Problem*, the usual objective is to allocate the facilities in the layout for each period in the planning horizon, minimizing the total material handling cost for all periods, and the costs of layout rearrangements to adjust it to the production necessities of different periods.

Production characteristics

There are different layout distributions depending on the volume and variety of products. In this respect, Dilworth (1996) suggested the following types of organizations: *fixed product layout*, *process layout*, *product layout* and *cellular layout*.

Fixed product layout addresses an organization where products do not circulate within the facilities, but tools and resources which are moved to perform the manufacturing product, which is generally static because of its size or special conditions. This type of distribution is used for example in industries that build a ship, a submarine, or an aircraft.

In *product layout*, the layout is oriented totally to the product, so that, the facilities are organized in function of the operation sequence that are necessary to obtain the final product. This layout organization has sense when a great volume of production and a low variety of products exists.

Process layout is used for industries where a great variety of products exists. In this organization, the facilities are grouped according to their functions. Thus, the facilities with a similar function are grouped together.

In the case of *cellular layout*, machines are divided into clusters to process families of similar parts.

Additional devices

The FLPs can incorporate additional devices as passages or aisles (Wu and Appelton, 2002; Gómez et al., 2003); inner walls (Lee et al., 2003; Lee et al., 2005); robots, conveyors, automated guided vehicles (Hassan, 2004); elevators (Matsuzaki et al., 1999) and stairs, among others.

2.3. Unequal Area Facility Layout Problem

Unequal Area Facility Layout Problem (UA-FLP) was originally formulated by Armour and Buffa (1963). They supposed that there is a given rectangular region, or plant layout, with fixed dimensions $H \times W$, and a collection of n required facilities of specified area. Each ordered pair of facilities (i, j) is associated a material flow $f_{i,j}$ that also it is known in advance. The objective is to partition the region into n subregions, of appropriate area, so as to minimize the total costs of the material flow movements. This is expressed as follows:

$$Cost = \sum_i \sum_j f_{ij} c_{ij} d_{ij} \quad i \neq j$$

Where:

n: number of facilities that make up the layout.

$f_{i,j}$: material flow from facility i to facility j.

$c_{i,j}$: cost associated to move a unit of material flow from facility i to facility j.

$d_{i,j}$: distance (using a pre-specified metric) between facilities i and j.

Having into account that $i, j = 1, 2, 3, 4, \ldots, n$.

In order to enhance the UA-FLP methods to produce a more realistic solution, a *Maximum Aspect Ratio* has been defined by Camp et al. (1989), which is calculated by the formula that appears below. By means of using the maximum aspect ratio, it is ensured that the UA-FLP approaches obtain feasible physical layout solutions. Thus, the more small is the maximum aspect ratio, the more restricted are the facility dimensions, and then, the UA-FLP becomes highly constrained.

$$\alpha_{max} = \frac{\{max\, l_i, w_i\}}{\{min\, l_i, w_i\}}$$

Where:

α_{max}: the maximum aspect ratio.

l_i: length of facility *i*.

w_i: width of facility *i*.

Having into account that $i = 1, 2, 3, 4, ..., n$.

As it is said previously, the main of UA-FLP is to allocate the facilities into the layout having the minimum material handling cost as possible, this cost increases proportionally with the distance that the material should cover. There are different ways to measure the distance between facilities, although, the most common used are:

Distance between centroids. In this case, the distance is calculated between the centroids (centres of mass) of the facilities.

Distance between input and output points. In this case, the distance is calculated having into account the facility points of input and output of material flow. In problems that used specific devices as aisles, it is also necessary to measure along the aisles that exist in the layout (Tretheway and Foote, 1994).

In order to obtain these distances, there are different metrics to apply, two of them can be: *Euclidean distance* and *Manhattan distance*. The first one, is the segment length that joins two points (for example, the facility centroids). In order to calculate it, the following equation is used:

$$Euclidean\,distance(x,y)=\sqrt{(x_1-x_2)^2+(y_1-y_2)^2}$$

Where:

x_1, y_1: coordinates of point 1.

x_2, y_2: coordinates of the point 2.

In the second one, in order to measure the *Manhattan distance* between two points 1, 2. Firstly, the distance horizontal between x_1 *and* x_2 is calculated, and then, the vertical distance between y_1 *and* y_2 is added. This metric can be computed as follows:

$$Manhattan\,distance(x,y)=\left|(x_1-x_2)+(y_1-y_2)\right|$$

Where:

x_1, y_1: coordinates of point 1.

x_2, y_2: coordinates of the point 2.

2.3.1 Layout representations

UA-FLP can be modelled using various representations. These representations can be grouped into two main categories. The first one, is the *continuous representation*, and the second representation, is the *discrete model*.

Continuous representation

In continuous representation, there are two possible structures of representation: *Flexible Bay Structure* and *Slicing Tree Structure*, which will be explained below.

Flexible Bay Structure

Flexible Bay Structure was proposed by Tong (1991). Currently, it is receiving great attention from researchers (Wong and Komarudin, 2010b). In this representation, the plant layout is delimited by height and width dimensions. This rectangular area is divided in one direction into bays or columns of varying width. Then, each bay is subdivided to allocate the facilities that make up the layout. The bays are flexible this means their widths will vary with the number of facilities that can contain (Tate and Smith, 1995a). This way, the problem becomes simpler and easier to solve, and the problem complexity is reduced into determining the order of facility placement and the total number of facilities that each bay contains (Komarudin, 2009). Moreover, the representation of Flexible Bay Structure has the advantage that the bays usually create aisle structures. This favours to the Decision Maker to translate the model into a real facility design (Konak et al., 2006).

This representation is shown in Figure 3, which is an example taken from (Aiello et al., 2006). In the related literature, several authors have used flexible bay structure representation, for example, Tate and Smith (1995a), Mak et al. (1998), Lee and Lee (2002), Lee et al. (2003, 2005), Enea et al. (2005), Gómez et al. (2005), Norman and Smith (2006), and Chae and Peters (2006).

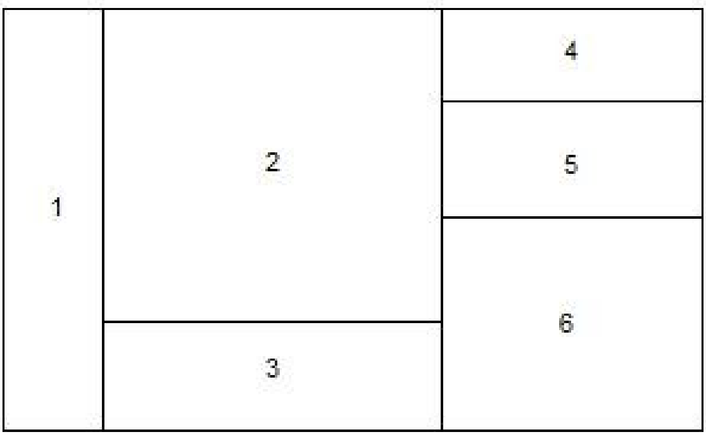


Figure 3: Flexible Bay Structure Representation.

Slicing Tree Structure

Slicing tree structure uses a tree representation to describe a layout. In order to translate it, each leaf node represents a facility, and each internal node is the slicing operator that divides the layout into portions or allocations. These operators could be '*v*' and '*h*' for vertical or horizontal cuts respectively, as they has been defined by Wu and Appelton (2002); or they could be more detailed such as, '*b*' for below cut, '*u*' for up cut, '*r*' for right cut, and finally '*l'* for left cut, this way has been used by Tam (1992a,b) and Matsuzaki et al. (1999). In Figure 4, it can be seen the slicing tree representation and its associated layout, this example has been taken from Tam (1992b). Also, *Slicing tree structure* has been applied by Honiden (2004) to solve UA-FLP.

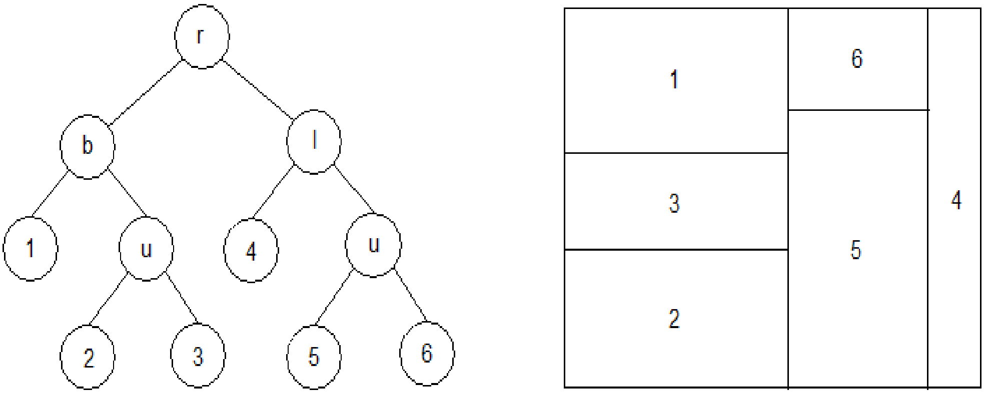


Figure 4: Slicing Tree Structure Representation and its associated layout.

Discrete representation

In *discrete representation* the plant layout is divided into squares or grids that have equal areas and dimensions. If the facilities have equal dimensions and regular shapes, we have a problem of allocating n facilities into *m* positions, that is to say, the QAP. However, if the dimensions are unequal and/or the shape is irregular, it becomes necessary to adopt another additional structure in order to gather the grids that belong to the same facility into an interconnected region. Depends on the additional structure that is selected, it is possible to obtain different facility shapes. In this sense, Balakrishnan et al. (2003) use as additional structure that is called *Space Filling Curve.* This additional structure enables the identification of each square within a determined facility, as is illustrated in Figure 5.

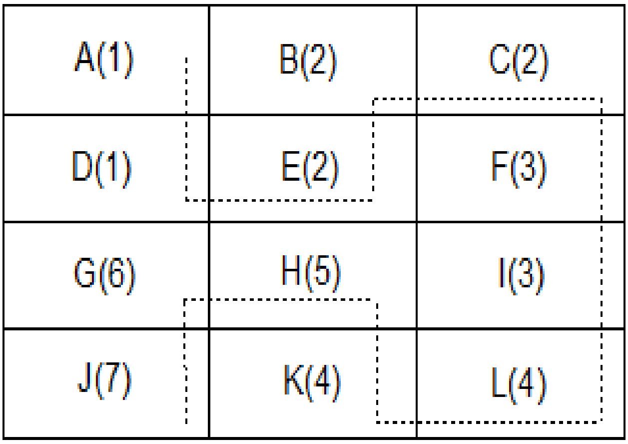


Figure 5: An example of a 12 square layout with SFC.

Many authors have applied the *discrete representation* for solving FLPs, for example, Armour and Buffa (1963), Chan and Tansri (1994), Conway and Ventakaramanan (1994), Tate and Smith (1995b), Mak et al. (1998), Singh et al. (1998), Tavakkoli-Moghaddain and Shayan (1998), Balakrishnan et al. (2003a, 2003b), El-Baz (2004), Hu and Wang (2004), Wang et al. (2005), and Rankumar et al. (2008), among others.

2.4. Resolution approaches

There are many approaches to solve the different FLPs. A diagram of them is in Figure 6. As it can be seen, it is possible to identify two main categories of resolution approaches: *exact procedures* and *approximate approaches*. The last one can be also into three groups, such as, *heuristics methods*, *meta-heuristic methods*, and *other approaches*. These resolution approaches will be explained below.

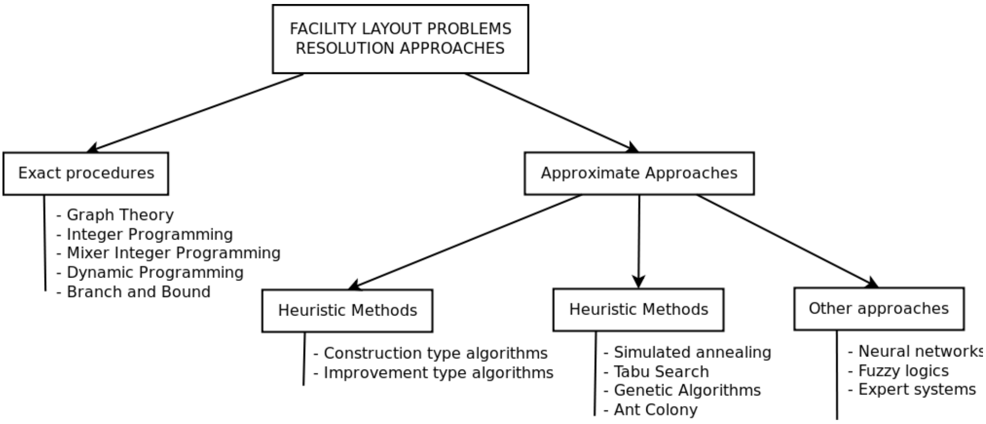


Figure 6: Resolution approaches applied to FLPs.

2.4.1 Exact procedures

Several approaches exist to solve any FLP by means of an exact procedure. The FLPs may be modelled using *graph theoretic, mixed integer programming, dynamic programming,* and *branch and bound algorithm.*

Graph Theoretic

In *graph theoretic* approaches, it is assumed that the desirability of locating each pair of facilities adjacent to each other is known (Foulds and Robinson, 1978). Unequal area problems of even small size cannot be solved optimally by *graph theoretic* approaches (Meller and Gau, 1996). A review of the results of graph theoretic approaches can be found in Foulds (1991) and Hassan and Hogg (1987).

Mixer-integer Programming

Montreuil (1990) introduced a *mixer-integer programming* to UA-FLP, which objective is based on the product of the material handling costs and the rectilinear distance between facility centroids. Although this is a powerful approach, only problems with six or less facilities can be solved optimally (Meller and Gau, 1996). Sherali et al. (2003) presented an improved *mixed-integer programming model* that is motivated in the work of Meller et al. (1999), and is capable to obtain optimal solutions for the UA-FLP with up to nine facilities. For that purpose, they used a polyhedral outer approximation of the area constraints ans branching priorities. Konak et al. (2006) used a *mixed integer programming approach* for UA-FLPs arranged using *flexible bay structure*. In their approach, the nonlinear facility area constraints are modelled in a continuous plane without using any surrogate constraints. Their method was extensively tested, and they can obtain optimal solutions to problems with up to fifteen facilities.

Dynamic Programming

Rosenblatt (1986) seems to be the first in *dynamic facility layout problem*. He raised the problem with equal size facilities, using a *dynamic programming method*, where the objective was minimizing the sum of the material handling costs and the rearrangement costs over all periods. But he can only resolve the problem for layouts with less of six facilities and five time periods, moreover. He did not always produce expected solutions (Kulturel-Konak, 2007).

Branch and Bound

Kouvelis and Kim (1992) used a *branch and bound algorithm* for the loop layout problem. Meller et al. (1999) proposed general classes of valid inequalities that are based on an acyclic sub-graph structure, and then, they incorporated them in the *branch and bound algorithm.* They achieved to solve the UA-FLP optimally with up to eight facilities. Kim and Kim (1999) suggested an approach to find the optimal location of the pick-up and drop-off points of each facility that uses a *brand and bound algorithm* to solve it.

2.4.2 Approximate approaches

Since optimal methods are limited by the number of facilities, other suboptimal methods have been developed to address more complex problems. Thus, several authors have used *heuristics methods* and *meta-heuristics methods* for solving FLPs.

Heuristic methods

Heuristic algorithms can be classified as *construction type algorithms* where a solution is constructed from scratch, and *improvement type algorithms* where an initial solution is improved (Singh and Sharma, 2006).

Construction type algorithms

Construction type algorithms are considered the simplest heuristic approach, but the solution obtained is considered in terms of quality as not satisfactory. There are some approaches that use this type of algorithms, which are detailed as follows.

ALDEP was developed by Seehof and Evans (1967). This approach works in the following way, first, a facility is selected randomly and it is assigned to the upper left corner of the layout. The next facility selected for being allocated is the one which has a relationship that is greater than or equal to a user specified relationship, with a randomly selected first facility. This procedure is repeated until all facilities are allocated in the layout.

CORELAP was created by Lee and Moore (1967). They used the total closeness rating of each facility to determine a layout. That way, the facility with highest total closeness rating is selected and assigned to the centre to the centre of the layout. Then, the subsequent facilities are added to the layout depending upon their relationships to the facilities already assigned.

MAT was proposed by Edwards et al. (1970). This approach ranks pair of facilities according to their flow values and location pairs according to their distance values. Then, this information is used to determine a layout. It allows the user to assign facilities to any desired location.

PLANET was created by Deisenroth and Apple (1972). This algorithm assigns the facilities in three stages. Firstly, the cost of unit flows between each pair of facilities is determined. Secondly, the facility order is selected. Finally, the facilities are placed in the layout in the order in which they have been selected in the second stage.

LSP was developed by Zoller and Adendorff (1972). This algorithm consist of a simulator which generates the sequence in which facilities are to be allocated in a layout, and a construction mode which determines a two-dimensional layout for the sequence generated previously.

COFAD was formulated by Tompkins and Reed (1976). This algorithm is a modification of CRAFT (explained below) that includes move costs for all alternative material handling systems, thus this algorithm integrates the material handling system selection problem with the layout problem. Later, Shore and Tompkins (1980) modified COFAD so as to incorporate flexibility in the design process, this new version was called COFAD-F.

SHAPE is a *construction type algorithm* that was proposed by Hassan et al. (1986). It uses a *discrete representation* and an objective based on rectilinear distance between facility centroids. The facility selection is dependent on a ranking, which is based on each facility flow and a user-defied critical flow value. Nevertheless, because the facility shape is controlled by the objective function, the shape of facilities may deteriorate toward the end.

NLT was developed by Camp et al. (1991). This algorithm is based on nonlinear programming and used *Euclidean distance* as distance metric. In NLT there are three set of constrains. Authors transformed this constrained model to an unconstrained one by using exterior point quadratic penalty function method. With a three-stage approach, successively more difficult problems are solved using the solution from previous stage as an initial solution point.

Improvement type algorithms

Improvement algorithms realize iterations in order to improve the initial solution. This methods can be combined with construction methods easily. In this respect, CRAFT (Armour and Buffa, 1963) seems to be the oldest *improvement-type approach.* It begins by determining the centroid of each facility. Then, It performs two-way or three-way exchanges of the centroids of non-fixed facilities that are also equal in area or adjacent in the current layout. For each exchange, CRAFT calculates and estimated reduction in cost and it chooses the exchange with the largest estimated reduction. It then exchanges the facilities exactly and continues until there exists no estimated reduction due to two-way or three-way exchanges. Hicks and Cowen (1976) criticized the exchange procedure because it may lead to facility with irregular shape.

H63 was developed by Hillier (1963). This heuristic algorithm is based on a move desirability table that consists of values which represent the cost changes that would result by moving a facility from its current location to an adjacent one. H63 considered only pairwise exchanges between adjacent facilities, which have equal areas.

FRAT has been implemented by Khalil (1973). This algorithm uses principles from other well known algorithms as CRAFT, H63. First, it determines the difference between the longest and the shortest distance, and then, the algorithm carries out two procedures, that is, the total cost determination procedure and the exchange procedure. This algorithm can be only applied to problems which facilities have equal areas.

DISCON was developed by Drezner (1980). This approach modelled FLP as a nonconvex mathematical programming problem. For solving this problem, a two-phase algorithm called dispersion-concentration is used. In the first phase, good initial conditions are found using the Lagrange differential gradient method. The second phase consist of concentrating the facilities so that they are close as possible. In this approach, although the dispersion phase provides good starting points, it is difficult to justify this outcome.

MULTIPLE is a multi-floor *improvement-type approach* that was proposed by Bozer et al. (1994). In order to represent a layout, they used *discrete representation*. MULTIPLE extends CRAFT by applying space filling curves. This approach improved CRAFT by increasing the number of exchanges considered at each iteration, and also, it can restrict the irregularity of facility shapes by using a irregularity measure. However, because it uses the *discrete representation*, the facility shapes may be not rectangular.

Meta-heuristic methods

Recently, many meta-heuristic approaches have been used in FLP, such as *Simulated Annealing*, *Tabu Search*, *Genetic Algorithms* (GAs) and *Ant Colony Algorithms* (ACO).

Simulated Annealing

The *Simulated Annealing algorithm* is based on the process of annealing of solid metals or ceramics where the material temperature is varied in order to change their physic properties. By analogy, this process is applied for solving optimization problems. Thus, in each iteration, some neighbours are evaluated with a certain probability in order to decide if to change to a new state or to remain in the actual one. The Simulated Annealing has been applied for many authors to FLPs. Thus, Burkard and Rendl (1984), and Chiang and Chiang (1998) derived a *Simulated Annealing* for the QAP. Tam (1992a) has been also used *Simulated Annealing* to solve UA-FLP, he developed LOGIC, Layout Optimization using Guillotine-Induced Cut. In order to represent a layout, he used a *Slicing Tree Structure*. This algorithm applies *Simulated Annealing* in an attempt to find a better layout by two-way exchanges of branching operators. Meller and Bozer (1996, 1997) proposed SABLE for solving the *multi-floor facility layout problem.* SABLE extends

MULTIPLE by employing a *Simulated Annealing* meta-heuristic based search and by generalizing the facility-exchange algorithm. SABLE is shown to produce lower cost layout solutions than MULTIPLE or LOGIC. Chwif (1998) used Simulated Annealing for solving FLPs having into account aspect ratio sizes of facilities. He proposed two neighbourhood. Procedures: a pairwise exchange between facilities and random moves on the planar site in the four main directions (upwards, downwards, leftwards, and rightwards). This meta-heuristic is also applied to the *dynamic facility layout problem* by Baykasoĝlu and Gindy (2001), McKendall et al. (2006), and Sahin et al. (2010).

Tabu Search

Tabu Search meta-heuristic is an optimization method that uses a system of memory structures to improve the performance of a local search method. The TS method work in the following way: when a potential solution is founded, it is tagged as taboo, and the algorithm does not explore this solution again. This meta-heuristic has been applied to FLPs by many authors. Thus, Hasan and Osman (1995) used *Tabu Search* with a hashing function are developed to obtain near-optimal solutions. Chiang and Kouvelis (1996) developed a *Tabu Search Algorithm* to solve a FLP. They used a neighbourhood based on the exchange of two locations of facilities and included a long term memory structure, a dynamic tabu list size, an intensification criteria and diversification strategies. Kaku and Mazzola (1997) applied *Tabu Search* to solve the *dynamic facility layout problem,* Chiang and Chiang (1998) used this meta-heuristic for the QAP. McKendall and Jaramillo (2006) also applied Tabu Search to dynamic facility layout problem, they compared its results with others taken from the literature, and they concluded that their approach obtain good solutions. Recently, Scholz et al. (2009) proposed a *Tabu Search* algorithm for solving UA-FLP. They used a slicing tree representation and they incorporated a bounding curve for solving fixed and flexible facilities in UA-FLPs. Their *Tabu Search* incorporated four types of neighborhood moves to find better solutions. They compared their algorithm with previous research and showed large improvements.

Genetic Algorithms

GAs is a search meta-heuristic that imitates the process of natural evolution. This meta-heuristic is usually used to generate useful solutions to optimization and search problems, which are generated inspired by natural evolution, such as inheritance, selection, mutation and recombination. GAs seem to become quite popular in solving FLPs (Pierreval et al., 2003). For this reason, there are numerous articles that apply GAs for solving FLPs, such as: Tam (1992b), Banerjee and Zhou (1995), Mak et al. (1998), Matsuzaki et al. (1999), Tam and Chan (1998), Azadivar and Wang (2000), Lee and Lee (2002), Lee et al. (2003, 2005), Dunker et al. (2003), Hu and Wang (2004), El-Baz (2004), and Ficko et al. (2004) for the *static facility layout problems;* and Conway and Ventakaramanan (1994), Balakrishnan and Cheng (2000), Balakrishnan et al. (2003), and Dunker et al. (2005) for the *dynamic layout problems*.

If we focus on UA-FLP, many authors addressed the problem using GA, for instance, Tate and Smith (1995a) proposed a GA for solving UA-FLPs using *Flexible Bay Structure* representation. A dynamic or adaptive penalty function is used to guide the search into feasible solution regions. The algorithm generates good layouts and it is shown to outperform CRAFT and NLT. Wu and Appelton (2002) presented a GA method to solve the UA-FLP and aisle structure problems simultaneously by a *Slicing Tree Structure* representation. They decomposed the problem into two stages. The first stage minimises the material handling cost with aisle distance, and the second stage optimises the aisles in the aisle structure. Gómez et al. (2003) applied GAs to solve UA-FLP. They focused a particular case which involves the explicit consideration of passageways between sections along with the possibility of being these sections variable in width. Wang et al. (2005) implemented and analysis of variance of statistics to find out the best site size of layout by genetic algorithm applied to UA-FLP. They considered as objective function the minimum total layout cost that combines material flow factor cost, shape ratio factor, and area utilization factor. They used the discrete representation and a rule-based of expert system to create space-filling curve. Enea et al. (2005) implemented a GA to search for a near optimal solution in a fuzzy contest. They adopted A *flexible bay structure* as a physical model of the system. Moreover, constraints on the aspect ratio of the facilities are taken into account using a penalty function introduced into the fitness function of the genetic algorithm. Aiello et al. (2006) suggested a multi-objective approach to UA-FLP that uses a genetic search algorithm and Electre method. They represented the layout by means of *Flexible Bay Structure*. Norman and Smith (2006) addressed the UA-FLP using a GA meta-heuristic with a *flexible bay structure*. They considered uncertainty in material handling costs on a continuous scale by use of expected values and standard deviations of product forecasts. Liu and Meller (2007) proposed an approach to solve UA-FLP represented as sequence pairs, by using GA and MIP. They used GA to modify the solutions represented as sequence-pairs, which have the purpose of eliminating all infeasible binary variables which make large UA-FLP difficult to solve. They concluded that their method could achieve optimal solutions for problems with up to eleven facilities. Besides this, they have shown some improvements when solving problem instances with larger data sets.

Ant Colony Optimisation

ACO was originated by Marco Dorigo (1992). This search meta-heuristic imitates the behaviour of ants to found the paths from the colony to the food. Recently, ACO has been applied to FLPs. In this sense, Bland (1999) seems to be the first author that applies ACO to FLP. Talbi et al. (2001), Ramkumar and Ponnambalam (2006), Ramkumar et al. (2009), and Wong and See (2010) have been solved the QAP by means of ACO meta-heuristic. Corry and Kozan (2004) applied ant colony optimization for *machine layout problems*. Solimanpur et al. (2005) proposed an ant algorithm for the *single row layout problem* in flexible manufacturing systems. McKendall and Shang (2006) Baykasoglu et al. (2006), and Rezazadeh et al. (2009) used this meta-heuristic to address *dynamic facility layout problem*. Singh (2010) proposed an ant system embedded with local search for solving FLP. Komarudin and Wong (2010) applied an Ant System to solve UA-FLP. They used a *slicing tree representation* to represent the layout. It proposed an algorithm that uses several types of local search to improve its search performance. Wong and Komarudin (2010b) also used ACO referred to UA-FLP using flexible bay structure. Moreover, the same authors (Wong and Komarudin, 2010a) realized a comparison of ACO techniques for dealing with empty spaces in UA-FLP.

Other approaches

Other approaches that are also possible to apply for solving FLP are *artificial neural network*, *fuzzy logic* and *expert system* (Singh and Sharma, 2006). For example, Tsuchiya et al. (1996) used a neural network for solving the QAP; Grobelny (1988), Raoot and Rakshit (1991, 1994), Badiru and Arif (1996), and Dweiri (1999) have been employed a *fuzzy* approach has been employed to deal with FLPs; and Kumar et al. (1988), Malakooti and Tsurushima (1989), Heragu and Kusiak (1990), Abdou and Dutta (1990), and Sirinaovakul and Thajchayapong (1994) have been applied a knowledge based expert system to solve FLPs.

2.5. Conclusions

In this chapter, the basic knowledge about FLPs has been revised. For that purpose, an analysis of works published in the area has been performed having into account the workshop characteristics, and the resolution approaches used by researchers in order to solve the different FLPs.

From the this literature review, it can be said that UA-FLP is still an active and open area. This stimulates the author to work with this main category of the FLPs. Thus, the rest of the thesis has been focused on the UA-FLP. It can be modelled by different layout representations, which has been also identified and explained in this chapter.

3. Genetic Algorithms in Facility Layout Problems

3.1. Introduction

The allocation of facilities in a plant layout is a complex problem. In order to solve this problem, many techniques have been applied to deal with FLP. As it has been said in the previous chapter, one of the approaches most widely used are the Genetic Algorithms (GAs).

In fact, the success of this type of algorithms depends partly on the consideration given to restrictions in the evaluation function (Michalewicz et al. 1996), as well as in the chosen coding of possible solutions (individuals) and in the selection and reproduction operators used. Genetic algorithms can be used successfully in problems in which the search space is large or not well understood and the evaluation function is complex, and if the problem does not require a global optimum but only a sufficiently good solution, as in the case of the facility layout design problem (Mitchell, 1998).

As it is said in the previous chapter, there are a few surveys on FLPs, but they have not addressed evolutionary issues in depth. This chapter presents a review that focuses on encoding schemes and related operators used in GAs, and suggests a method of classifying the different encoding structures described in the bibliography. Also, it studies their main characteristics and objectives, and the crossover and mutation operators that could be utilized depending on the type of encoding scheme that has been selected.

3.2. Genetic Algorithms

As it is described in chapter 2, GAs is a search meta-heuristic that imitates the process of natural evolution. This meta-heuristic is usually used to generate useful solutions to optimization and search problems, which are generated inspired by natural evolution, such as inheritance, selection, mutation and recombination.

GAs contain at least the following elements: population of candidate solutions; selection according to fitness; crossover to generate the next population; and random mutation. The steps that compose a GA are listed as follows:

1. Initialization of the population. Initially, many individual solutions are randomly generated in order to create the initial population.

2. Selection. At each iteration of the algorithm, a number of the

existing individual solutions are selected to pass to new population. This selection is performed using a fitness function, where fitter solutions are those that have more probability of being selected.

3. Reproduction. This step is carried out to generate the following generation of individual solutions. It is performed using the genetic operators, as recombination (also called crossover) and mutation.

This process is repeated until it is reached a termination condition, as for example, it is satisfied the established number of algorithm iterations. Figure 7 illustrates the general scheme of a GA as flow-chart. It is taken from Eiben and Smith (2007).

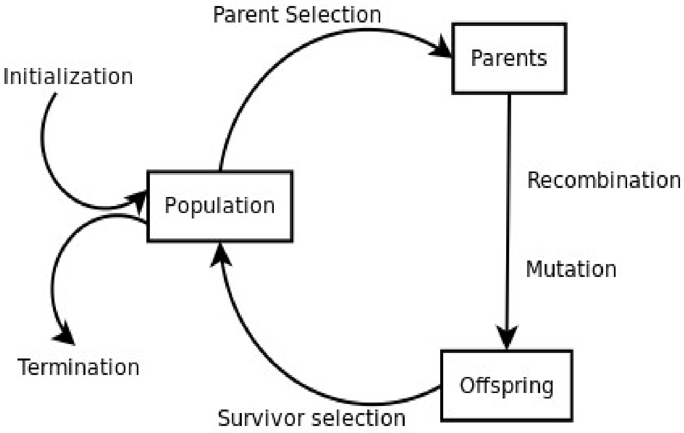


Figure 7: The general scheme of a GA as flow-chart

GAs require the codification of candidate solutions (*phenotype*) as individual data structure (*genotype*). Thus, an essential step in building a GA is to define an encoding scheme. In this sense, Eiben and Smith (2007) stated that an important and difficult part of designing a good GA, is choosing the appropriate encoding scheme, as the choice also determines the operators such as crossover or mutation that could be applied. This structure defines the types of solutions that can be obtained, and influences the GA's ability to find good solutions.

3.3. Encoding schemes for Facility Layout Problems

3.3.1 Basic functions in Facility Layout Problem

Usually the data structure that represents a facility layout is complex. To improve encoding schemes, in this section, the component functions that lead to a complete structured plant design is identified. Each of these functions could be encoded in different ways that are described in the next section. The identified elemental functions are:

Place

This function places a facility in a location determined by its coordinates. From Figure 8 it can be seen that the encoding schemes that implement this function are the *float permutations* (Dunker et al., 2005) and *float strings without restrictions* (Lee et al., 2003) (Lee et al, 2005). In the former, the *float strings* are permutations of the facility centre coordinates. The latter encoding divides the distance proportionately between the origin and the centre of aisles.

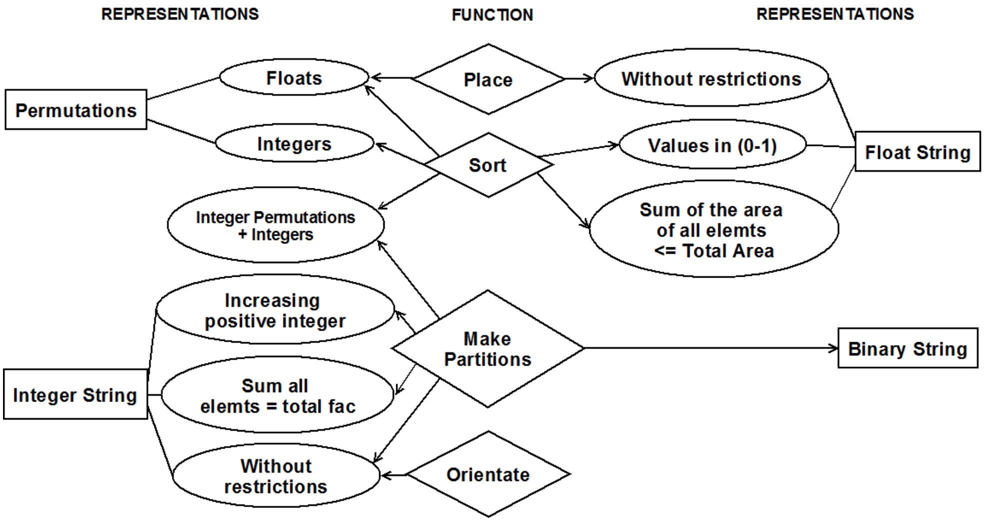


Figure 8: Relations between the functions and their associated encoding schemes.

Sort

This function arranges in order the facilities in the layout of a plant, and determines their sequence (for instance, it is obtained a different sequence of facilities if the facility sequence is read from top to bottom and from left to right than if it is read in the reverse order). From Figure 8, it is possible to find that to provide the *sort* function, the *permutations* are normally used. Logically, when *integer permutations with integers* as operators are intercalated (Matsuzaki et al., 1999), the sequence of the facilities in the layout also appears. Tam (1992b) described another way to sort the order of the facilities. They used, a comprised value between '0' and '1' randomly assigned to each facility for determining the facility sequence by sorting values. The last encoding, that allows sorting of the elements in the plant is the *float string* with the restriction that the aggregate of all the string elements is less or equal to the total area of the plant (Lee et al., 2003; Lee et al., 2005).

Partitioning

This function divides the plant into portions (for example, when the layout is divided into bays). There are several options for encoding this function (see Figure 8).

The first of these options is the combination of *integer permutations and integers*. Matsuzaki et al. (1999) used this method in the slicing tree structure, where the *integer permutations* indicate the facility sequence, and the other *integers* are operators that enable division of the plant into sections.

The second option is a *string of increasing positive integers* (Tate and Smith, 1995), which indicates the locations of the breakpoints.

The third way of grouping is through the *integer string*. In this case, the elements could be inserted without restrictions, being operators that represent the plant divisions, it has been used by Honiden (2004), Tam (1992), and Wu and Appelton (2002); or they could show the way to group the facilities through the sweeping direction and the sweeping band (Hu and Wang, 2004), (Wang et al., 2005). Another grouping option used by Enea et al. (2005), Lee et al. (2005), Aiello et al. (2006), and Chae and Peters (2006); is the *integer string*, where the element adds the total number of facilities that exists in the layout. This string indicates the number of facilities in each bay block, such that the string has the same elements as the bays in the plant.

The last option for grouping is *binary* encoding that is used by Gómez et al. (2003), Hu and Wang (2004), Wang et al. (2005), and Dunker et al., (2005). When the value '0' appears in the binary string, it indicates that the equivalent facility is in the same group or block; when the value '1' appears in the string, it is the indication to begin with another block.

Orientation

Orientation is the last function seen in Figure 8. This function allows rotation of a facility over its central axis with respect to the point of origin. For setting the orientation of the facility, a *integer string* is used by Wu and Appelton (2002), where each element is an operator that provides this facility orientation.

3.3.2 Encoding structures

Having analysed the studies that have investigated this aspect, it is possible to classify the encoding schemes into several types: *Integer/Real Permutations*, *Integer Permutations and Integers*, *Integer String*, *Float String*, and *Binary String*.

Integer/Real Permutations

The objective of this encoding is to determine the facility sequence that comprises a plant. Generally, this encoding is a string of *n* sizes, where *n* is the number of facilities in the layout. Logically, the string can not have repeated elements, because the same facility can not be placed in two locations of the layout. In order to establish the facility sequence, *integer strings* have been applied by many authors, for example, Chan and Tansri

(1994), Balakrishnan et al., (2003a, 2003b), Chae and Peters (2006), Aiello et al., (2006), among others. However, only a Lee et al., (2003, 2005) have used *real strings*. In the case of *dynamic facility layout problem*, Conway and Ventakaramanan (1994), and Balakrishnan et al. (2003) represented the corresponding layout for each period with *permutations of integers*; and Dunker et al. (2005) represented it with *permutations of floats*. In the last case, the authors use the *real string* to establish simultaneously the facility sequence and position the facility centres.

Integer permutations and integers

This encoding was proposed by Matsuzaki et al. (1999) to determine the facility sequence and to simultaneously group the facilities in the layout. For the first one, this method uses *integer elements* that can not be repeated. To represent the cut operators, they used 4 characters (that can be translated into integers) that can be repeated. Both types of elements are combined in the string. The size of the string is the sum of the number of facilities and the numbers of cut operators (which are equal to the number of facilities minus one).

Integer string

This type of encoding scheme could be divided into three types: *Increasing positive integer string*, *sum of all elements equal to total number of facilities*, and *without restrictions*.

Increasing positive integer string. The integer string is created because each element is larger than the next. Tate and Smith (1995) used this encoding to group into bays the elements of the layout, which consists of an *integer string* where each element represents the last facility of the bay. The total number of elements of the string plus one, is equal to the total number of the bays in the plant.

Sum of all elements equal to total number of facilities. The *integer string* is created because each element is greater than '1', and the sum of all elements is equal to the number of facilities that make up the layout. Enea et al. (2005), Lee et al. (2005), Aiello et al. (2006), and Chae and Peters (2006) have used this encoding to group the facilities into bays, and hence they proposed an *integer string* where each integer element represents the number of elements that exist in a bay.

Without restrictions. This encoding is used to group facilities and to determine the orientation of the facility. Honiden (2004) employed an *integer string* to show the grouping order of facilities. Tam (1992b) used a string composed of characters (that can be translated to integers), each of them of a value of four possible operators: bottom, upper, right, and left, which determine the cuts of the slicing tree. Wang et al. (2005), and Hu and Wang (2004) utilized this coding scheme to show the sweeping band, that determines the method of grouping the layout. Wu and Appelton (2002) used this encoding for two functions. On the one hand, they employed a *string of integers* that represents the cutting levels and allows grouping of the facilities in the plant. On the other hand, they used another *integer string* to indicate the orientation of the facility. Each element of this string could associate one of four possible values, for example, 0 degrees, 90 degrees, 180 degrees and 270 degrees.

Float String

This encoding scheme could be divided into three cases, too:

Without restrictions. The *real or float string* is used to place the element position in the layout. Thus, Lee et al. (2003, 2005) applied it in order to allocate the vertical and horizontal passages in the plant.

Values are in in the interval (0,1). The *real or float string* is created considering that the value each element has is included in the range (0-1). Norman and Smith (2006) used this encoding to arrange the sequence of the facilities of the plant by assigning a random value between '0' and '1' to each facility and then, arranging the string from the smaller to the higher value.

Sum of all elements area are less or equal to total area. The *float string* is created considering that each element value is included between lower and higher bounds. Moreover, it is necessary that the sum of all elements be lower or equal than the total area of the distribution. In this case, the string is composed of float elements (that are organized as the string of facility sequence) which offer the area information of each facility in the layout.

Binary String

This type of encoding groups the facilities in the layout to enable the determination of the orientation of the facility. Gomez et al. (2003) employed a *binary string* of elements to divide the plant into bays. When the value '1' appears in the string, the facility is the last among the bays, in the other case, the value '0' appears in the string. Moreover, Dunker et al. (2005) used a *binary string* to establish the facility orientation in the dynamic layout. If the value is '0', the orientation is vertical, or else, it is horizontal.

3.3.3 Evolutionary operators

The evolutionary operators analysed are: *Crossover operator*, and *Mutation operator*. They will be explained below.

Crossover operator

The *crossover* is the process whereby a new individual solution is created from the information contained within two (or more) parent solutions, is considered by many to be one of the most important features in GAs (Eiben and Smith, 2007). Most of the operators analysed are well known and are illustrated in Eiben and Smith (2007). The crossover operators that have been studied are *Uniform Crossover*, *Partial Mapped Crossover* (PMX), *Order Crossover* (OX), *Cycle Crossover* (CX), *N-Point Crossover*, and the selection of the best parent (is taken for the child created).

The *Uniform Crossover* (Syswerda, 1989) selects randomly a gen from each parent until the offspring is completed. Many authors have been used this *Uniform Crossover* to FLP, for example, Tate and Smith (1995a), Balakrishnan et al. (2003b), Aiello et al. (2006), among others.

The *PMX* was proposed by Goldberg and Lingle (1985). In this crossover method, two cut points are randomly selected, then the segment between them is copied from the first parent into first child, and from the second parent into second child. Next, the first child is completed with the second parent, and the second child with the first parent. If any element will be repeated, the element inserted will be selected by equivalence. This method of crossover has been widely applied to FLP by researchers, for instance, Chan and Tansri (1994), Mak et al. (1998), Sigh et al. (1998), Tavakkoli-Moghaddain and Shayan (1998), Gómez et al. (2003), El-Baz (2004), Honiden (2004), Dunker et al. (2005), and Chae and Peters (2006). This crossover method is illustrated in Figure 19.

Table 2: Relation of the crossover methods used by each encoding scheme.

Representation		**Crossover**					
Structure	**Subtype**	**Uniform**	**PMX**	**OX**	**CX**	**One point**	**Select the best of set**
Permutation of	integers	✓	✓	✓	✓	✓	✓
	floats	O	✓	O	O	✓	O
Integer permutations + Integers		✓	O	O	O	O	O
Integer String	Increasing positive	X	X	X	X	O	O
	Sum all = total fac.	X	✓	O	O	X	O
	Without restrictions	O	O	O	O	✓	O
Float String	Without restrictions	O	O	O	O	✓	O
	Values (0-1)	X	X	X	X	O	O
	Sum of the elements area <= total area.	X	✓	O	X	X	O
Binary String	Binary values	O	✓	O	X	O	O

The *OX* was designed by Davis (1991). This method is similar to *PMX*, except in the order to insert elements from the parents, in this case, it is begin to insert elements in the position of the second cut point. Chan and Tansri (1994), Ficko et al. (2004), Honiden (2004), and Ramkumar et al. (2008) applied this crossover method to FLP.

The *CX* (Oliver et al., 1987) divides the elements into cycles of element which has the quality that each element always occurs paired with another element of the same cycle when the two parents are aligned (Eiben and Smith, 2007). Then, the offspring is creating selecting alternative cycles from each parent. The *CX* has been employed to deal with FLP by Chan and Tansri (1994), and Honiden (2004).

The *N-Point Crossover* divides the parents into segments, and then, the child is created by taking alternative segments from the parents. This method of crossover has been used in FLP by many authors, as Tam (1992b), Conway and Ventakaramanan (1994), Wu and Appelton (2002), Gomez et al. (2003), Hu and Wang (2004), Lee et al. (2003, 2005), and Wang et al. (2005). This crossover method is illustrated in Figure 19.

Balakrishnan et al. (2003a) used as crossover method the selection of the best parent, that will be taken for creating the new child created.

Mutation operator

The *mutation* is the process whereby a parent solution is modified to obtain a new offspring. The purpose of mutation in GAs is to allow the algorithm to escape from local minima. Normally, this process is applied with a low probability called mutation rate. The mutation operators that have studied are: *Random Pair-wise interchange mutation* (PM), *Random Adjacent interchange mutation* (AM), *Random Slicing mutation* (SM), *Inverse mutation*, *PM if the individual improve* (the mutation is done if the new individual is better), *Insert/Delete* or *Increase/Decrease* a gen, *Divide* or *Join* genes.

In *PM*, two positions are randomly selected a its content is interchanged. This is the most common mutation method, it has been applied in most of revised works.

The case of *AM* is similar, but two positions are randomly selected a its content is interchanged with the content of its neighbour, an example of the application of this mutation method is in Ramkumar et al. (2008).

The *SM* selects two positions randomly, then the content of the first position is copied into the second position, from now on, the following values are copied in the same sequence, this mutation method has been applied by Ramkumar et al. (2008), among others.

The *inverse mutation* selects two positions randomly in the string, and then, reverses the order in which the values appear between those positions.

Enea et al. (2005), and Aiello et al. (2006) applied a mutation that is based on *Insert/Delete* or *Increase/Decrease* a gen. Thus, in the vector of bay divisions with a probability a gen is increased or decreased, also it is possible that a gen will be inserted or deleted.

Tate and Smith (1995) used as mutation method, the division of a bay gen in order to obtain two adjacent bay genes, moreover, they also join two adjacent bay genes into one.

Table 3: Relation of the mutation methods used by each encoding scheme.

Representation		**Mutation**								
Structure	**Subtype**	**PM**	**AM**	**SM**	**Inv**	**PM if improve**	**Ins/Del a gen**	**Inc/Dec a gen**	**Div**	**Join**
Permutations of	integers	✓	✓	✓	✓	✓	X	X	X	X
	floats	✓	O	O	O	O	X	X	X	X
Integer permutations + Integers		O	O	O	✓	O	O	O	✓	✓
Integer String	Increasing positive	X	X	X	X	X	O	O	X	X
	Sum all = total facilities	✓	O	O	O	O	✓	✓	O	O
	Without restrictions	✓	O	O	O	O	X	X	X	X
Float String	Without restrictions	O	O	O	O	O	X	X	X	X
	Values (0-1)	X	X	X	X	X	X	O	X	X
	Sum of the elements area <= total area.	X	O	O	O	X	X	✓	X	X
Binary String	Binary values	✓	O	O	O	O	X	X	X	X

We can see the analysis of the *Crossover* operators are in Table 2 and *Mutation* operators in Table 3. The operators that have been studied in the revised works, are marked '√'. The methods that could not be applied by the encoding nature are marked 'X', and finally, it is marked with the symbol 'O' those that can be applied but are not used in reviewed literature.

3.4. Conclusions

In this chapter, a survey that focuses on encoding schemes and the evolutionary operators used by GAs applied to FLPs is presented. Other surveys have examined FLPs, but they have not studied evolutionary techniques in depth. Although, this overview can not be exhaustive, the analysis carried out enables us to identify:

1. The manner of placement of facilities on the surface.
2. The component functions that could be used to create the facility layout solutions.
3. The techniques to encode them.

Combining the identified component functions could create new unexplored encoding schemes.

In this manner, many different ways of encoding the facility layout solutions are available. Logically, crossover and mutation operators also depend on the encoding scheme selected. Moreover, the evolutionary operators that could be applied to each encoding scheme have been identified. Some of them have not been tested yet. These encoding schemes and their operators will determine the ability of the GA to obtain good solutions.

The classifications and analyses described in this chapter, could prove useful for future studies in FLPs. In this context, the next step of research could be to evaluate new encoding schemes and untested evolutionary operators. This would enable achieve the aim of improving results and recommending the best among them.

4. The proposed Genetic Algorithm for the Unequal Area Facility Layout Problem

4.1. Introduction

In this chapter, it is presented an evolutionary approach for solving the Unequal Area Facility Layout Problem (UA-FLP). For that purpose, a new GA is suggested, which includes a new way to represent the plant layout.

The suggested approach considers aspects that can be quantified, such as: material handling costs; logical relations between spaces, and the shape of each area.

4.2. Algorithm formulation

In order to solve the UA-FLP a Genetic Algorithm (Goldberg, 1989) has been designed according to the following specifications:

- It is based on *n* facilities with known surface areas s_i distributed in a rectangular area with $H \times W$ dimensions.
- The necessary closeness or distance ratios for each pair of facilities are indicated in a relation matrix and expressed with codes from Table 4. These ratios are represented in a triangular relational matrix (*REL*).

Table 4: Closeness or Distance ratios

Symbol	Closeness/Distance ratios
A	Essential closeness
E	Very important closeness
I	Important closeness
O	Normal closeness
U	Indifferent closeness
X	Undesirable closeness

- The density of material flows (for example in kg/hour) between each pair of facilities are also known. This matrix does not have to be symmetric.

In the definition contained in the *REL* table, causes of closeness or distance requests may be, for example, the logical organisation of the production system, the absence or presence of noise or safety reasons. Therefore, users may voluntary or inadvertently assign closeness requests in the *REL* table according to the flow of materials, which would be redundant, although this is not necessarily problematic for generating layouts.

4.2.1 Evaluation function

The evaluation function consider three aspects: minimisation of the distance covered by materials; compliance with the ratios expressed in the *REL* matrix; and the rectangular shape assigned to each facility.

In order to evaluate the distance covered by materials, the following expression is used:

$$F_1 = \sum_i \sum_j D_{ij} f_{ij} c_{ij}$$

Where:

D_{ij}: distance between the centroids of the facilities measured according to the Manhattan distance and excluding the distance covered inside the facilities.

f_{ij}: flow of materials from facility i to facility j.

c_{jj}: cost to move a unit of material from facility *j* to facility *i*.

The following expression has been used to evaluate compliance with the logical ratios between facilities:

$$F_2 = \sum_i \sum_j E_{ij}$$

Where:

$$E_{ij} = \begin{Bmatrix} REL_{ij} \times D_{ij}^2 \quad if\, REL_{ij} \geq 0 \\ \dfrac{|REL_{ij}|}{D_{ij}^2} \quad if\, REL_{ij} < 0 \end{Bmatrix}$$

The *REL_{ij}* values depended on the logical relationship existing between the pair of facilities *ij*. By default, these have assigned the following values: A=40, E=12, I=4, O=1, U=0 and X=-1. Nevertheless, they may be modified by users according to the characteristics of the problem.

Finally, for the desired aspect ratio (*b*), a value has been established for the areas assigned to the facilities. The aspect ratio is evaluated as follows:

$$\delta = \sum_i \sqrt{(b - x_i)^2}$$

where:

b: optimum aspect ratio (i.e. 1.5, 1.6, etc.).

x_i: aspect ratio of the facility *i* (largest side divided by the smallest side).

The global evaluation function it is:

$$min\ C=\left(\alpha_1 \times F_1 + \alpha_2 \times F_2\right) \times \delta$$

where:

α_1 and α_2 are weighting factors that had to add up to 1.

Users can either consider or ignore the facility shape factor, in which case the value of δ would be forced to 1.

4.2.2 Layout representation

In order to encode the possible solutions of the algorithm, the following structure of representation have been proposed. It uses a three-row matrix with *n* columns as shown in Table 5.

Table 5.- Coding of an example solution.

G	H	B	D	F	C	E	A
1	1	0	0	0	1	1	0
1	3	0	1	2	0	3	1

The first row indicates the order in which the facilities have been arranged on the available surface area (GHBDFCEA). The second row contains random zeros and ones and indicated the groups that would be selected to distribute the facilities. In this case, the first section G has been grouped individually because there was only one 1 at the beginning. It is followed by three zeros, corresponding to the next three sections (HBD). F, C, E have been grouped together, corresponding to three consecutive ones. Finally, section A is grouped individually. The third row corresponded to orientation: 0, left vertical line; 1, right vertical line; 2, bottom horizontal line; 3, top horizontal line. Thus, the matrix in Table 5 represents a layout like the one shown in Figure 9.

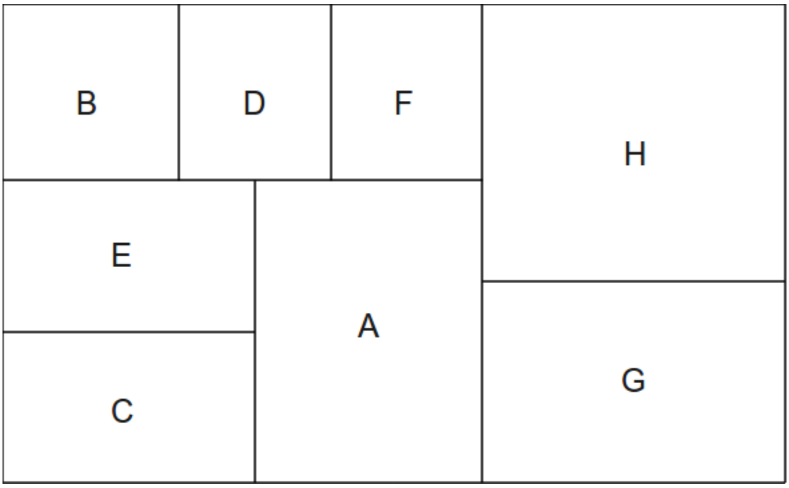


Figure 9: Layout resulting from the coding in Table 5.

If the available area was larger than necessary, the excess space could remain in the centre or on any of the edges.

4.2.3 Genetic Algorithm steps

The steps of the proposed GA are explained below:

1. An initial random population of *N* individuals is generated.
2. The selection method is applied to select the individuals that will be

involved in the evolutionary operations.

3. Crossover and Mutation operators are applied to the individuals with a probability given by the user.

4. Elitism is applied on the new population. The process continues and goes to step 2, until the number of iterations is reached.

4.2.4 Crossover and mutation mechanisms

Crossover has been performed by exchanging complete rows among the matrices representing the two selected individuals. A random number between 0 and 2 is obtained. If the result is 0, the first row is exchanged; if it is 1, the second is exchanged; and if it is 2, the third row is exchanged. Similarly, for mutation one of the three rows is modified randomly.

4.2.5 Selection and replacement methods

Various selection methods have been used to allow users to select the most appropriated one in each situation. These include roulette wheel, sigma scaling, rank selection and steady state. Similarly, the option of elitism between one generation and another is offered for selecting the number of individuals to be rescued.

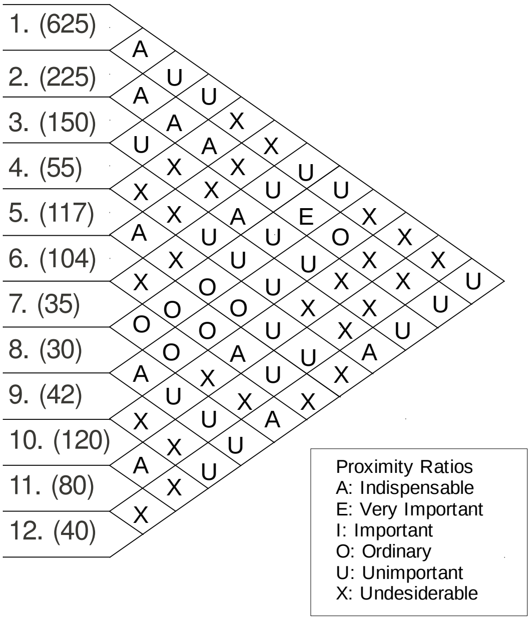
4.3. Empirical evaluation

In this section, the evaluation of the suggested GA is presented. The proposed algorithm has been integrated into a software application. In order to test our approach, two UA-FLP examples have been selected. They are taken from Salas-Morera et al. (1996) and Aiello et al. (2006), respectively.

Case 1

This case consists of a rectangular area measuring 65 x 25 in which 12 facilities should be arranged with the surface areas, dimensions, and closeness and distance ratios indicated in Table 6.

Table 6.- Ratios between facilities in case 1 (surface areas in brackets).



	2	3	4	5	6	7	8	9	10	11	12
1. (625)	A	U	U	X	X	U	U	X	X	X	U
2. (225)		A	A	A	X	U	E	O	X	X	U
3. (150)			U	X	X	A	U	U	X	X	U
4. (55)				X	X	U	U	U	X	X	A
5. (117)					A	X	O	O	U	U	X
6. (104)						X	O	O	A	U	X
7. (35)							O	O	X	X	A
8. (30)								A	U	U	U
9. (42)									X	X	U
10. (120)										A	X
11. (80)											X
12. (40)											

Proximity Ratios
A: Indispensable
E: Very Important
I: Important
O: Ordinary
U: Unimportant
X: Undesiderable

The material flows among the different facilities are shown in Table 7. In order to resolve this, tests have been performed with 3 repetitions and different combinations of weighting parameters and different crossover and mutation percentages, always based on 10,000 iterations with populations of 500 individuals (Table 8).

Table 7: Movement between work centres for case 1.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	---	80	0	0	0	0	0	0	0	0	0	0
2	0	---	20	2	50	0	0	0	0	0	0	0
3	0	0	---	0	0	0	20	0	0	0	0	0
4	0	0	0	---	0	0	0	0	0	0	0	2
5	0	0	0	0	---	50	0	0	0	0	0	0
6	0	0	0	0	0	---	0	0	0	50	0	0
7	0	0	0	0	0	0	---	0	0	0	0	20
8	0	0	0	0	0	0	0	---	0	0	0	0
9	0	0	0	0	0	0	0	0	---	0	0	0
10	0	0	0	0	0	0	0	0	0	---	0	0
11	0	0	0	0	0	0	0	0	0	0	---	0
12	0	0	0	0	0	0	0	0	0	0	0	---

The material flows between the work centres and the ratios in the *REL* table show that all the pairs of facilities between which material movement exist, are marked with 'A'. Therefore, one cause considered in this table has been precisely the flow of materials; hence, this cause is considered twice in the analysis. The decision is therefore taken to perform a set of tests weighting compliance with the *REL* table and the minimization of materials flows to 50%, and another test in which the latter has been eliminated.

Table 8: Results of the tests for different values of the parameters in case 1.

Rep	**Mut.**	**Cross.**	α_1	α_2	**Iterat.**	F_1	F_2	δ	C
1	100	100	0.5	0.5	8382	440.97	42.66	7.98	1929
2	100	100	0.5	0.5	8511	2273.11	550.39	4.21	5943
3	100	100	0.5	0.5	8423	1666.90	284.31	8.10	7902
1	100	50	0.5	0.5	1420	767.86	144.00	7.95	3625
2	100	50	0.5	0.5	3947	3113.05	422.40	3.12	5515
3	100	50	0.5	0.5	4343	917.94	202.28	6.08	3405
1*	50	100	0.5	0.5	9385	295.42	**0.00**	**1.98**	**292**
2	50	100	0.5	0.5	174	2339.60	351.30	5.91	7952
3	50	100	0.5	0.5	3000	3114.05	422.40	3.12	5517
1	50	50	0.5	0.5	8758	**287.01**	**0.00**	10.65	1528
2	50	50	0.5	0.5	3798	637.00	140.00	14.58	5664
3	50	50	0.5	0.5	672	3113.05	422.40	3.12	5515
1	100	100	1	0	4343	1720.45	10.15	2.50	4301
2	100	100	1	0	3255	235.27	194.10	25.70	6046
3	100	100	1	0	8312	1776.50	298.00	9.32	16557
1*	100	50	1	0	1134	**78.59**	0.00	6.76	**531**
2	100	50	1	0	8661	2030.14	422.40	**2.16**	4385
3	100	50	1	0	6877	636.91	140.00	14.60	9299
1	50	100	1	0	6311	2030.14	422.40	**2.16**	4385
2	50	100	1	0	4762	86.26	0.00	10.74	926
3	50	100	1	0	7965	89.35	0.00	6.03	**539**
1	50	50	1	0	2314	637	140.00	14.60	9300
2	50	50	1	0	7357	136,85	60.00	13.46	1842
3	50	50	1	0	1307	87.29	0.00	10.45	912

The dark areas in Table 8 represent the solutions in which the lowest values have been obtained for each evaluation criterion and for the global evaluation in each set of tests. This would allow designers of the industrial plant to select the most interesting design according to the importance attributed to each criterion.

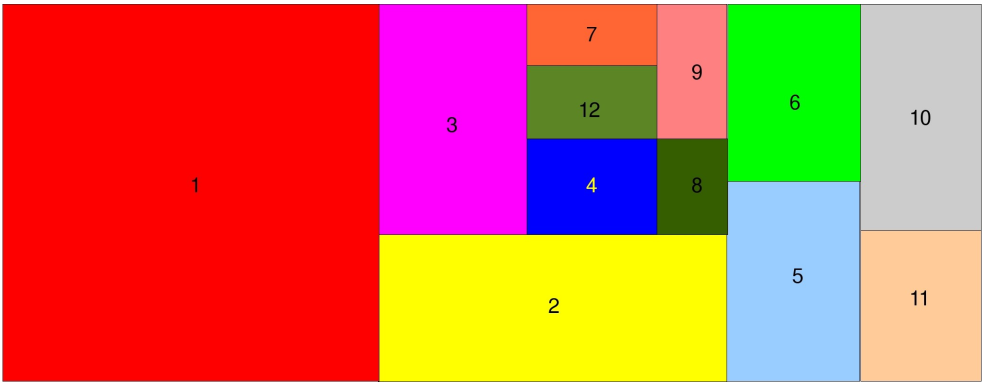


Figure 10: Best layout found in the first set of tests in case 1.

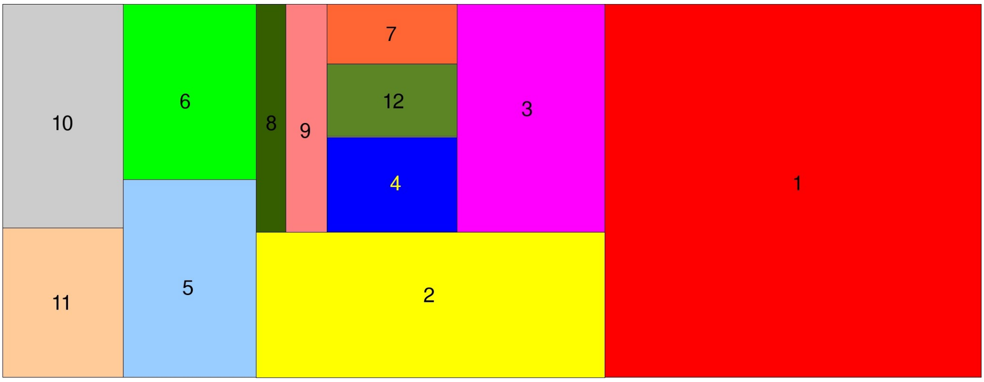


Figure 11: Best layout found in the second set of tests in case 1.

Figure 10 and Figure 11 represent, respectively, the best solutions found for the two sets of tests performed (marked with * in Table 8). These figures show that the two layouts are practically the same, except for the positions of facilities 8 and 9, thus also generating a larger shape factor in the latter one.

Case 2

This problem case is taken from Aiello et al. (2006), who considered the problem of finding layouts to minimize material handling costs and to maximise an adjacency function that qualitatively expressed closeness requests and distance requests. It is also took into account the form of the facilities, considering those with a ratio of 1:1.5 as optimum. The problem consists on 20 facility areas or centres with strongly inter-related movements of materials between most of these centres.

Because of Aiello et al. (2006) utilized the same method to evaluate the costs of material flow between facilities that is used in the suggested approach, it is possible to compare directly the results obtained by them and by the proposed strategy. However, it is not possible do the same for comparing the closeness relationships because they used different ratios to measure them. Thus, in order to know if the suggested approach offers good solutions, these requirements will be analysed qualitatively. In the case of the desired aspect ratio, the formulation given by them has been implemented and incorporated to the proposed approach. So that, also this value can be compared directly.

To test this problem using the suggested approach, the test strategy applied is the same that it has been described in case 1. Thus, the tests that have been realized use the combination of the parameters that appears in the Table 9.

Table 9: Parameters for the performed tests in case 2.

Repetitions	**Crossover**	**Mutation**	**α1**	**α2**
3 repetitions	50.00%	50.00%	0.5	0.5
3 repetitions	50.00%	50.00%	0.5	0
3 repetitions	50.00%	50.00%	1	0.5
3 repetitions	50.00%	50.00%	1	0
3 repetitions	50.00%	100.00%	0.5	0.5
3 repetitions	50.00%	100.00%	0.5	0
3 repetitions	50.00%	100.00%	1	0.5
3 repetitions	50.00%	100.00%	1	0
3 repetitions	100.00%	50.00%	0.5	0.5
3 repetitions	100.00%	50.00%	0.5	0
3 repetitions	100.00%	50.00%	1	0.5
3 repetitions	100.00%	50.00%	1	0
3 repetitions	100.00%	100.00%	0.5	0.5
3 repetitions	100.00%	100.00%	0.5	0
3 repetitions	100.00%	100.00%	1	0.5
3 repetitions	100.00%	100.00%	1	0

In the problem taken from Aiello et al. (2006). The material flow that exists between the facilities is displayed in Table 10.

Table 10: Material flow between facilities

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
1	0	150	200	280	240	55	0	50	95	55	890	0	0	320	655	395	0	845	80	95
2	25	0	0	235	935	0	0	515	0	0	0	75	0	0	95	840	50	915	135	0
3	935	0	0	910	675	0	0	265	60	800	180	0	70	0	0	0	90	0	665	995
4	620	75	160	0	80	60	180	165	0	385	175	890	955	0	60	0	430	345	555	90
5	0	75	0	50	0	80	0	70	520	95	70	435	0	0	65	95	50	0	175	0
6	0	0	925	50	55	0	510	0	760	0	0	95	0	0	0	0	195	900	110	0
7	55	60	305	235	385	0	0	305	0	0	0	0	95	760	60	60	75	80	0	555
8	380	65	50	80	525	90	975	0	85	120	400	980	0	95	0	830	0	55	90	0
9	50	70	65	0	90	95	60	530	0	0	0	90	80	265	0	60	0	85	95	85
10	170	50	90	90	0	665	50	975	85	0	0	75	90	55	640	0	255	385	0	80
11	50	0	90	765	0	0	0	980	180	425	0	75	65	725	515	930	180	85	515	65
12	90	195	0	110	0	585	185	385	95	60	55	0	0	545	0	0	0	0	220	670
13	0	0	135	550	55	690	310	410	60	0	0	50	0	165	85	0	195	545	80	55
14	65	90	220	0	80	0	65	605	90	425	0	0	70	0	65	750	95	0	0	785
15	80	0	0	55	70	0	75	0	70	0	545	90	95	0	0	0	80	775	70	755
16	65	140	0	0	730	80	55	0	80	50	90	80	740	65	0	0	95	0	455	70
17	0	70	880	95	0	0	50	685	70	0	870	725	0	450	0	70	0	0	450	50
18	70	75	0	60	80	65	0	50	65	0	430	80	0	130	190	80	90	0	765	0
19	80	725	310	0	0	0	85	0	885	50	0	85	85	90	75	0	485	0	0	65
20	80	60	365	0	80	0	0	0	50	0	50	0	0	110	65	0	90	0	0	0

Besides, there are certain qualitative requirements. The first one are the closeness requests which are expressed in Table 11. The second one, it is referred to the distance requirements, which are displayed in Table 12,

Table 11: Closeness requests.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
6							4		4		11									
9												8		8						8
11							2							2						2

Table 12: Distance requests.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1				8	8			8					8		8			8		
2				2	2			2					2		2			2		
3				4	4			4					4		4			4		

After of the realization of tests. The solutions that are presented in Figure 12 and Figure 13 have been the best solutions obtained by the proposed approach. Regarding Table 13, it is possible to analyse quantitatively the results obtained by the suggested approach and the two best achieved by Aiello et al. (2006) (which are displayed into Figure 14 and Figure 15). Thus, it could say that with the proposed algorithm, solutions with better material cost than those achieved by Aiello et al. (2006), are obtained with an approximately similar aspect ratio.

In order to compare qualitatively the solutions, it is analysed if the closeness and distance requirements which are given in Table 11 and Table 12 are satisfied. This way, regarding visually the solutions obtained the proposed approach (Figure 12 and Figure 13) and these that are obtained by

Aiello et al. (2006) (Figure 14 and Figure 15) it is possible to extract the information that is shown in tables 14, 15, 16 y 17.

Table 13: Quantitative results obtained for case 2.

Solution obtained by the proposed approach				Solutions obtained by Aiello et al. (2006)			
Solution 1		Solution 2		Solution 1		Solution 2	
Material cost	Aspect ratio	Material cost	Aspect ratio	Material cost	Aspect ratio	Material cost	Aspect ratio
$2.43 \cdot 10^6$	0.82	$2.9 \cdot 10^6$	0.6	$2.88 \cdot 10^6$	0.84	$2.9 \cdot 10^6$	0.88

In Table 14 and Table 15 displays which of the defined closeness requests are satisfied by Aiello et al. (2006) and by the suggested approach, respectively. Thus, it can be seen that both solutions obtained by the proposed approach are adjusted to them better than the solutions achieved by Aiello et al. (2006).

In Table 14 and Table 15 are displayed which of the defined distance requirements are satisfied by Aiello et al. (2006), and by the suggested approach, respectively. In this case, it can be also seen that both solutions obtained by the proposed approach are adjusted to them better than the solutions achieved by Aiello et al. (2006).

Taking into consideration the obtained results, it can be stated that the first solution that has been obtained by the proposed approach, offers better results than any other achieved by Aiello et al. (2006). Due to this solution presents a lower value of material handling cost with a similar aspect ratio, and also satisfies more of the closeness and distance requirements than solutions obtained by Aiello et al. (2006).

Table 14: The satisfaction of the closeness requests for the solutions obtained by Aiello et al. (2006).

Solution 1							**Solution 2**					
	7	**9**	**11**	**12**	**14**	**20**	**7**	**9**	**11**	**12**	**14**	**20**
6	✓	✓	✓				✓	X	✓			
9				✓	✓	✓				✓	✓	✓
11	X				✓	✓	✓				✓	X

Table 15: The satisfaction of the closeness requests for the solutions obtained by the proposed approach.

Solution 1							**Solution 2**					
	7	**9**	**11**	**12**	**14**	**20**	**7**	**9**	**11**	**12**	**14**	**20**
6	✓	✓	✓				✓	✓	✓			
9				✓	✓	✓				✓	✓	✓
11	✓				X	✓	✓				✓	✓

Observing the second solution that have been obtained by the suggested approach, it can be seen that it has a material handling costs similar to the solutions given by Aiello et al. (2006). Besides, this solution satisfy all the requirements of closeness and distance, which have not been satisfied by they. However, the aspect ratio of this solution is substantially worse than the one achieved by Aiello et al. (2006).

Table 16: The satisfaction of the distance requirements for the solutions obtained by Aiello et al. (2006).

	Solution 1						**Solution 2**					
	4	**5**	**8**	**13**	**15**	**18**	**4**	**5**	**8**	**13**	**15**	**18**
1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2	✓	✓	✓	X	X	X	✓	X	X	✓	✓	✓
3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 17: The satisfaction of the distance requirements for the solutions obtained by the proposed approach.

	Solution 1						**Solution 2**					
	4	**5**	**8**	**13**	**15**	**18**	**4**	**5**	**8**	**13**	**15**	**18**
1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3	✓	✓	✓	✓	✓	X	✓	✓	✓	✓	✓	✓

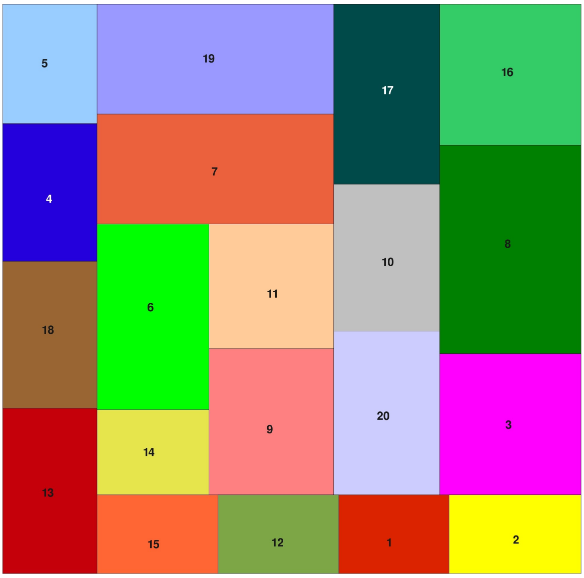


Figure 12: The first of the two best solutions achieved by the proposed approach.

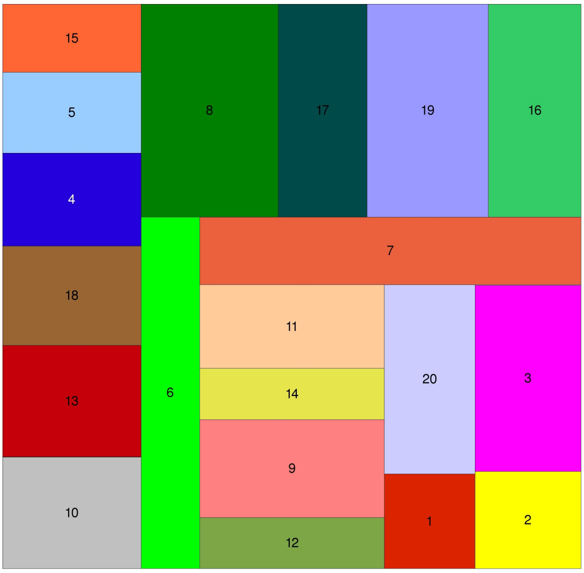


Figure 13: The second of the two best solutions achieved by the proposed approach.

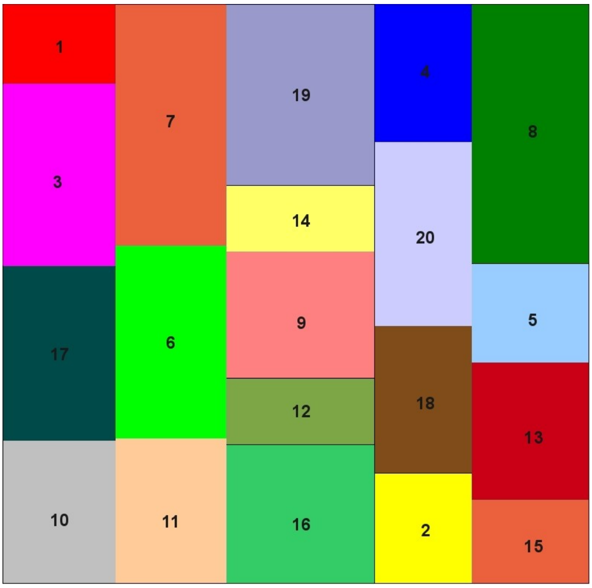


Figure 14: The first of the two best solutions achieved by Aiello et al. (2006)

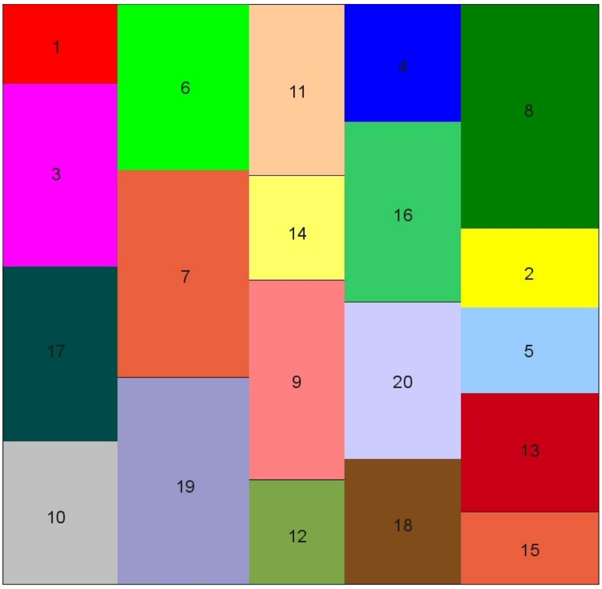


Figure 15: The second of the two best solutions achieved by Aiello et al. (2006)

4.4. Conclusions

A useful genetic algorithm has been proposed for the UA-FLP. This algorithm includes a new, simple and easy-to-implement method for coding possible solutions.

Although the algorithm is relatively simple, it is able to generate good solutions in all the cases tested, which varied in type and complexity; this is also true when compared with other algorithms described in the bibliography.

The evaluation of the solutions considered both qualitative aspects such as closeness or distance requests between facility centres due to logical production processes, information flows, existence of noise or thermal environments, and quantitative aspects such as material flows. Optionally, the algorithm can also take into account the appearance of the layout when considering the shape of each facility.

According to the characteristics of the problem, the weights assigned to the evaluation criteria can be easily modified, making it easier to obtain good solutions in a wide range of practical scenarios.

5. The proposed Interactive Genetic Algorithm to Unequal Area Facility Layout Problem

5.1. Introduction

Unequal Area Facility Layout Problem (UA-FLP) has been addressed using several methods that are explained in chapter 2 of this thesis. Most researchers have addressed UA-FLP using quantitative performance criteria (e.g. material handling cost, closeness or distance relationships, adjacency requirements, aspect ratio), which are used in an optimization approach. However, qualitative features sometimes also have to be taken into consideration, for instance: preferences about the location of specific facilities, distribution of the remaining spaces, relative placement preferences, or any other subjective preference that can be considered as important by the Decision Maker (DM). Such qualitative features are complicated to include with a classical heuristic or meta-heuristic optimisation (Brintup et al., 2007). As a consequence, the participation of the DM is essential to include qualitative considerations in the design. Moreover, involving the DM into the design process provides additional advantages, such as including expert knowledge, finding a solution that satisfies the DM but that is not necessarily an optimal solution (Avigad and Moshaiov, 2009), selecting the best trade-off solution when a conflict among objectives or constraints exists (Jeong and Kim, 2009), helping the algorithm in guiding the search process to the user preferences (Luque el al., 2009; Quiroz et al., 2008), eliminating the need to specify all the required preference information in advance, giving the DM the ability to learn about his/her own preferences (Jeong and Kim, 2009), stimulating the user's creativity (Sato and Hagiwara, 2001), and obtaining original, innovated and practicable solutions.

As it is said in the second and third chapters, several Evolutionary Computation (EC) approaches have been applied to UA-FLP. Among these, the Genetic Algorithms (GAs) (Holland, 1992) are commonly used. Brintup et al. (2006) have highlighted the fact that Interactive Evolutionary Computation (IEC) can greatly contribute to improving optimised design by involving users in searching for a satisfactory solution (Brintup et al., 2007). Interactivity allows more qualitative considerations, which can be more subjective, to be taken into account. In IEC, the fitness function is based on a human evaluation (Takagi, 2001). Thus, intuition, emotion, and domain knowledge can be involved in the identification of good designs (Quiroz et al., 2007). Such an approach has been suggested in (Quiroz et al., 2009) to handle collaborative design issues in constructing floor-plans. However, to the best of our knowledge, there seems to have no article that proposes interactive approach for UA-FLP.

In this chapter, an IGA that uses the DM's expert knowledge to address the UA-FLP is presented. This approach allows the DM to interact with the algorithm guiding the search process. In this way, the algorithm is adjusted to the DM's preferences through his/her subjective evaluations of representative solutions, which are sufficiently different from each other and are chosen using a clustering method. This is performed in order to not overburden the DM. Thus, the whole population has been classified into clusters by means of the *c-Means clustering* method and only the representative element of each cluster is evaluated.

The remainder of this chapter is organised as follows. In Section 2, the problem formulation is presented. The proposed approach is described in Section 3. In Section 4, this approach is evaluated using two examples. Finally, the conclusions of the chapter are given in Section 5.

5.2. Problem formulation

UA-FLP (Armour and Buffa, 1963) considers a rectangular plant with fixed dimensions ($H \times W$) and a set of facilities , each of them with a given required area (A_i), where the sum of the facility areas must be less than, or equal to, the plant area; see the Equation below. The aim is to allocate the facilities in the plant so as to optimize a given criterion, subjected to the restriction that facilities cannot overlap.

$$\sum_{i}^{n} A_i \leq W \times H$$

Different quantitative criteria have been considered in UA-FLP: material handling cost, adjacency, distance requests or desired aspect ratio. The optimization is performed with one criterion or a combination (Aiello et al., 2006). In this chapter, emphasis is put on qualitative criteria that are difficult to elicit from the expert or difficult to quantify, for example, because they are not known in advance or explicitly given. The goal of the presented approach is to take into account several types of qualitative features that the DM would like to consider in the solution. The DM's interests could be, amongst others:

1. The distribution of remaining space in the plant layout. In this respect, the DM may want solutions that have, for instance, all the remaining space either concentrated in a determined location or distributed in some useful way in the plant layout, for example, it can be dispersed in the plant layout to be used as storage rooms among facilities.

2. The facility placement preferences, which could imply that a certain facility will be placed in the south front, in the centre or in a corner of the plant layout, in order to satisfy transport needs, marketing, or just aesthetic preferences, among others.

3. The facility orientation. This aspect involves the orientation that the DM prefers for a certain facility, for example, to better suit the sequence of the productive process.

4. The desired locations to avoid. This aspect could be interesting for the DM when undesirable factors (e.g., noise, bad smells, humidity) exist in the plant, and it is necessary to avoid certain locations for

certain facilities.

5. Any other subjective interest that the DM would like to consider.

5.3. Interactive Genetic Algorithm Proposed

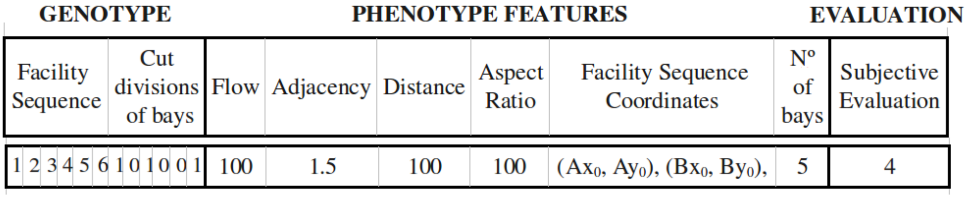
Below, the characteristics of the IGA proposed to solve the UA-FLP are explained. These have been previously described.

5.3.1 Layout representation

In order to represent the plant layout as a chromosome, the *Flexible Bay Structure* (FBS) proposed by Tong (1991) is employed, which is currently receiving widespread attention from researchers (Wong and Komarudin, 2010). The plant layout is delimited by its height and width dimensions. This rectangular area is divided in one direction into bays of varying width. Then, each bay is subdivided to allocate the facilities that make up the layout. The bays are flexible in that their widths will vary with the number of facilities that they can contain (Tate and Smith, 1995b). Figure 3 shows an example of a flexible bay structure.

5.3.2 Encoding Structure

Each individual of the population has the encoding structure shown in Figure 16, which is made up of the following three different parts: *Genotype* part, *Phenotype* features, and *Evaluation* part. These parts will be explained as follows.



GENOTYPE		PHENOTYPE FEATURES						EVALUATION
Facility Sequence	Cut divisions of bays	Flow	Adjacency	Distance	Aspect Ratio	Facility Sequence Coordinates	Nº of bays	Subjective Evaluation
1 2 3 4 5 6	1 0 1 0 0 1	100	1.5	100	100	$(Ax_0, Ay_0), (Bx_0, By_0),$	5	4

Figure 16: The proposed Encoding Structure together with its associated Phenotype and Evaluation.

Genotype

To encode a plant layout, the chromosome used is inspired from that proposed by Gomez et al. (2003), and it is made up of 2 segments. The first segment represents the facility sequence that is read bay by bay, from top to bottom and from left to right. In order to interpret it, a permutation of the integers 1 through *n*, is used, where *n* is the total number of facilities in the plant layout.

The second segment contains the necessary information about where the bay divisions are in the plant layout. For that purpose, (*n*-1) binary elements are employed. When the value 1 appears in the second segment, the facility that is in the same position in the first vector, is the last element of the bay. In this way, the chromosome of Figure 16 corresponds with the representation of Figure 3.

Phenotype features

This part of the encoding structure contains the features of the physical shape of the facility layout that can be quantified, using the formulation given by Aiello et al. (2006). In these respect, it has been considered material handling costs, adjacency requests, distance requirements, and aspect ratio satisfaction. This part of the encoding structure also, includes the coordinates of each facility centre that compose the plant, and the number of bays that divide the surface. The inclusion of these quantitative aspects offers the DM additional information that can be useful to him/her for selecting the final solution that he/she prefers.

Evaluation field

In this part of the encoding structure, the subjective evaluation of each solution is stored. This evaluation is either assigned by the DM or derived from one assigned by the DM, as it is explained in the next section.

5.3.3 Evaluation

The evaluation is made by the DM and therefore is purely subjective. In order to avoid the DM fatigue, the population is classified into clusters in each generation, and only a subset of individuals that are representative elements of each group are displayed to the DM, who assigns a subjective mark to each one in a range between 1 (the shown solution does not satisfy the DM) and 5 (the solution displayed satisfies the DM). An element is considered as representative of the cluster when it has most of the characteristics of the elements that compose the cluster. Each element of the population belongs to each cluster with a value that depends on the similarity grade between the individual and each group. This value is called the *membership grade* m_{ij}. Using the membership grade of the individual in each cluster and the mark assigned by the DM to the representative element of each cluster, the subjective evaluation of the remaining individuals that make up the population are calculated using the next equation:

$$s.e._j = \sum_i^c m_{ij} e_i$$

Where:

$s.e._j$: the estimated subjective evaluation of individual.

c: number of clusters.

m_{ij}: the membership grade of the individual j to the cluster i.

e_i: the mark assigned by the DM to the representative element of cluster i.

Recall that the sum of all the m_{ij} of each individual is equal to 1.

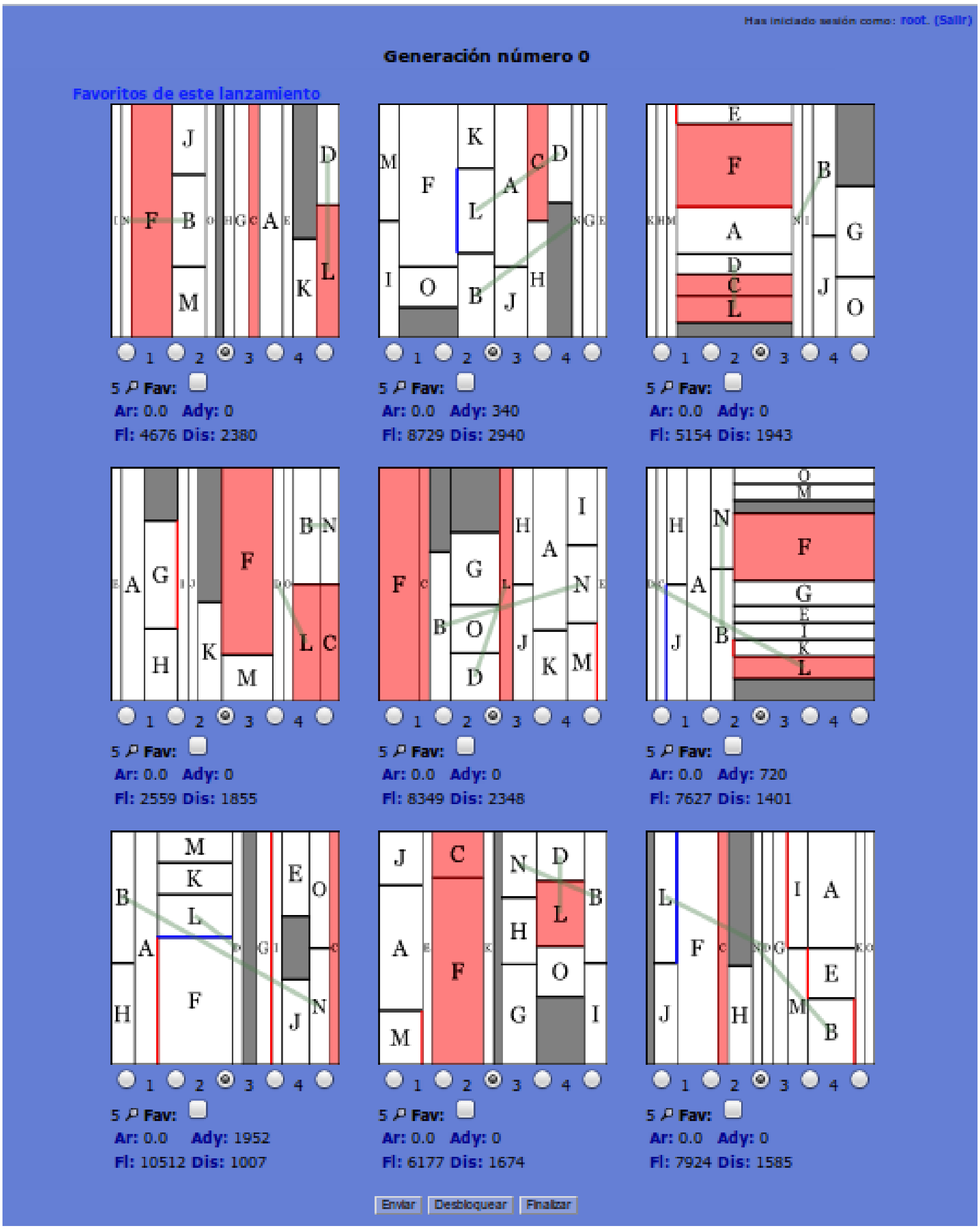
Clustering

To avoid tiring the DM with too many individual evaluations and to offer a choice between sufficiently different solutions, only a representative subset of the population of solutions is submitted to the DM. In this context, Gong et al. (2009) display 8 representative solutions to be evaluated by the user, in each generation. In turn, Kamalian et al. (2004) suggest 9. In our approach, the DM evaluates a subset that consists of 9 solutions in each iteration because they fit well on the screen (see Figure 17), although this parameter can be configurable in order to offer another number of representative solutions to the DM. These solutions should be representative elements from the initial population and sufficiently different from each other. In order to select the elements to display to the DM, a *clustering* *method* has been used.

A *clustering method* is a unsupervised learning that tries to divide a data set of elements into subsets (clusters) depending on certain characteristics. In this way, the elements that are in the same subset or group are similar in certain way. Thus, using the clustering allows to group the population into different categories and chooses the element to represent each one of them.

Because of the number and complexity of the features that define the UA-FLP individuals, it is preferable to allow each element to belong to more than one cluster simultaneously. This way, it can receive inherited evaluations from more than one representative element, which allows the algorithm to adjust the evaluations of the elements that are near the bounds of the clusters accurately. Because of these requirements, an *overlapping* method of clustering, such as the *Fuzzy c-Means Clustering Algorithm* described in Bezdek et al. (1984), has been selected. This approach chooses as *centroid* of a cluster, the mean of all elements, weighted by their degree of belonging to the cluster.

In our particular case, our approach selects the nearest element to the cluster centroid as representative element. Then, a membership value for each one of the remaining elements of the population is calculated for each representative cluster element, m_{ij}. In this way, given the membership grade between a certain element and each of the clusters, this element can be categorised as being in the cluster where it has the higher membership value. Thus, if a cluster representative element gets a good mark from the DM, any element that belongs strongly to this cluster also will obtain a good mark.



Has iniciado sesión como: root. (Salir)

Generación número 0

Favoritos de este lanzamiento

○ 1 ○ 2 ● 3 ○ 4 ○ 5 **Fav:** ☐
Ar: 0.0 **Ady:** 0
Fl: 4676 **Dis:** 2380

○ 1 ○ 2 ● 3 ○ 4 ○ 5 **Fav:** ☐
Ar: 0.0 **Ady:** 340
Fl: 8729 **Dis:** 2940

○ 1 ○ 2 ● 3 ○ 4 ○ 5 **Fav:** ☐
Ar: 0.0 **Ady:** 0
Fl: 5154 **Dis:** 1943

○ 1 ○ 2 ● 3 ○ 4 ○ 5 **Fav:** ☐
Ar: 0.0 **Ady:** 0
Fl: 2559 **Dis:** 1855

○ 1 ○ 2 ● 3 ○ 4 ○ 5 **Fav:** ☐
Ar: 0.0 **Ady:** 0
Fl: 8349 **Dis:** 2348

○ 1 ○ 2 ● 3 ○ 4 ○ 5 **Fav:** ☐
Ar: 0.0 **Ady:** 720
Fl: 7627 **Dis:** 1401

○ 1 ○ 2 ● 3 ○ 4 ○ 5 **Fav:** ☐
Ar: 0.0 **Ady:** 1952
Fl: 10512 **Dis:** 1007

○ 1 ○ 2 ● 3 ○ 4 ○ 5 **Fav:** ☐
Ar: 0.0 **Ady:** 0
Fl: 6177 **Dis:** 1674

○ 1 ○ 2 ● 3 ○ 4 ○ 5 **Fav:** ☐
Ar: 0.0 **Ady:** 0
Fl: 7924 **Dis:** 1585

Figure 17: A screen shot of the web application developed.

5.3.4 Interactive genetic algorithm steps

The steps of the proposed IGA are shown in the flow diagram of the Figure 18 and explained below:

5. An initial random population of *N* individuals is generated.

6. The process of clustering is applied over the initial population, grouping the individuals into *c* categories.

7. The representative elements of the clusters are displayed to the DM.

8. If the DM is satisfied with the algorithm result, then, the process ends. Otherwise, the system takes the subjective evaluation from the DM about the representative solutions of the population.

9. If one or more solutions are judged interesting to the DM, he/she can select them for storage in the system memory in order to recover them for further analysis. These solutions, called *favourites,* will be visible to the DM during the entire process. This allows the DM to compare each set of new solutions to the best achieved here. This assures an improvement. In this way, none of the solutions that the DM considers interesting will be lost in the IGA evolution.

10. Considering the marks given by the DM to the representative elements of the clusters and the membership grade to each cluster, the fitness evaluation for each individual is computed.

11. The selection method, here the Tournament Selection, is applied to select the individuals that will be involved in the evolutionary operations.

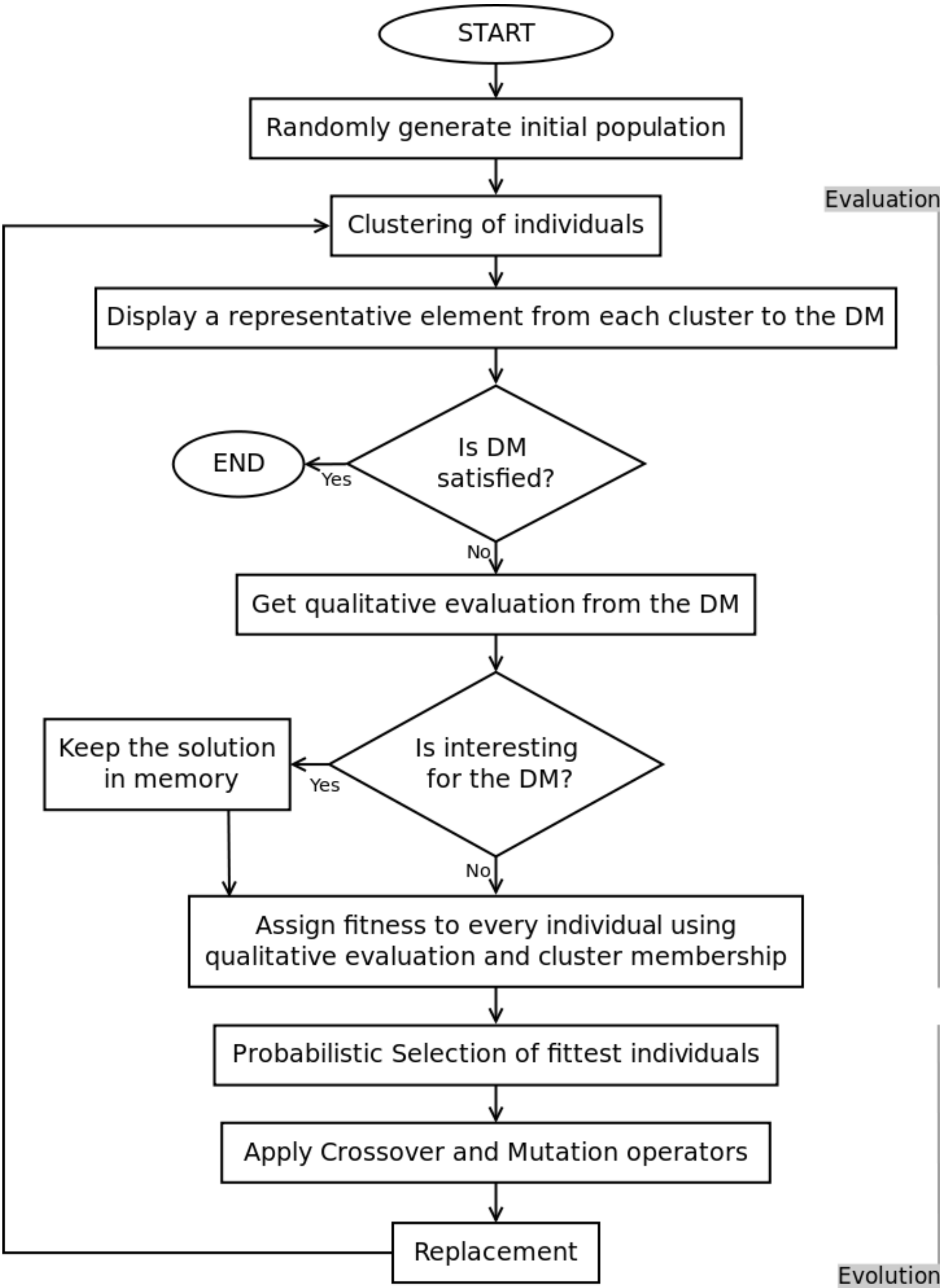


Figure 18: Flow diagram of the proposed IGA.

12. Crossover and Mutation operators are applied to the individuals with a probability given by the DM.
13. Elitism is applied on the new population. Go to step 2.

5.3.5 Selection operator

On the basis on the subjective evaluations, each individual will have a determined probability of passing to the next generation. In order to select the individuals that will made up the new offspring, the method of Tournament Selection (Mitchell, 1998) is applied. Moreover, to force the IGA to keep some number of the best individuals (given by the DM) at each generation, the Elitism method (Mitchell, 1998) has been included.

Moreover, the memory system that has been implemented stores the solutions that are interesting to the DM, avoiding to lose them in the IGA evolution. At same the time, the DM can see on one screen, the solutions generated by the system for him/her to evaluate, and on the other screen, the solutions that he/she has kept as favourites. This allows the DM to compare each new solution to the best achieved here so far and ensure that there is an improvement.

5.3.6 Crossover operator

The way in which the different segments of the chromosome are involved in the recombination process is illustrated in Figure 19. The crossover operator is applied depending on the chromosome segment. In this way, in the first segment, which corresponds to the sequence of facilities in the plant layout, the Partial Mapped Crossover (PMX) (Eiben and Smith, 2007) has been implemented because this method ensures that no elements are repeated. In the second one, which corresponds to the vector of bay divisions, the recombination method used is N-Point Crossover (Holland, 1992; Starkweather et al., 1991).

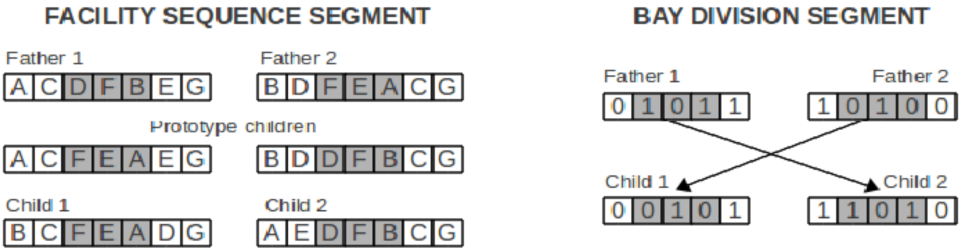


Figure 19: Crossover operator example

5.3.7 Mutation operator

The mutation operator is applied with a certain probability in the following way:

1. In the facility sequence segment, positions are randomly chosen and their content is switched.

2. In the segment of bay divisions, a random position is selected and its value is changed to its opposite.

5.3.8 Visual information

The usefulness of visualizing the information in layout has been highlighted in Chiang (2001). In order to show the most relevant information about each facility layout to the DM in an easily understandable way, in our interactive approach (see Figure 20), the following type of graphical information has been employed:

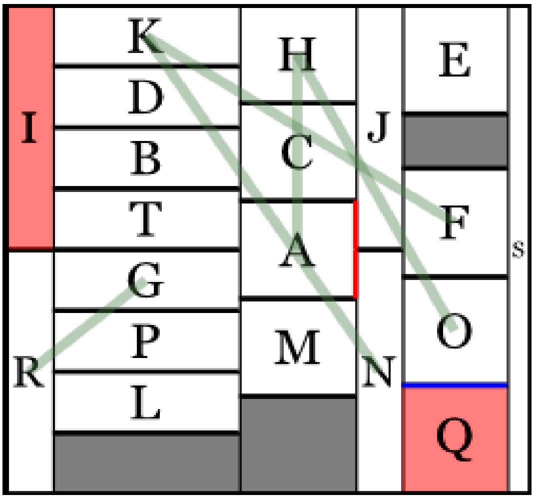


Figure 20: A particular solution.

1. A grey line shows the material flow relationship between each pair of facilities. In order to avoid overloading the visual representation of a solution, only the flows with the highest values are displayed to the DM. There is a parameter to choose how many of these highest values are shown, up to all the material flow relationships that exists in the plant. The grey line represents the flow between facilities rather than, their paths. It is supposed that there is enough space among facilities to transport the material flow.

2. A blue line between a pair of facilities informs the DM that the

adjacency relationships that could exist between them are satisfied. However, if a facility has not satisfied all its adjacency relationships, then that facility's background is coloured in soft red.

3. A dark red line between a pair of facilities indicates to the DM that their distance requirements have not been satisfied.
4. The facilities with grey background represent the remaining spaces left in the plant layout.

5.3.9 Remaining space management

In order to deal with the possible remaining space, first, the average area of all the facilities that make up the plant layout is calculated. Then, the remaining space is divided into as many portions with the average area calculated as possible, and if there exists any remainder space, it is joined with the remaining fraction. By these means, all of the remaining space is allocated into blocks whose area is not greater than the average area of all the facility that made up the plant. Then, these remaining spaces are incorporated into the IGA to be manipulated as dummy facilities.

5.4. Empirical Evaluation

In this section, the evaluation of the suggested IGA is presented. The proposed algorithm has been integrated into a web application. This allows the DM to use the IGA from several computers at different locations. Figure 17 shows an application screen shot of this system where two windows can be seen. The first one contains the nine solutions that are displayed to the

DM to be evaluated; the second one shows all the solutions that have been considered as *favourites* by the DM. In order to test our approach, two UA-FLP examples have been selected. They are taken from Aiello et al. (2006) and Salas-Morera et al. (1996), respectively.

In Figure 21, the proposed approach is graphically summarized. This offers a general idea about how our suggested approach works.

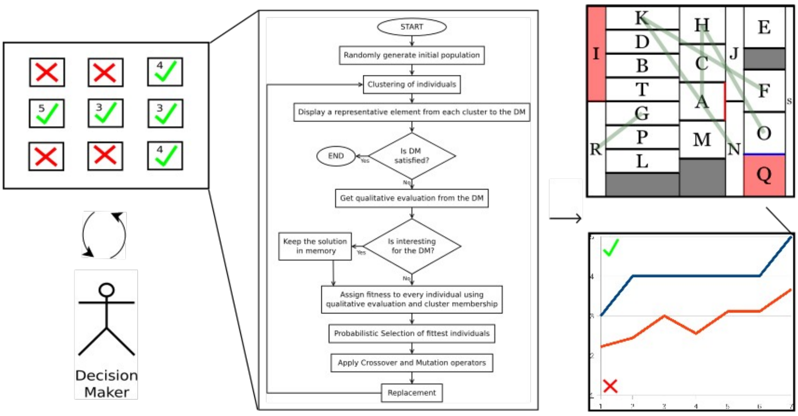


Figure 21: Graphical Abstract of the proposed approach.

5.4.1 Methodology

Original UA-FLP problems from Aiello et al. (2006) and Salas-Morera et al. (1996) consider aspects that can be quantified. However, the DM could have any qualitative interests, which are difficult to consider with an optimisation strategy. In this chapter, the focus is on finding solutions considering certain interests of the DM that are hard to obtain without including the DM's expert knowledge into the algorithm process. Indeed, the DM can have in mind several types of considerations, which seems important to him/her, and they can be very different from one case to the next one. In many problems, several important considerations can also not be perceived or known a priori.

Because the DM must evaluate nine solutions at each iteration of the algorithm, it is not possible to demonstrate the suggested approach with large case tests. In this way, running a test case consists in executing the proposed approach taking into account, for the evaluation of each displayed individual, the particular interests that the DM would like in the final solution. Thus, it can be evaluated how well the suggested IGA could adapt to the DM desires.

The main aim is to achieve a solution that satisfies the DM. This is a solution that satisfies all the interests established by him/her, or in other words, a solution that is valued with the maximum possible punctuation or mark (5) by the DM. On the other side of the balance, the DM should not be overloaded with excessive evaluations to avoid fatigue. In this way, it is desirable to reach a good solution with the minimum possible number of user evaluations.

The experiment consists of three diverse test cases of four interests representing the DM desires. The sets of interests that the DM would like for the example problem taken from Aiello et al. (2006) are described below.

1. The DM would like a solution that has the plant layout divided into 4 bays, where facility 'G' touches any side of the plant, facility 'J' is located in any corner of the layout and facility 'G' is adjacent to facility 'T'.

2. The DM is interested in a solution that has the plant layout divided into 4 bays, where facility 'G' touches the left side of the plant and facility 'J' is located in any right corner of the plant layout, but, he/she would not like a solution with facility 'G' adjacent to facility 'T'.

3. The DM would like a solution whose blocks of remaining space are connected in the layout, where facility 'G' is located in the left side of the layout, and facility 'J' is an interior facility, that is to say, one that avoids any side of the plant layout. Also, he/she is interested in a solution that has the plant layout divided into 4 bays.

For the example problem taken from Salas-Morera et al. (1996), it is considered that the user would prefer solutions that have the following characteristics:

1. The DM is interested in a solution that has the plant layout divided into 3 bays, where facility 'B' touches any side of the layout, and facility 'A' is located in the bottom right corner of the plant layout and also adjacent to facility 'F'.

2. The DM would like a solution that contains the remaining space in any corner, where the plant layout is crossed completely by facility

'C', facility 'B' is located in a right corner of the plant layout, and facility 'A' is adjacent to a block of remaining space.

3. The DM would like a solution whose blocks of remaining space are dispersed in the layout, in other words, the DM rejects solutions that include adjacencies between blocks of remaining spaces. Also, he/she is interested in a solution whose plant layout is divided into 4 bays, where facility 'C' is an exterior facility, and the higher dimension of facility 'A' is parallel to the top side of the plant layout.

Each test case has been repeated three times to assure that the results are not obtained by chance. In order to evaluate how well the proposed IGA could adapt to such DM's interests, the maximum mark assigned by the DM and the average mark of all displayed solutions are stored for each IGA iteration. In the same way, the number of iterations until reaching a good solution (marked with 5) is used to measure the cost in terms of DM fatigue.

Table 18: IGA parameters.

Parameter	Chosen value	Tested Values		
Elitism	15.00%	5.00%	10.00%	15.00%
Population size	100	100	200	300
Clustering fuzzyness	1.2	1.2	1.4	1.6
Crossover probability	0.5	0.4	0.5	0.8
Mutation probability	0.01	0.01	0.05	0.1

The proposed IGA has several parameters that have been tuned empirically using several test cases. In Table 18, the tested and chosen parameter values are shown. Finally, the parameter values that work better with the proposed IGA have been selected. They are indicated in Table 18 and have been used for the rest of the experiment on our interactive approach.

5.4.2 Results

In order to study the improvement of solutions through generations, the evolution of the proposed IGA is presented in Figures 22, 23, 24, 25, 26, and 27. The maximum mark and the average of all displayed solutions in each algorithm iteration are shown. On average, one or two of the DM's interests are satisfied in the first iterations. Then, it can be seen that in all of the test cases, a solution with the maximum mark (5) is obtained. Furthermore, the maximum mark obtained in each iteration evolves with losses of no more than one level. The average shows an increasing tendency in all cases and repetitions.

As it can be seen on the next graphics (see Figures 22, 23, 24, 25, 26, and 27), the number of iterations necessary to achieve an acceptable solution for the DM are different in the test cases carried out. Table 19 displays the number of iterations necessary to obtain a solution that satisfies all the interests desired by the DM. This number ranged between 3 and 7 for the first problem and between 7 and 16 for the second one. This number of evaluations turns out to be reasonable regarding a possible fatigue of the DM. The sets of interests have been chosen considering different levels of complexity to achieve an acceptable solution; for example, it is more difficult to achieve a solution that requires a facility to be located in a certain corner than one that simply requires the facility to touch any side. The speed to attain a satisfactory solution depends on the complexity of the considerations that the DM wants to be taken into account (there may be conflicting preferences, important considerations can not be known at the beginning of the study and can be discovered along the generations evaluating the solutions, among others.) and the problem.

Table 19: Number of iterations that are necessary to satisfy each set of the DM interests

Aiello et al.					
Case	Iterations			Average	Std. Dev
1	5	7	7	6.33	1.15
2	4	3	6	4.33	1.53
3	4	3	7	4.67	2.08
Salas-Morera et al.					
Case	Iterations			Average	Std. Dev
1	8	10	10	9.33	1.15
2	9	14	16	13	3.61
3	15	11	7	11	4

The randomness of GA is the reason why there are differences between the numbers of iterations needed to obtain a satisfactory solution for the DM among repetitions of the same test case. In this respect, the third test case of the second example shows the greatest difference among repetitions of the same case, with a number of 8 iterations.

In summary, the results prove that the proposed algorithm satisfies the pursued aim, so that, in all of the testing cases, a solution that carries out the interests defined by the DM is obtained. Moreover, this solution is achieved in a reasonable number of iterations without tiring the DM.

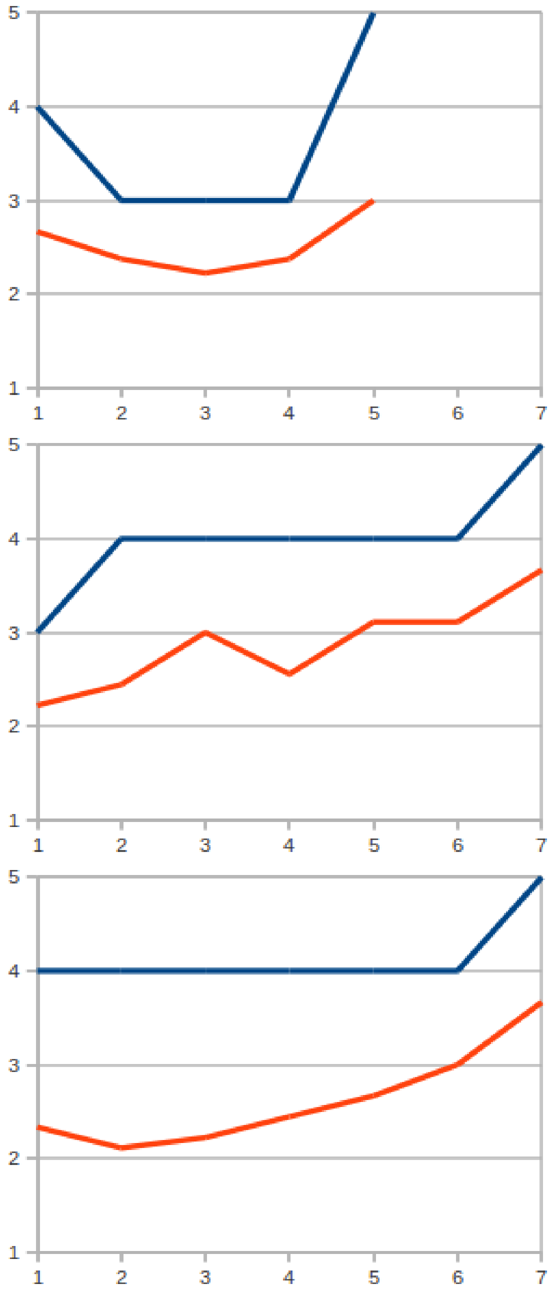


Figure 22: Evolution of the DM evaluations for the first case applied to the problem taken from Aiello et al. (2006)

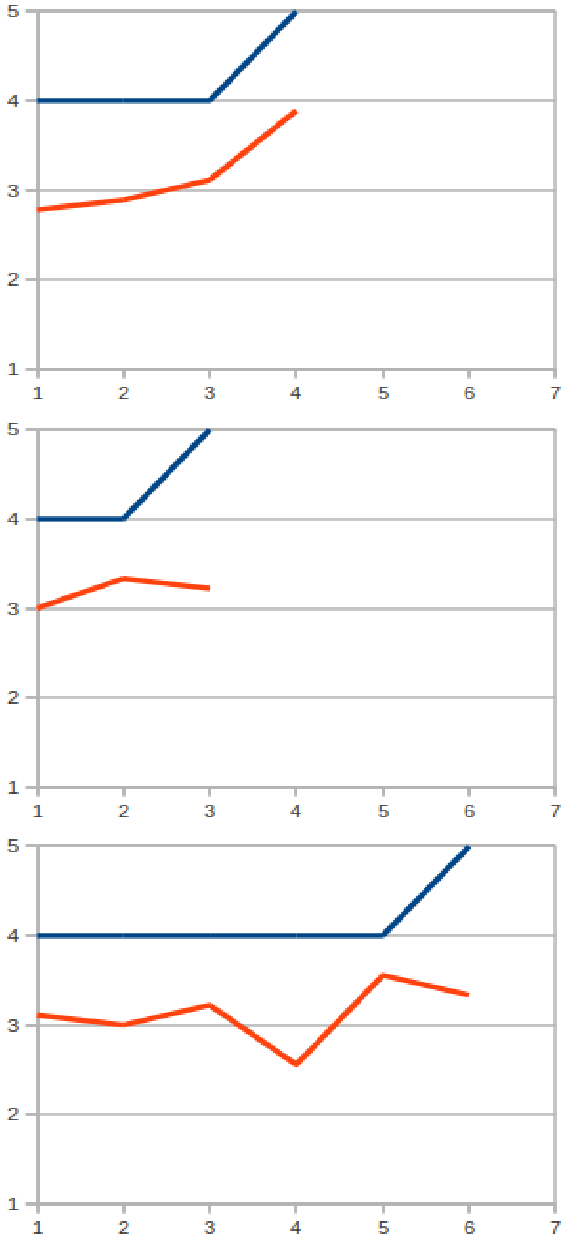


Figure 23: Evolution of the DM evaluations for the second case applied to the problem taken from Aiello et al. (2006).

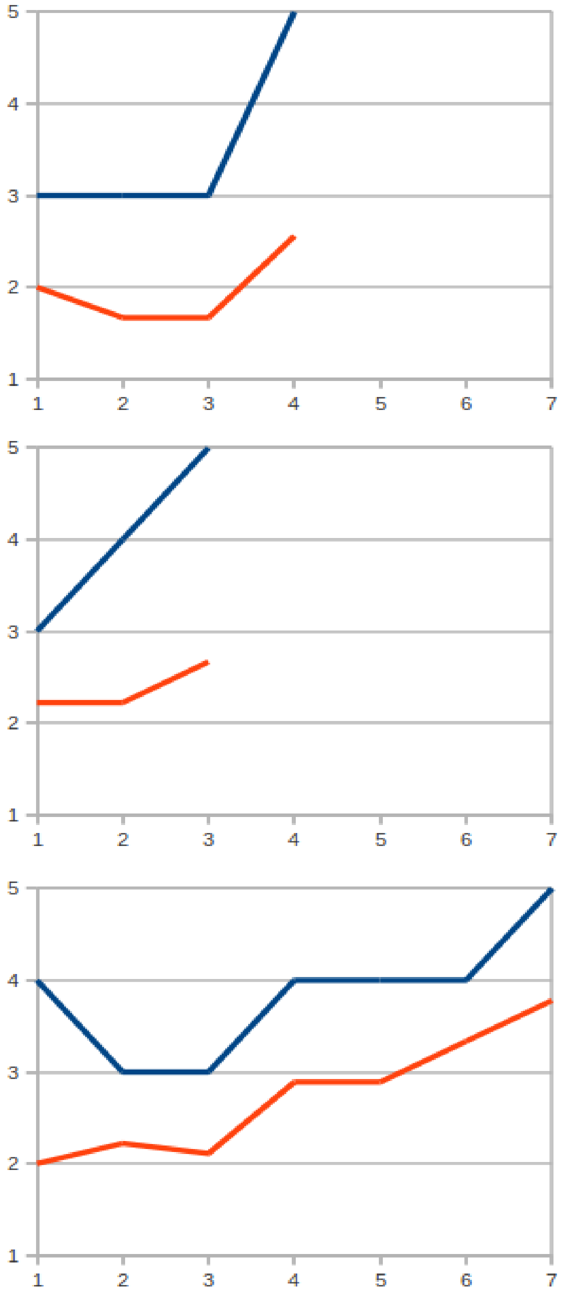


Figure 24: Evolution of the DM evaluations for the third case applied to the problem taken from Aiello et al. (2006)

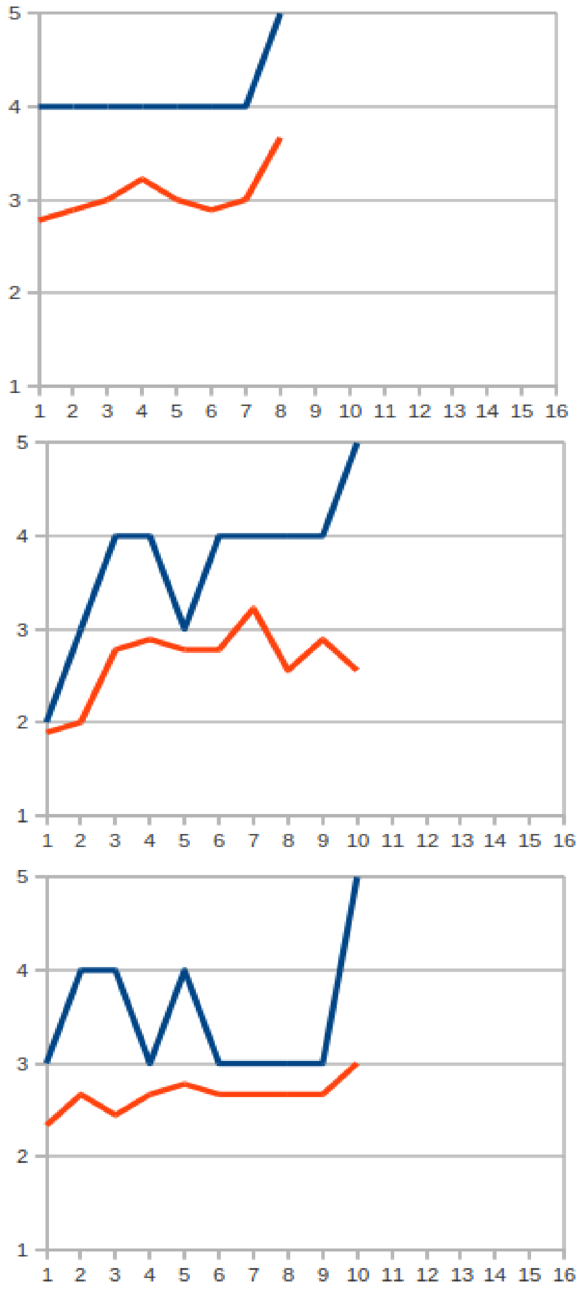


Figure 25: Evolution of the DM evaluations for the first case applied to the problem taken from Salas-Morera et al. (1996)

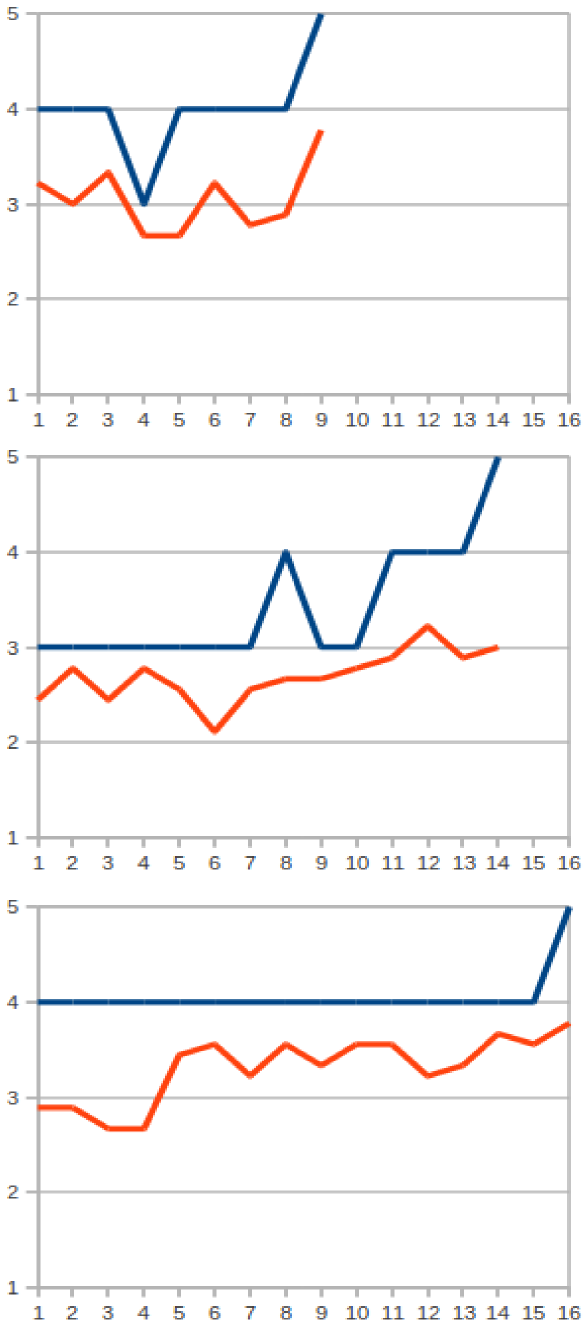


Figure 26: Evolution of the DM evaluations for the second case applied to the problem taken from Salas-Morera et al. (1996)

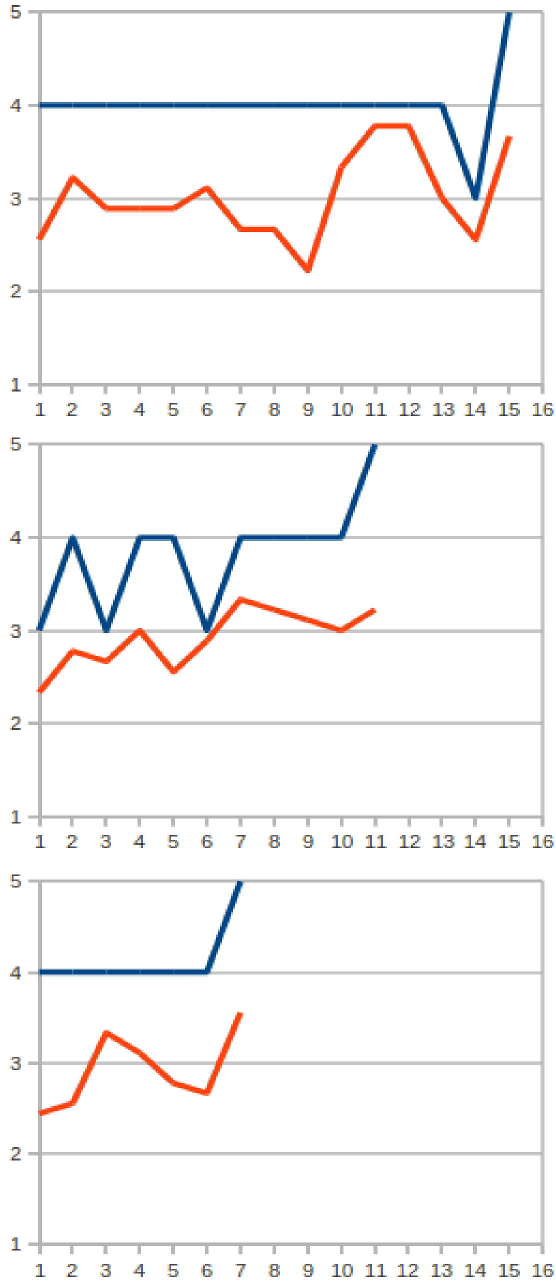


Figure 27: Evolution of the DM evaluations for the third case applied to the problem taken from Salas-Morera et al. (1996)

5.5. Conclusions

In this chapter, an IGA that uses the DM's expert knowledge to address the UA-FLP is proposed. Our approach allows the DM to interact with the algorithm, guiding the search process by means of his/her evaluations. In order not to overburden the DM with excessive evaluations, these evaluations have been realised exclusively over a subset of representative solutions of the total population in each IGA iteration, which are sufficiently different and are chosen using the c-Means clustering method. Thus, the chosen solution is determined in accordance with the considerations that are judged to be important by the DM, which are difficult to consider in a classical optimisation approach and which may not always be known in advance.

From the empirical study, it is shown that the proposed IGA is capable of capturing the aspects that the DM would like in the solution. In fact, solutions found to be acceptable by the DM have been reached in all the test cases performed. Moreover, this solution is achieved in a reasonable number of iterations. These numbers of iterations depended on the randomness of the initial population and on the complexity of the DM's interests. The stricter the interests are, the more iterations will be necessary to obtain individuals that satisfy them.

The direct intervention of the DM in the evolution process improves not only the chance that his/her predefined interests will be satisfied but also the chance that new solutions that have features that can be appropriated into the problem will be discovered by the DM and taken into account in the following generation. This can stimulate the DM's originality and creativity in the search for solutions.

Furthermore, the proposed approach save solutions that are interesting to the DM in certain iterations in memory during the evolution of the algorithm, thus preserving those solutions for future reference. In such way, at each stage, the DM can compare new solutions with the best achieved so far, which contributes to an improvement of the new solutions proposed by the IGA. This memory is an important reference used and enriched all along the process.

Due to the fact that many features of the solutions should be considered at the same time, the DM could end up distracted. In future work, a promising line of research could be to add some quantitative aspects to the approach without losing the efficient adaptation of our IGA to the interests that the DM would like in the final design. Furthermore, to improve the reduction of DM fatigue, different techniques to avoid tiring the DM could also be investigated. Finally, another interesting research direction could be to study alternative methods of offering visual information to the DM with the aim of transmitting this information in a more ergonomic way.

6. Concluding remarks

In this thesis, the existing approaches to solve the Facility Layout Problems (FLPs) and, in particular, the Unequal-Area Facility Layout Problems (UA-FLPs) has been reviewed. This way, the basic knowledge of these problems has been provided. For that purpose, an analysis of the literature published in the area has been performed having into account the workshop characteristics, and the resolution approaches used by researchers in order to solve the different FLPs.

From the previous literature review, it can be said that UA-FLP is still an open and active area. This fact has stimulated the author to work with this main category of the FLP. Thus, the emphasis has been put on the UA-FLPs. This problem can be modelled by different layout representations, which has been identified and described in this thesis.

Additionally, an study of the encoding schemes and the evolutionary operators used by GAs for solving FLPs and UA-FLPs, has been performed. This has lead to discover which of them is the most adequate for each proposal and the unexplored combinations to research. Although there are surveys which have examined FLPs, there seems to be no studies which have reviewed FLPs focused on the evolutionary techniques in depth. Although this overview can not be exhaustive, the analysis carried out enabled us to identify:

- The manner of placement the facilities on the surface.
- The component functions that could be used to create the facility layout solutions.
- The techniques that are used to encode this elementary functions.

From the study carried out, it is possible to extract as conclusion that combining the identified component functions could create new unexplored encoding schemes. In this manner, many different ways of encoding the facility layout solutions are available. Logically, crossover and mutation operators also depend on the encoding scheme selected. Besides, we have identified the evolutionary operators that could be applied to each encoding scheme. These encoding schemes and their operators will determine the ability of the GA to obtain good solutions. Thus, the classifications and analyses about the encoding schemes and the evolutionary operators used by GAs for solving FLPs, which have been described in this thesis, could be useful for future studies in FLPs.

Besides, a new GA for solving UA-FLP is suggested. In this approach, a new, simple and easy-to-implement method for encoding and representing possible solutions has been designed and implemented. The evaluation of the solutions considered both qualitative aspects that are quantified such as closeness or distance requests between facility centres due to logical production processes, information flows, existence of noise or thermal environments, and quantitative aspects such as material flows. According to the characteristics of the problem, the weights assigned to the evaluation criteria can be easily modified, making it easier to obtain good solutions in a wide range of practical scenarios. Optionally, the algorithm can also take into account the appearance of the layout when considering the shape of each facility. The algorithm is able to generate good solutions in all the cases tested, which varied in type and complexity; this is also true when compared with other algorithms described in the bibliography.

Additionally, a new IGA for solving UA-FLP is proposed. This interactive approach allows to introduce qualitative considerations in the design using the expert knowledge from the DM to address the UA-FLP. The idea of using an interactive approach for handling qualitative aspects in UA-FLP is a novel concept because from the best of our knowledge, there is no interactive approach applied to UA-FLP. The proposed approach enables the DM to interact with the algorithm, guiding the search process by means of his/her evaluations. In order not to overburden the DM with excessive evaluations, these evaluations have been realised exclusively over a subset of representative solutions of the total population in each IGA iteration. For that purpose, a c-Means clustering method has been integrated into the IGA in order to group the population into clusters and to choose the representative from each one. Thus, the solutions found are determined in accordance with the considerations that are judged to be important by the DM, which are difficult to consider in a classical optimisation approach and which may not always be known in advance.

From the empirical study, it is shown that the proposed IGA is capable of capturing the aspects that the DM would like in the solution. In fact, solutions found to be acceptable by the DM have been reached in all the test cases performed. Moreover, this solution is achieved in a reasonable number of iterations. These numbers of iterations depended on the complexity of the DM's interests. The stricter the interests are, the more iterations will be necessary to obtain individuals that satisfy them.

The direct intervention of the DM in the evolution process improves not only the chance that his/her predefined interests will be satisfied but also the chance that new solutions that have features that can be appropriated into the problem will be discovered by the DM and taken into account in the following generation. This can stimulate the DM's originality and creativity in the search for solutions.

Furthermore, the proposed approach save solutions that are interesting to the DM in certain iterations in memory during the evolution of the algorithm, thus preserving those solutions for future reference. In such way, at each stage, the DM can compare new solutions with the best achieved so far, which contributes to an improvement of the new solutions proposed by the IGA. This memory is an important reference used and enriched all along the process.

As final concluding remark, it can be said that the goals set at the beginning of this study, have been satisfied. This way, the thesis performed incorporates two contributions to the UA-FLP. A new genetic approach that has into account tangible aspects, and an interactive genetic strategy that considers the qualitative features that the DM could desire in each particular situation.

7. Future work

The investigation has been successful in terms of results achieved, but it has also marked the beginning of a new grounds which exploration seems to be a promising lines of future work in order to obtain new interesting results. Thus, these lines are:

1. The implementation and evaluation of new encoding schemes created by combination of the elemental components identified in the Chapter 3, together with the empirical evaluation of the untested evolutionary operators that have been identified. This would enable to achieve the aim of improving results and recommending the best among them.

2. The incorporation into the approach of additional constraints or devices, as for example, elevators. This inclusion enables to the Decision Maker (DM) to facilitate his work with more realistic designs.

3. The application of the proposed approaches to another Facility

Layout Problems (FLPs), such as, the Dynamic Facility Layout Problem or Multi-Floor Facility Layout Problem.

4. The combination of the presented approaches with other methods, for instance, a multi-objective algorithm, another meta-heuristic search, a artificial neural networks, among others, in order to improve the performance of the proposed approaches.

5. Due to the fact that many features of the solutions should be considered at the same time, the DM could end up distracted. For that reason, it should be interesting to create a new system that integrates both strategies of evaluation: quantitative from traditional UA-FLP and qualitative from interactive evaluation, but without losing the efficient adaptation of our IGA to the interests that the DM would like in the final design.

6. To improve the reduction of the DM fatigue. For that purpose, different techniques to avoid tiring the DM could also be investigated, implemented and valued. In this respect, a learning strategy seems to be a promising approach.

7. To study and evaluate alternative methods of offering visual information to the DM with the aim of transmitting this information in the most ergonomic way.

8. The implementation of a collaborative system that allows the introduction of several DMs into the approach. This way, the knowledge of several experts can guide the Interactive Genetic Algorithm (IGA) to the final solution. In advance, it seems that

the obtain solution will be better if there are more experts that give their knowledge and experience that if only one of them realize this action.

9. To investigate techniques for preserving the diversity of the solutions. This could assure that the same solution will not be displayed to the DM for being evaluated more than once.

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