Faculdade de Engenharia da Universidade do Porto

Flexible and Reconfigurable Layouts in Complex Multi-Facility Manufacturing Systems

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“*O período de maior ganho em conhecimento e experiência,*
é o período mais difícil da vida de alguém”

Dalai Lama

Dedico este trabalho à minha Família, em especial aos meus filhos João, Pedro e Margarida e ao meu marido Jorge, por todo o Amor e alento durante esta longa fase da nossa vida!

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Abstract

This thesis addresses the facility layout problem in a new perspective (the multi-facility layout problem), at two decision levels: locating departments in a network of facilities, and positioning resources inside departments.

The facility layout problem (FLP) involves the physical organization of the resources needed for the production of goods or delivery of services. Due to the large impact that a layout configuration has in the performance of an industrial company, this is an intensively investigated area, but in general the published research has only addressed the case of a single facility. However, companies operate more and more as parts of large networks, or they have multiple facilities geographically distributed, this creating a need for tools to support the integration of operations in a flexible and efficient way. To cover this need we propose the multi-facility layout problem, that can be viewed as an innovative extension of the traditional facility layout problem, with a significant practical potential.

This research was pursued in a strong collaboration with an industrial partner, that inspired the developed models. A first part of this dissertation consists in a comprehensive revision of the problems associated to layout design. The approach proposed by our work allows for two layout reconfiguration types: *small* and *large changes*, that differ in the level and frequency of the layout modifications.

The formulated mathematical models were based on the Quadratic Programming Problem, with multi-periods and multiple objectives and unequal areas. The multi-period analysis allows us to handle market changes (new demand volumes or new products introduction). The objectives of the model are: the minimization of costs (material handling inside facilities and between facilities, and re-layout); the maximization of adjacency between departments; and the minimization of the "unsuitability" of department positions and locations. This unsuitability measure is a new objective proposed in this work, to combine the characteristics of existing locations with the requirements of departments.

The proposed models were tested with data from the literature, as well as with some problems inspired in a first-tier supplier in the automotive industry (the case study). The results show that this work can be viewed as an innovative and promising integrated approach for tackling real, complex facility layout problems.

Keywords: Multi-facility layout problems; Dynamic layout problems; Multi-objective optimization; Reconfigurable layouts; Flexible layouts.

Resumo

Esta tese estuda o problema de *layouts* industriais numa nova perspetiva, considerando um grupo de instalações, e em duas vertentes distintas: a localização dos departamentos numa rede de fábricas, e a localização dos recursos nos departamentos, dentro de cada fábrica.

O problema de *layouts* de instalações *(facility layout problem - FLP)* envolve a organização física dos recursos necessários para a produção de bens e serviços. Dado o grande impacto que a configuração do *layout* tem no desempenho de uma empresa, esta é uma área intensamente investigada. No entanto, os trabalhos publicados nesta área, focam-se apenas, e em geral, no caso de uma única fábrica. Por outro lado, as empresas operam cada vez mais como partes de grandes redes, ou têm várias instalações dispersas geograficamente, tendo assim uma maior necessidade de ferramentas para apoiar a integração de operações de forma flexível e eficiente. Para fazer face a estas necessidades, propomos neste trabalho o problema de *layout de múltiplas instalações*, que pode ser visto como uma extensão inovadora do problema tradicional de *layouts* com um significativo potencial prático.

Este projeto de investigação, foi desenvolvido em colaboração com um parceiro industrial, que inspirou os modelos desenvolvidos. A primeira parte do trabalho consistiu numa revisão exaustiva dos problemas de desenho e reconfiguração de *layouts*, que permitiu identificar algumas lacunas importantes na literatura, levando-nos a desenvolver uma abordagem que permite dois tipos de reconfigurações (as pequenas e grandes mudanças) que diferem na profundidade e frequência das mudanças do *layout*.

Os modelos foram formulados como problemas de programação quadrática, com múltiplos objetivos e áreas diferentes, permitindo reconfigurações do *layout* em cada período de planeamento. Os objetivos do modelo são: a minimização de custos (manuseamento de materiais, dentro e entre instalações, e custos de reconfiguração); a maximização da adjacência entre departamentos; e a minimização da *inadequação* das posições e os locais dos departamentos. Esta medida de *inadequação* é um novo objetivo, proposto neste trabalho, para combinar as características dos locais existentes com as exigências dos departamentos e máquinas.

Os modelos propostos foram testados com dados da literatura, bem como com alguns problemas inspirados num fornecedor de primeira linha na indústria automóvel (o caso de estudo). Os resultados mostram que este trabalho constitui uma abordagem integrada inovadora, e com um grande potencial para ser usada em problemas reais e complexos de *layout* de instalações.

Palavras chave: Problema de layouts de múltiplas instalações; Problemas de layouts dinâmicos; Otimização multiobjectivo; Layouts reconfiguráveis; Layouts flexíveis.

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Glossary and abbreviations

ACO – ant colony optimization
AHP – analytical hierarchy process
ANN – artificial neural network
CFLP – cyclic facility layout problem
CMS – cellular manufacturing system
CN – collaborative network
DFLP – dynamic facility layout problem
DM – decision maker
DSS – decision support system
EU – European Union
FLP – facility layout problem
GA – genetic algorithm
GT- group technology
MCDM – multi criteria decision making model
MHC – material handling cost
MHE – material handling equipment
MHS – material handling system
MFLP – multi-facility layout problem
MIP – mixed integer programming
PSO – particle swarm optimization
QA – quadratic assignment
QAP – quadratic assignment problem
QTP – quadratic transportation problem
RMS – reconfigurable manufacturing system
RQ – research question
SA – simulated annealing
SFLP – static facility layout problem
SLP – systematic layout planning
SME – small and medium enterprise
VE – virtual enterprises
VO – virtual organization
WIP – work in process

1. INTRODUCTION

This chapter provides a brief introduction and description of the work done in this research project
Contents of the chapter:

- *Problem relevance*
- *Objectives and main research question*
- *Methodology*
- *Thesis overview*

1.1 Problem relevance

In a world with increasing uncertainty and accelerated changes, companies need advanced and innovative tools to quickly and efficiently respond to emerging and unexpected requirements. This is particularly critical with Small and Medium Enterprises (SME) as they are very vulnerable to changes in normal business environments. The European Commission (EU) considers SMEs and entrepreneurship as key to ensuring economic growth, innovation, job creation, and social integration in the European Union (EU). Representing 99% of all business in the EU, SMEs are the backbone of Europe's economy. In the last five years, they have created around 85% of new jobs and provided two-thirds of the total private sector employment in the EU[1].

The globalization of markets significantly changed manufacturing environments from traditional single-companies to decentralized multi-enterprises, thus promoting the so-called distributed manufacturing (Naderi & Azab, 2015). In a more and more competitive world, companies easily recognize they need to permanently develop new and more sophisticated strategies, in order to maintain and increase their performance (Azevedo et al., 2016). The reconfiguration and continuous optimization of resources and production processes can be a way to reduce cost and increase their opportunities and profit (Afsarmanesh et al., 2009).

The integration in Collaborative Networks (CN) can also be an important step to make organizations more effective and agile, as part of broader manufacturing systems, and this may be especially important for SMEs, due to their reduced dimensions and high vulnerability. In this context, one of the current big challenges for industry is clearly the permanent need for rapid reconfiguration of manufacturing enterprises, in response to changing requirements and opportunities (Camarinha-Matos et al. 2009). This new reality of collaboration between companies, based on temporary relations, increases the need to evaluate layout changes when establishing new collaborations.

In fact, given the high variety of products manufactured simultaneously and the ever-decreasing lifetime of these products, the need for adjustments in the layouts of the companies also grows proportionally. Quite often, machines are large and difficult to move, and therefore most of the times these changes are not performed or they are

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[1] *http://ec.europa.eu/growth/smes/ at 22 march 2016*

continuously postponed. Frequently, new machines are located in unplanned places, creating difficult material flows, and thus decreasing efficiency. Such situations require that the configuration of the facilities is rethought regularly. Moreover, when new facilities are added, new spaces are added (or subtracted) from existing spaces. The problem is even more difficult when there is collaboration (product sharing) between various facilities. The new reality based on complex very personalized products with reduced life cycles, leads to the need of establishing dynamic networks between companies that can share physical and logistical resources. This creates a new problem, how to align the productive processes of the companies the best possible way.

The Facility Layout Problem (FLP) involves the physical organization of the resources needed for the production of goods or delivery of services. This is an intensively investigated area, due to the large impact that a layout configuration has in the performance of an industrial company (Drira et al., 2007). The FLP has been studied from many different perspectives, considering: the types of layout configuration (single row, multi-rows, multi-floor, etc.); the types of problem (facility location, department allocation, routing, etc.); the objectives and constraints; the static or dynamic nature of the problem; the large variety and combination of resolution approaches (exact methods, heuristics, etc.). There are in the literature several surveys related with the FLP, such as Keller and Buscher (2015), Chen et al. (2014), Moslemipour et al. (2012), Arabani and Farahani (2012) and Drira et al. (2007), but in general, the described approaches are focused on single facilities (Azevedo et al., 2017).

However, the vast diversity of research work on the FLP, several authors identify the need of new developments in this area, such as:

i) the lack of research on layout reconfiguration, since most of the existing literature is in the design of new plants layouts (greenfield design) (Kulturel-Konak, 2007);

ii) the need of detailed and flexible design layout ((Dong et al., 2009); (Kia et al., 2012));

iii) the need to incorporate multiple facilities in the analysis of facility problems (Arabani & Farahani, 2012), reinforced by the need of tools for combining a plant-level and a network-level analysis as a way to understand the continuous interaction between individual plants and their constituent network (Cheng et al., 2015);

iv) there are a few works considering the capacity constraint of the Material Handling Equipment (MHE) (Shah et al., 2015);

v) the need for real case studies, referred by several authors of surveys, such as (Drira et al., 2007), (Kulturel-Konak, 2007), (Singh & Sharma, 2006);

Our problem is directly inspired by a real case study. The company is a first-tier supplier of the automotive industry that comprises several facilities around the world. This industry is characterized by the constant introduction of new products and fluctuations in demand, and the company must, therefore, frequently rethink the layout of each department and of each facility, even re-organize production among the facilities of the group.

Based on the identified gaps of the literature and inspired by a rich, interesting case study, this research project proposes a new extension of research on the FLP, the *multi-facility layout problem* (MFLP) (see Figure 1. 1).

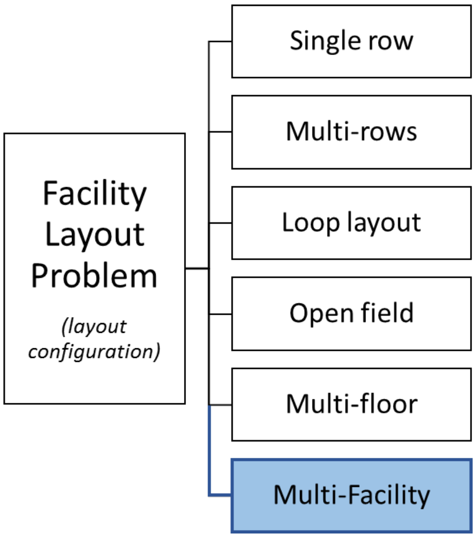

Figure 1. 1 – Extensions of the Facility Layout Problem (adapted from (Drira et al., 2007)).

In this work, we consider a set of geographically separated facilities that can produce and store the same type of products and components. Each facility has more or less the same department structure, with the same type of equipment and machines (see Figure 1. 2). These facilities are served (and linked) by a distribution system that uses trucks to move the raw materials, components and products between the factories. So, the variety of flows is large: there are flows inside each facility (between departments and machines) and there are flows between facilities.

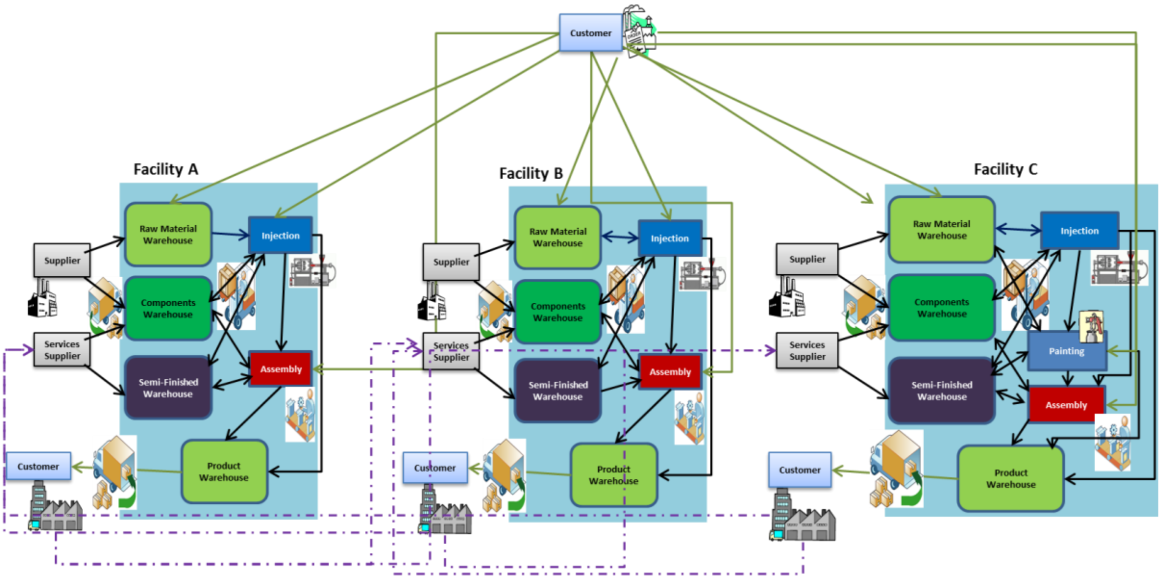

Figure 1. 2 – Flows inside and between the facilities.

In this context, the *multi-facility layout problem (MFLP)* involves the physical organisation of departments between and inside several geographically dispersed facilities, that collaborate in manufacturing a complex product, in a given time window. The problem consists therefore in finding the best global layout for a given *project*. In order to optimise operations, we can use the flexibility of the system to exchange the location of departments between the facilities, in different periods of time.

1.2 Objectives and Research question

Considering the referred needs to extend the research on facility layouts to a collaborative group of facilities, and the need of the industry, for tools to support the design and the reconfiguration of layouts, the main research question of this work was stated as follows:

How to improve the facility(ies) layout for a network of factories in very dynamic environments?

To answer this question, we have defined three main objectives to be accomplished:

i) Understand if the classical FLP can be applied to a set of collaborative facilities, or if there are more specific characteristics that must be added to the models. And understand the type of reconfiguration that are needed - exchange an entire department between facilities can possible be different than changing the location of a single machine, inside a department. Will these changes occur with the same frequency? Can the same model encompass all these aspects?

ii) Develop a generic model, that can be applied to other real cases, but capable of incorporating specific characteristics, resulting from the concrete case being analyzed, in an easy way. The case study led us to incorporate in the model the following capabilities:
    a. the reconfiguration of departments or machines, must guarantee that some departments, with specific needs, are only positioned at specific locations, with these characteristics; otherwise, these locations have to be adapted, probably implying more costs and time to make the reconfiguration (for example, injection machines and departments need sturdy surfaces, so they can be only allocated to positions with this floor resistance);
    b. the possibility of organizing the layout considering different production strategies (for instance, joining the product warehouses, at the same facility, or organizing the machines, by products);
    c. take into account the transport system and its characteristics and vulnerabilities (for example, in the case study, they have a distribution system with trucks, but it could be interesting to analyse if these trucks are enough, or if more capacity will be needed, or it is better to rent this logistic service only for a specific period or definitely).

iii) Develop a decision support tool to analyse the impact of decisions such as: introduction of new projects; changes in the network formation by adding or withdrawing facilities; customer requirements during the negotiation phase of the contract; or strategic management decisions.

Thus, the proposed model must help the Decision Maker (DM) to analyse the possibility of designing and reconfiguring the layout of a network of companies, and to explore various situations, considering multiple objectives and several constraints (such as adding a department to a facility, or during contract negotiations with customers).

1.3 Methodology

In the literature, there are several approaches to solve the FLP, according to the type of formulation adopted, and to the particular problem dimension. These approaches aim either at finding good solutions, satisfying certain constraints expressed by the decision maker, or at searching for global or local optimum solutions, given one or several performance objectives (Drira et al., 2007). Normally, these groups of methods are called respectively *exact methods* (e.g. Branch-and-Bound, Dynamic Programming) and *approximate methods* (e.g. heuristics or meta-heuristics).

As we are starting a new extension of the FLP (the MFLP) and developing the bases for new research lines it is important to find optimal solutions, and to establish and prove the importance of this new problem. We are therefore using *exact methods* to solve the proposed *multi-facility layout* models.

On the other hand, there are several optimization softwares, (such as CPLEX, GUROBI, MATLAB, LINGO, GAMS, etc.) (Hillier & Lieberman, 2010) that can be used to solve small to medium size problems, and are increasing their efficiency to find, not only near optimal solutions, but in fact the optimal solutions. CPLEX is currently viewed as probably one of the most advanced optimization software, integrating quite sophisticated features for dealing with complex integer, non-linear models, and was recently upgraded with interesting developments to solve quadratic problems. To solve our MFLP, we have therefore used CPLEX version V12.6.1.

1.4 Thesis overview

The development of the present research was based on a real need of tools to help a first-tier supplier of the automotive industry to design and redesign the layout configuration of a group of companies, taking into account all the factors that directly and indirectly affect these decisions. The research starts from the general concept of facility design and layout reconfiguration, going deeper through more detailed and specific questions of the case study.

In this introductory chapter, the scope and relevance of this research work were presented, and the objectives and research questions were explained. *Chapter 2* presents the main concepts and the state-of-the-art of the areas related with the *multi-facility layout problem*. This second chapter is divided in four main sections. First, the main concepts about facility layout design are explained and the design process is explored at its different phases (problem characteristics, problem formulation, and resolution approaches). Then the state-of-the-art about reconfigurable layouts are analysed, as well as the main characteristics and related concepts, such as dynamics, flexibility, collaboration, material handling, and layout evaluation. Finally, the main conclusions and the identified gaps on the literature are detailed, supporting and justifying the importance of this research work.

Then, in *chapter 3*, the real case, that inspired this research work is described, as well as some particularities of the automotive industry, that can influence the layout design process and configuration (e.g. product complexity). The real problem is explained, as well as the production process and physical characteristics of the existing facilities, followed by the description of the current layout design and reconfiguration process.

The main innovative work developed in this research project, is presented in the following chapters (see Figure 1. 3). C*hapter 4* presents the proposed new extension to the classic *Facility Layout Problem* the *Multi-Facility Layout Problem,* and the approach taken to address this new problem.

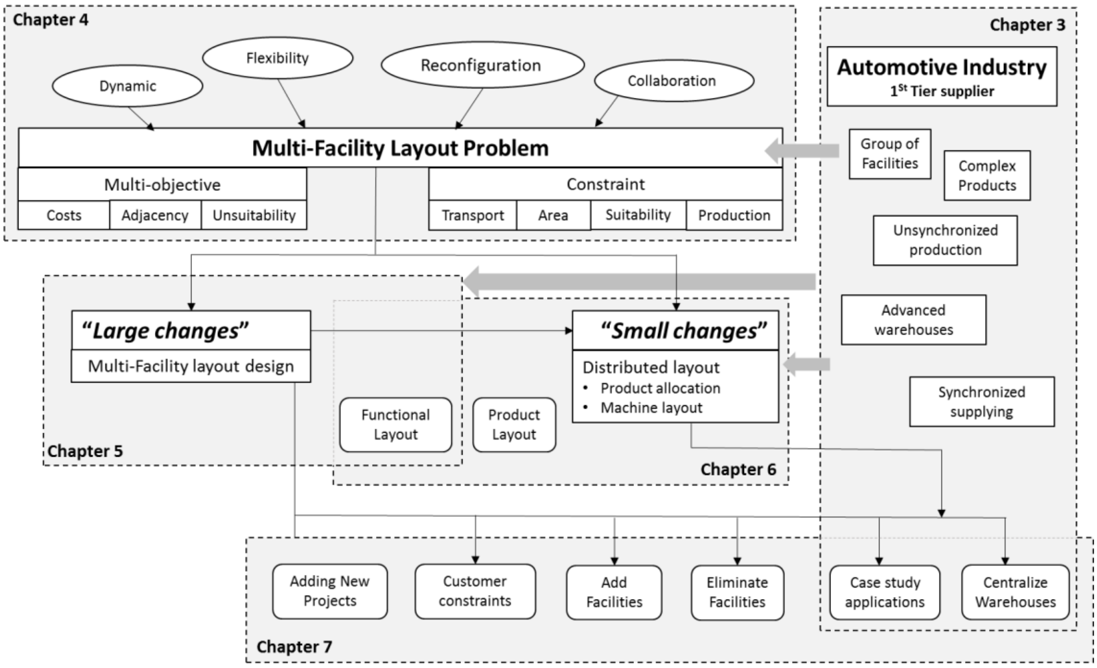

Figure 1. 3 – Problems addressed in the thesis.

Chapter 5 presents a mathematical model and its computational assessment for the location of departments. This is the "*large changes*" model for this new perspective of FLP (the *multi-facility layout problem*), and it is a multi-objective model, based on: *minimization of costs* (material handling inside facilities and between facilities, and re-layout); the *maximization of adjacency* between departments; and the *minimization of unsuitability* of department positions and locations. This *unsuitability* measure is a new objective proposed in this work, presented in detail in this chapter. The performance of the model was tested with data from the literature, as well as with a small illustrative example inspired in the case study, this assessment was complemented with a sensitivity analysis of the model.

Next, *chapter 6* presents a mathematical model and its computational assessment for the so-called "*small changes*" in the layout of a company. This is performed by selecting the machines to produce each product, and organizing their location inside a facility or a department, based on the concept of distributed layout. This dynamic multi-objective model *minimizes costs* (production, material handling and reconfiguration), *maximizes adjacency* between machines, and *minimizes unsuitability* (to combine characteristics of machines and the existing locations – this is a new objective, proposed in this work). The model is illustrated with two small examples, inspired in the case study: one is used to design an entire facility; and the other to design a specific department. The adjacency effect is exemplified by testing different production organization policies (functional layouts, and product layouts).

As the main objective of this work is the development of a decision support tool, in *chapter 7*, several scenarios and problems extensions have been tested. We show how the proposed models can be combined and used to support decision-making in different scenarios, for example comparing the current situation with the minimization of total material handling costs, and with centralizing product warehouses at the same facility. In this chapter, some possible extensions of the proposed MFL models are also presented. The emergence of new *projects* requires further functionality to support decision-making during the negotiation process, by predicting the capacities of each company in the network under formation. Changing the dimension of the network is another extension explored here, by adding or eliminating facilities at the network.

Finally, in *chapter 8*, the main achievements and contributions of this research work are outlined, and some future developments and extensions are suggested for the Multi-Facility Layout Problem model presented in this dissertation.

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2 . LITERATURE REVIEW

This chapter provides a brief description of the main concepts and theories applied in this work, as well as a literature review and a state of the art on the main areas covered by this research. This review served as a basis for the development of this work.

Contents of this chapter:

- *Facility layout design*
    - *Problem characteristics*
    - *Problem formulation*
    - *Resolution approaches*
- *Layouts Reconfiguration*
    - *Dynamics*
    - *Flexibility*
    - *Collaboration*
    - *Material handling*
    - *Layout evaluation*
- *Conclusions*

2.1 Introduction

With the scope and context of this research project defined, the main concepts related with Facility Layout Problem (FLP) will be explored in this chapter, along with a comprehensive revision of the existing literature. This literature review was carried out at different times during the PhD project. Initially, for getting a general knowledge of the problem, understanding how it was addressed, and identifying the main existing gaps. Once the research plan and the objectives had been defined and structured, a new search was conducted to know in detail the main features, formulations and techniques used to solve the FLP and its variants (such as reconfigurable layouts, dynamics, flexibility, machine layouts, etc.). Throughout the research, the work also involved other areas directly related with layouts and their efficiency, such as logistics, routing, supply-chains, and manufacturing (see Figure 2. 1).

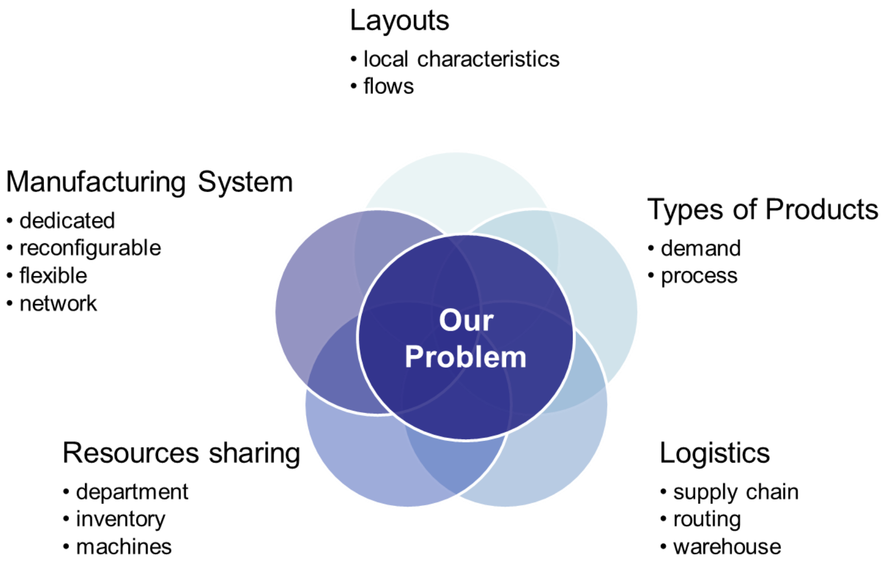

Figure 2. 1 – Research areas.

This chapter starts by presenting the main concepts behind the FLP, and how it has been studied (e.g. its main characteristics, or the applied formulations and approaches). While the main focus of this research is the reconfiguration of layouts, the main characteristics of these type of layouts were analysed in terms of dynamics, flexibility, collaboration, material handling and layout evaluation. Finally, we present the main existing gaps and opportunities for research, in this research area. Three main findings of this analysis are then summarised.

2.2 Facility layout design

The expression used by the pioneers in facilities planning was *plant layout*, combining the terms *physical arrangement, efficiency, work-force, materials and machinery,* as it is the case of the definition proposed by Moore (1962):

> *"Plan of, or the act of planning, an optimum arrangement of industrial facilities, including personnel, operating equipment, storage space, materials-handling equipment, and all other supporting services, along with the design of the best structure to contain these facilities. Good plant layout is fundamental to the operation of an efficient industrial organization."*

In the meanwhile, the term *plant layout* was changed to *facilities layout*, defined by Aplle (1977) as:

> *"the design of an arrangement of the physical elements of an activity.*"

But the confusion of terms went on, even if the definition of *facilities planning hierar*chy proposed by Tompkins and White (1984) has better organised these concepts, considering that *facilities design* broadens the concepts of *facilities system design, layout design* and *handling systems design,* with *facilities planning* widening *facilities location* and *facilities design.*

Later Marcoux et al. (2005) define *facilities layout design* as:

> *"The physical arrangement in a certain space of all activities (e.g., production, handling, warehousing and services to production and staff) related to materials, equipment and workforce to allow efficient production according to market specifications."*

More recently Garcia-Hernandez et al. (2013) consider that *facility layout design,*

> "*determines the placement of facilities or departments in a work plant with the main aim of obtaining the most effective arrangement according to some criteria or preferences and ensuring some constraints*".

We agree with all these definitions (and especially with that of Garcia-Hernandez et al. (2013)), and consider that they are complementary. Therefore for this research work, we will consider:

Facility is an entity that facilitates the performance of any job – it can be a machine tool, a work centre, a manufacturing cell, a machine shop, a department, a warehouse, etc. (Heragu, 1997). The *configuration of facility layouts* comprises the physical organization (of departments, machines, workstations, storage spaces, etc.) inside a plant, facilitating production and material handling, and allowing flexible and efficient operations (Azevedo et al., 2013).

According to (Tompkins, 2003) the material handling cost comprises 20 to 50% of the total manufacturing costs, and it can be decreased by at least 10 to 30% with an efficient layout design. In fact, this is one of the main reasons for the continuous research interest in these problems.

The need to organize space for work and for carrying things efficiently, is an old concern. According to the records of the *Scopus* database, the first work in this area was published in 1928 – a conference paper by Whitham ("Design and operation of modern garages"), a study about the requirements of a garage, to be taken into consideration when designing a layout (e.g. the number of floors, if it should have ramps or elevators, what dimensions each space should have, and what kind of services the garage should offer). They have considered three important aspects when designing a garage layout: the time savings of customers and garage operators; the comfort of customers and operators; and avoiding their dissatisfaction. It is interesting to note that the main objectives still remain the same now, after so many years.

The interest for this area grew, with the number of practitioners and researchers making attempts to apply mathematics and statistics to layout problems as it is the case of the thesis by J. Freeman, in 1947, with the title "*Optimum transportation cost as a factor in plant layout*", a study based on the reduction of handling as the major objective, as a way to achieve a more efficient layout.

Since the 60's, the evolution of research has greatly improved the tools for the solution of the facilities layout problem, especially with the classical computer aided techniques – CRAFT, CORELAP, ALDEP and PLANET (Marcoux et al., 2005), which are still used in many real applications. Then there was a significant increase on optimization research tools, resulting in models and techniques from different areas such as graph theory, expert systems, simulated annealing, tabu search, fuzzy theory, genetic algorithms (Marcoux et al., 2005), and more recently in hybridization approaches, used to develop better facilities layout design methods.

Facility layouts has been an intensive research area, with the publication of several reviews along the years. The first survey we found was written by Grantz (1950) "A proposal of criteria for the evaluation of industrial physical-plant utilization", an extensive survey of the literature encountered on quantitative measures for evaluating plant layouts. Since then, several surveys and reviews have been published (see a summary of the main surveys in Table 2. 1).

The last survey on the facility layout problem was published in 2007 (Drira et al., 2007). Since then, we can find several reviews focusing on specific parts of facility layout problems, such as : Keller and Buscher (2015), about single row facility layout models; Negahban and Smith (2014) that surveys the application of simulation in manufacturing system design and operations; or the review about loop layouts by Saravanan and Kumar (2013). Another interesting example is the work by Moslemipour et al. (2011), a review on intelligent approaches for dynamic, robust, flexible layouts.

The well-known *Systematic Layout Planning (SLP)* method of Muther (1973) consists in several phases (location, macro layout, detailed layout, and implementation). Based on all the existing approaches, (Figure 2. 2) aims at clarifying the relationships between all these terms.

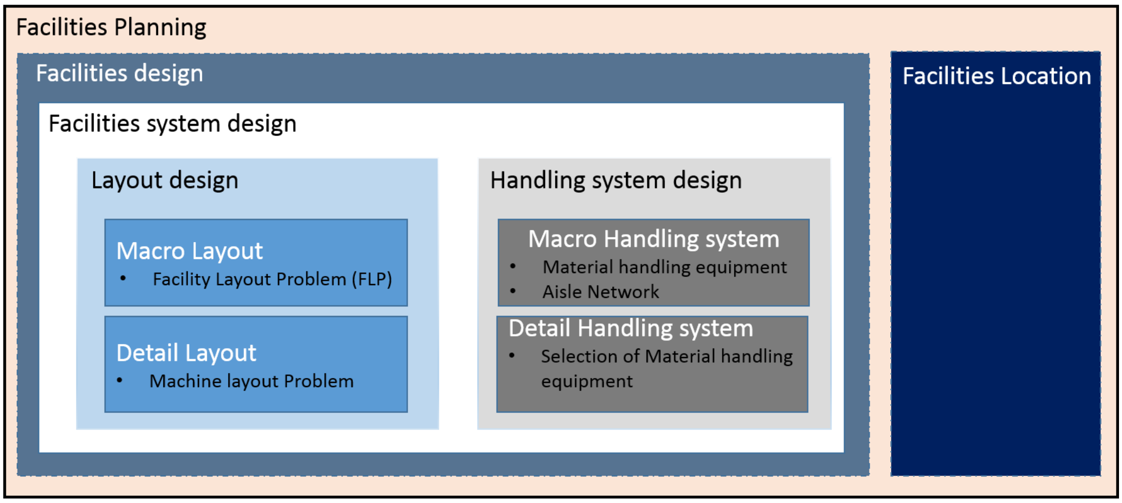

Figure 2. 2 - Facilities planning hierarchy (adapted from Marcoux et al. (2005)).

Table 2. 1 - Summary of surveys and literature reviews about *facility layout* problems.

Reference	Work title
(Kouki Amri et al., 2016)	Risk issues in facility layout design
(Delgoshaei et al., 2016)	Review of evolution of cellular manufacturing systems' approaches: material transferring models
(Cheng et al., 2015)	International manufacturing network: past, present and future
(Dongre & Mohite, 2015)	Significance of selection of material handling system design in industry: a review
(Fischer et al., 2015)	New exact approaches to row layout problems
(İşlİer & Yöntemler, 2015)	Cellular manufacturing systems: organization trends and innovative methods
(Juan et al., 2015)	A review of semi heuristics: extending metaheuristics to deal with stochastic combinatorial optimization problems
(Keller & Buscher, 2015)	Single row layout models
(Perera & Ratnayake, 2015)	Qualitative analysis on layout flexibility of machine layout configurations
(Rashid, 2015)	Research on nursing unit layouts: an integrative review
(Negahban & Smith, 2014)	Simulation for manufacturing system design and operation: Literature review and analysis
(Jain et al., 2013)	Facility planning and associated problems: a survey
(Saravanan & Kumar, 2013)	Different approaches for the loop layout problems: a review
(Hungerländer & Rendl, 2012)	A computational study and survey of methods for the single row facility layout problem
(Barsegar, 2011)	A survey of metaheuristics for facility layout problems
(Dutta & Sarthak, 2011)	Architectural space planning using evolutionary computing approaches: a review
(Kothari & Ghosh, 2012)	The single row facility layout problem: state of the art
(Moslemipour et al., 2011)	A review of intelligent approaches for designing dynamic and robust layouts in flexible manufacturing systems
(Arikaran et al., 2010)	Analysis of unequal areas facility layout problems
(Davoudpour et al., 2010)	Facility layout problems using bays: a survey
(Farahani et al., 2010)	Multiple criteria facility location problems: a survey
(Gu et al., 2010)	Research on warehouse design and performance evaluation: a comprehensive review
(Talbi, 2009)	Metaheuristics: from design to implementation
(Wang et al., 2009)	Assembly process planning and its future in collaborative manufacturing: a review
(Drira et al., 2007)	**Facility layout problems: a survey**
(Kulturel-Konak, 2007)	Approaches to uncertainty in FLP: perspectives at the beginning of the 21st century
(Koster et al., 2006)	Design and control of warehouse order picking: a literature review
(Loiola et al., 2007)	A survey for the quadratic assignment problem
(Pentico, 2007)	Assignment problems: a golden anniversary survey
(Singh & Sharma, 2006)	A review of different approaches to the facility layout problems
(Snyder, 2006)	Facility location under uncertainty: a review
(Snyder, 2006)	Loop based facility planning and material handling
(Liao, 2005)	Expert system methodologies and applications - a decade review from 1995 to 2004
(Marcoux et al., 2005)	Models and methods for facilities layout design from an applicability to real-world perspective
(Benjaafar et al., 2002)	Next generation factory layouts: research challenges and recent progress
(Shouman et al., 2001)	Facility layout problem and intelligent techniques: a survey
(Hassan, 2000)	Toward re-engineering models and algorithms of facility layout
(Liggett, 2000)	Automated facilities layout: past, present and future
(Bazargan-Lari,1999)	Layouts designs in cellular manufacturing
(Balakrishnan & Cheng, 1998)	Dynamic layout algorithms: a state-of-the-art survey
(Meller & Gau, 1996)	The FLP: recent and emerging trends and perspectives
(Hassan, 1995)	Layout design in group technology manufacturing
(Kusiak & Heragu ,1987)	The facility layout problem
(Wilson, 1995)	Facilities planning - the state of the art
(Grantz, 1950)	A proposal of criteria for the evaluation of industrial physical-plant utilization

Operations Research (OR) methods (such as mathematical modelling and optimization, statistical analysis, simulation, etc.) have been often used for addressing *facilities planning*, this including the location and design of facilities. *Facilities location,* dealing with searching a place to construct a factory, takes into account the relationship with the multiple stakeholders (customers, suppliers, legislation, environment, etc.), and is outside the scope of our research (as our focus is inside facilities, not in finding the best places for facilities). Our problems are, therefore, the design of the layout (finding the location of things) and the design of the handling system (defining how things will be moved). This design can be made at different levels – the macro level (considering departments) and the detailed level (considering machines).

The *macro layout*, commonly referred as *Facility Layout Problem (FLP,)* is the more explored area of facilities design, as Table 2.2 shows, with a summary of the main works from the literature (57 papers on department allocation and 26 papers on machine layouts). The FLP considers the layout as an arrangement of blocks (commonly departments), looking for the better location inside the facility, without considering a great detail inside those blocks. As presented along this chapter, a variety of characteristics has been considered in designing layouts, along with various combinations of objectives (e.g. costs, adjacency, profit, distances, etc.) Other works focus on testing and comparing distinct approaches, or hybridise some of those approaches (see e.g. Adrian et al. (2015) or Tuzkaya et al. (2013)), to solve large size, real problems.

The *detail layout*, commonly referred as *Machine Layout Problem (MLP),* looks inside the” block”, making the allocation of machines, corridors, etc. Marcoux et al. (2005). In fact, the majority of the published works considering machine layout problems, provide very complete models – e.g. some papers approach cell layouts, with a detailed allocation of machines to cells, location of cells, multi-floor, etc. (see e.g. Kia et al. (2013) or Sakhaii et al. (2016)). At this level, it is also common to design layouts considering rows (e.g. (Kia et al., 2014), (Ficko et al., 2004)), loop layouts (El-Baz, 2004) or other layout configurations, taking into account the characteristics of the production process or the machines, or the Material Handling Equipment (MHE).

Transportation of things plays an important role in *facilities design* and operations. The *handling systems* are essential in designing most production systems, since the efficient flow of materials between the activities is heavily dependent on their arrangement (location) – e.g. if two activities are adjacent to each other, then materials might be easily handed from one activity to another. But when departments / machines are at separated facilities, this cost will increase, as we need to use expensive industrial trucks, or overhead conveyors are required for transport, thus increasing cost and work in process (Hopp & Spearman, 2000).

Similar to layout design, there are papers on handling system design, with distinct levels – macro level (e.g. Kilic et al. (2012) determining the number of vehicles at an in-plant milk-run of a lean Material Handling System – MHS, without changes in the layout); and detailed level (e.g. Raman et al. (2009) defining the quantity of MHE required for effective handling of products among machines and facilities). Most of the published works consider materials are always available, and only take into account the distance travelled (e.g. Azadeh et al. (2016)). Other papers consider the transport costs, that can vary or not with time. Other way to take into account MHS has been by constraining transport capacity, such as in Shah et al (2015). These assumptions have some similarities with our work, but we take into account 2 different types of transport (inside facilities, and between facilities).

There are other works considering the design of layouts with MHS simultaneously, and with detailed information on the MHS and the MHE. Zhang et al. (2011) show the advantages of designing and re-designing both systems simultaneously, in congestion situations. Another example is the paper by Montreuil (1991) proposing several models to design layouts with the routing of the MHS, viewed as flow networks. In fact, this type of problems has not been so much explored, and we believe that could be quite interesting to consider in multi-facility layout problems.

The global process of facility layout design, to apply OR methodologies, can be viewed as a sequence of three phases: first we need to define and clarify the main characteristics of the problem - *problem characterization;* then we have to mathematically *formulate* the problem to solve; and finally, we select and apply one or more *resolution approaches.* All these phases will be now analysed in detail.

Table 2. 2 - Summary of the literature on the *facility layout* problem.

Reference	Problem Characteristics																																		Layout Formulations																																				Resulution approaches																Tests (data)		
	Type of Problem						Manufacturing process type					Evolution		Layout configurations								Material handling system					Layout strategies					Risk		Formulation								Objectives																Constrains											Exact methods		Heuristics							Other approaches									
																																						Representation				Minimize											Maximize																																	
	Machine Allocation Problem	Department allocation	Product flow	Routing Problem	Location Problem	Material handling system	Product layout	Functional layout	Cellular layout	Fractal Layout	Distributed layout	Static layout	Dynamic Layout	Unequal areas	Equal area	Multi-floor	Open field	Multi-row	Single-row	Loop layout	Fixed shape	Robot	Elevator	Train	forklift	AGV	Reconfigurable	Agile	Flexible	Robust	Distributed	Uncertainty	Safety	Quadratic Assignment Problem	Mixed Integer Programming	Multi-criteria decision-making	Fuzzy logic	Multi-atribute decision-making	Discrete	Continuos - Flexible bay	Continuos - Slicing tree	Total Costs	Transport Cost	Transport Time	Distance traveled	Backtraking	Trafic conjection	MHC	Flow	Reconfiguration costs	WIP	Distance / space	Max satisfaction	Max Profit	Efficiency	Adjacency / closeness	Distance request	Volume	Non Overlap	Area	Positioning	Budget	Orientation	Proximity	Capacity	Demand	Security	Drop-off/on points	Dynamic programming	Branch and Bound	Simulated Anneling	Genetic algorithms	Tabu search	Particule Swarm Optimizations	Ant colony optimization	Pairwise excenge heuristic	Others	Simulation	Artificial Immune System	Qualitative evaluation / Indices	Others	**Design Layout approachs (Quantitat**	**Evaluate / select Layout approach**	**From Literature**	**Simulated data**	**Case study**
Amri et al. 2016							✓	✓	✓				✓				✓	✓	✓	✓							✓					✓	✓				✓																							✓	✓	✓		✓																						
Hammad et al. 2016		✓				✓						✓																					✓		✓													✓								✓			✓		✓		✓	✓			✓	✓		✓												✓				✓
Jung, 2016		✓										✓																				✓	✓		✓							✓																	✓		✓		✓	✓			✓	✓													✓	✓				✓
Sakhaii et al. 2016	✓		✓	✓					✓				✓		✓												✓			✓				✓					✓			✓	✓					✓		✓									✓	✓	✓		✓		✓					✓												✓			✓	
Adrian et al. 2015		✓										✓		✓																									✓									✓																								✓			✓	✓							✓	✓	✓	
Azadeh et al. 2015	✓											✓																	✓			✓					✓			✓					✓											✓																						✓			✓	✓			✓	
Bonenberg, 2015								✓				✓																					✓																				✓		✓	✓			✓	✓	✓			✓			✓														✓	✓				✓
Caputo et al. 2015							✓					✓																					✓		✓							✓																✓		✓	✓			✓	✓		✓					✓										✓				✓
Derakhshan et al. 2015		✓										✓			✓						✓														✓					✓								✓											✓		✓		✓									✓		✓							✓	✓		✓		
Fischer et al. 2015		✓				✓						✓		✓	✓			✓								✓									✓																								✓		✓		✓							✓												✓		✓		
Kulturel-Konak and Konak, 2015		✓										✓	✓	✓	✓																				✓					✓								✓											✓		✓		✓							✓	✓											✓		✓		
Mallikarjuna et al. 2015	✓					✓								✓						✓						✓			✓				✓										✓	✓															✓		✓		✓		✓	✓						✓										✓		✓		
Martinez-Gomez et al. 2015		✓											✓	✓													✓															✓						✓											✓	✓	✓		✓	✓				✓		✓												✓				✓
Neghabi and Tari, 2015		✓										✓		✓		✓																			✓																					✓	✓		✓		✓			✓						✓												✓		✓		
Perera and Ratnayake, 2015		✓										✓																														✓	✓	✓								✓				✓		✓	✓	✓	✓		✓	✓	✓	✓																✓			✓	
Shah et al. 2015	✓			✓		✓							✓	✓													✓												✓			✓	✓					✓		✓															✓	✓						✓						✓				✓			✓	
Uluntas and Islier, 2015	✓											✓	✓		✓												✓		✓										✓			✓						✓		✓									✓		✓				✓														✓			✓				✓
Xu and Song, 2015		✓											✓																			✓					✓			✓		✓			✓					✓									✓	✓	✓													✓								✓				✓
Blanco-Fernandez et al. 2014									✓				✓														✓																		✓			✓								✓				✓	✓			✓																	✓	✓				✓
Bozorgi et al. 2014		✓											✓	✓													✓							✓					✓									✓		✓					✓	✓	✓		✓		✓			✓									✓									✓		✓		
Kia et al. 2014	✓								✓				✓		✓	✓		✓	✓				✓				✓		✓					✓	✓				✓			✓						✓		✓									✓		✓		✓		✓	✓				✓	✓											✓		✓	✓	
Abedzadeh et al. 2013		✓											✓		✓												✓								✓		✓			✓								✓		✓						✓			✓	✓	✓		✓														✓					✓		✓		
Arnolds and Nickel, 2013		✓										✓	✓	✓				✓									✓					✓	✓		✓					✓		✓						✓		✓									✓		✓									✓												✓			✓	
Azevedo et al. 2013		✓						✓					✓	✓													✓		✓						✓					✓								✓		✓									✓	✓				✓						✓												✓				✓
Drira et al. 2013	✓												✓		✓												✓			✓							✓		✓									✓		✓									✓		✓																				✓	✓		✓		
Emami and Nookabadi, 2013		✓											✓														✓											✓										✓		✓						✓			✓		✓			✓							✓	✓										✓		✓		
Gargia-Hernandez et al. 2013		✓										✓		✓																							✓			✓																																✓										✓		✓		
Jiang and Nee, 2013		✓										✓		✓																																		✓	✓			✓							✓	✓	✓		✓	✓								✓										✓				✓
Khaksar-Haghani et al. 2013	✓					✓			✓			✓		✓		✓							✓												✓							✓																	✓		✓		✓							✓												✓			✓	
Mazinani et al. 2013		✓											✓	✓																					✓					✓								✓											✓		✓		✓							✓		✓									✓	✓		✓		
Muritiba et al. 2013		✓										✓						✓																																			✓						✓		✓		✓																		✓	✓				✓
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Baykasoglu et al., 2010	✓					✓		✓				✓																			✓									✓					✓																												✓					✓				✓			✓	
Mckendall and Hakobyan, 2010		✓											✓	✓													✓								✓					✓		✓						✓		✓									✓		✓		✓										✓				✓					✓		✓		
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Chen and Rogers, 2009		✓											✓														✓																					✓		✓						✓			✓	✓	✓			✓											✓							✓		✓		
Dong et al. 2009	✓												✓	✓													✓														✓	✓																	✓		✓										✓						✓					✓				✓
Jaafari et al. 2009		✓										✓		✓																					✓					✓								✓								✓			✓		✓		✓	✓				✓		✓												✓		✓		
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Neumann, 2009		✓										✓																	✓													✓		✓	✓	✓	✓	✓		✓	✓			✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓												✓			✓			✓
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2.2.1 Problem characteristics

As referred before, the facility layout problem consists on the allocation of things to places, that can be done in different ways and taking into account diverse situations combined with several needs to be accomplished. In the literature, we can find researches covering numerous types of problems, like machine or department allocation, routing for material handling distribution or product collection, among others. We group the main characteristics used at Facility layout literature into 7 groups presented at (Table 2.3).

One of the first characteristics to take into account at the moment of designing a layout is the **manufacturing process type**, as it will define the general pattern of the work flow, constraining the way in which departments or machines should be arranged in a facility. There are four traditional types of configurations (process layout, product layout, fixed-position, and group technology). Recently, some new process manufacturing configurations or combinations have been considered, such as the fractal layout, distributed layouts, and hybrid layouts (see Table 2.3).

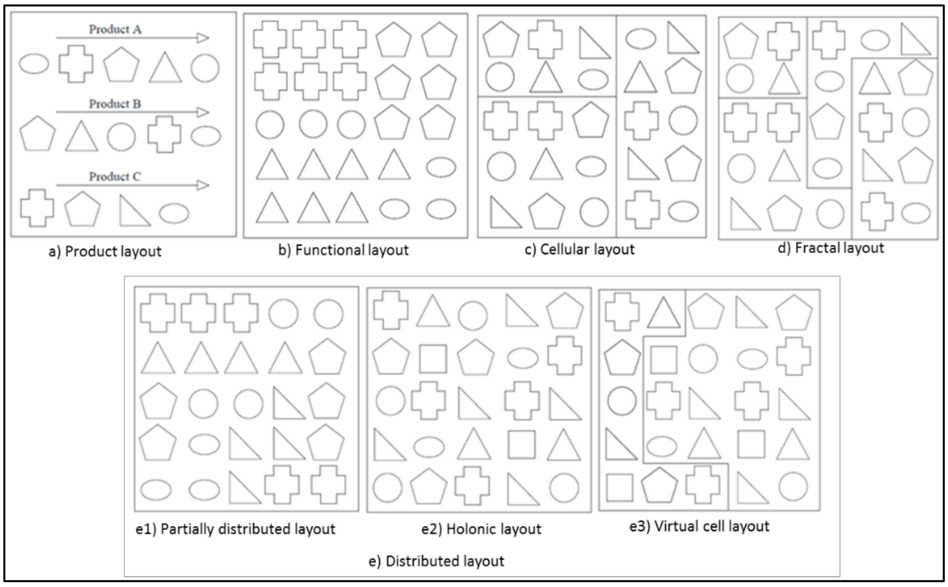

Figure 2. 3 - Manufacturing process layout types (Benjaafar et al., 2002).

In a *process layout*, also called *functional layout* or *job-shop*, similar equipment or functions are grouped together. A part being processed in such an environment then travels according to the established sequence of operations, from area to area, where the proper machines are located for each operation (Chase et al., 2005).

Table 2. 3 - Characteristics of the *facility layout problem*, as found in the literature.

Characteristics		This work	References
Manufacturing process type	Product layout	x	(Hasan et al., 2012), (Wang, 2011), (Wang et al., 2009)
	Functional layout	x	(Hasan et al., 2012), (Bonenberg, 2015)
	Cellular layout		(Delgoshaei et al., 2016), (İşlİer & Yöntemler, 2015)
	Fractal layout		(Perera & Ratnayake, 2015), (Venkatadri et al., 1997)
	Distributed layout	x	(Lahmar & Benjaafar, 2005a), (Benjaafar et al., 2002)
	Holonic layout		(Perera & Ratnayake, 2015), (Lahmar & Benjaafar, 2005)
	Virtual cell layout		(Xambre & Vilarinho, 2007), (Perera & Ratnayake, 2015)
Type of problem	Department allocation	x	(Aiello et al., 2006), (Nageshwaraniyer et al., 2013)
	Machine allocation	x	(Taghavi & Murat, 2011), (Kia et al., 2014)
	Product flow	x	(El-Baz, 2004), (Baykasoğlu & Göçken, 2010)
	Routing		(Koşucuoğlu & Bilge, 2012), (Wang, 2011)
	Material handling design	x	(Shah et al., 2015), (Asef-Vaziri & Laporte, 2005)
Layout configuration	Unequal area	x	(Kulturel-Konak & Konak, 2011), (Arikaran et al., 2010)
	Equal area		(Sakhaii et al., 2016), (Krishnan et al., 2012)
	Multi-floor		(Neghabi & Ghassemi Tari, 2015), (Kia et al., 2014)
	Open field		(Jung, 2016), (Xu & Song, 2015),
	Multi-rows	x	(Geldermann & Schöbel, 2011), (Ficko et al., 2004)
	Single-row		(Keller & Buscher, 2015), (Geldermann & Schöbel, 2011)
	Loop layout		(Saravanan & Kumar, 2013), (Mallikarjuna et al., 2016)
Material handling system	Elevator		(Neghabi & Ghassemi Tari, 2015), (Lee et al., 2005)
	AGVs	x	(Krishnan et al., 2012), (Wang, 2011), (Wang & Chang, 2015)
	Train	x	(Kilic et al., 2012)
	Robot		(Wang, 2011)
Layout evolution	Static		(Kulturel-Konak & Konak, 2011), (Krishnan et al., 2012)
	Dynamic	x	(Rosenblatt, 1986), (Moslemipour et al., 2011)
	Cyclic		(Kulturel-Konak & Konak, 2015)
Layout strategies	Reconfigurable	x	(Kia et al., 2012), (Meng et al., 2004), (Drira et al., 2013)
	Agile	x	(Hasan et al., 2012), (Raman, Nagalingam & Lin, 2009)
	Flexible	x	(Moslemipour et al., 2011), (Benjaafar & Sheikhzadeh, 2000)
	Robust		(Moslemipour et al., 2011), (Drira et al., 2013)
	Distributed		(Lahmar & Benjaafar, 2005)
Risk	Uncertainty		(Kulturel-Konak, 2007), (Krishnan et al., 2009)
	Safety		(Hammad et al., 2016), (Martinez-Gomez et al., 2015)

In a *product layout*, or *flow shop*, machines and work processes are arranged according to the progressive steps by which the product is made. Equipment or departments are dedicated to a particular product line, duplicate equipment is employed to avoid backtracking, and a straight-line flow of material movement is achievable. Assembly lines are a special case of this type of layout (Chase et al., 2005).

A *Group Technology Layout*, or *cellular layout*, allocates different machines to cells that work on products with similar shapes and processing requirements. This type of layout has been intensively researched, mainly due to their complexity, related to the design of cells, the location of machines inside the cells, the location of cells inside facilities, and different types of flows (inside the cells and between cells) – see e.g. Khaksar-Haghani et al. (2013), who consider the allocation of cells to different floors, or Delgoshaei et al. (2016) and İşlİer and Yöntemler (2015) for some recent reviews about these problems.

Fractal layouts are generated by grouping multiple different machines into fractal cells, each one capable of producing almost every product type manufactured in the company. One advantage of these layouts is their volume flexibility and routing flexibility, due to the presence of more or less identical cells (Perera & Ratnayake, 2015).

In *distributed layouts,* machines or departments are duplicated and strategically distributed throughout the plant floor, providing increased material handling flexibility, under fluctuations in product mix and product volume. According to Benjaafar et al. (2002) and Lahmar and Benjaafar (2005), these layouts are highly desirable for frequent demand fluctuations, and can effectively be kept fixed for multiple demand scenarios. There are two particular distributed layout types: the *holonic layouts,* also called *maximally distributed layouts*, where identical machines are distributed through the facilities, with especially application in labour-intensive industries (Perera & Ratnayake, 2015); and *virtual cells*, that are a logical grouping of resources dedicated to produce a particular part family (the resource grouping is not physically reflected in the system, therefore facilitating the rearrangement of resources when needed) (Xambre & Vilarinho, 2007).

In fact, companies usually combine several of these types of layouts, according to their specific needs, in order to be more effective and efficient. For this purpose, the new generation of layouts (fractal and distributed) can be very interesting, especially in terms of flexibility (Perera & Ratnayake, 2015). This is in fact one of the main goals of this work: to make operations more agile, with quick and flexible reconfigurations of layouts, involving a group of facilities.

Facility layout problems are related to different **types of problems**, such as the allocation of departments inside facilities (Aiello et al., 2006), or machines inside departments (Taghavi & Murat, 2011). Our work focuses on the allocation of departments inside facilities, and the allocation of machines inside departments and facilities, and defining a set of *product flows*, by identifying the facilities and machines that will produce each "project".

In terms of **layout configuration**, this will in general strongly depend on the characteristics of products or handling systems. The *row layout problem* (recently reviewed by several authors such as Keller and Buscher (2015), Hungerländer and Rendl (2012) or Geldermann and Schöbel (2011)) is becoming more and more relevant, mainly due to the growing use of automated guided vehicles or trains to transport materials, this leading to the design of rectangular layouts, with rows. In order to increase the *flexibility* of facilities, several papers consider layouts with *distinct areas* of the departments or the machines to be allocated, that change along time. The work by Derakhshan Asl et al. (2016) is a recent example, that is similar to our research work.

The *multi-floor layout problem* is a particular case of the FLP, allocating resources to different floors of a single building, with horizontal and vertical material flows (Neghabi & Ghassemi Tari, 2015). These vertical flows impose strong constraints, that are associated to the existence of a single place to enter and exit the floor (generally through elevators). It should be noted that in the multi-floor problem, the most commonly considered objectives are the minimization of total costs, including the cost of installing elevators or implementing layout reconfigurations, and the maximization of equipment adjacency and safety factors. This problem has some similarities with the problem considered in this work. The *multi-facility layout problem* assigns resources to different buildings / facilities, involving internal and external flows. External flows (between facilities) are quite costly since they are not continuous flows, and usually require the use of heavy vehicles (trucks).

The **material handling system** can directly bound the efficiency of a layout, the type of transport being therefore of vital importance – due to its high importance, this factor will be addressed in greater detail later in this work.

Other important characteristic of layout problems is the **layout evolution**. The first studies in the area consider layouts as static configurations, mainly due to the characteristics of few products, with long life cycles. With a strong evolution for product differentiation, characterized by short lifetimes, the need for reconfigurations led to the need of research about new types of layouts, that can change, from time to time. To cover these issues, Rosenblatt (1986) developed the idea of *Dynamic Facility Layout Problem (DFLP),* extending the *Static Facility Layout Problem (SFLP),* by assuming that the material handling flows can change over time. This might require layout rearrangements in one or more periods (Balakrishnan & Cheng, 1998). The DFLP has been a continuous research area, with the application of several combinations of approaches. This is a main issue considered in our research work, that will be later discussed in more detail. Recently, Kulturel-Konak and Konak (2015) presented the *Cyclic Facility Layout Problem (CFLP)*, a special case of dynamic layout problem, considering the seasonal nature of products.

In another research direction, several **layout design strategies** have been proposed in order to improve the performance of job shops, working under volatile manufacturing environments (Baykasoğlu & Göçken, 2010) and that can directly influence the FLP design. Some of those interesting strategies will be described later, with more detail.

Moreover, different types of **risks and other phenomena** can significantly influence the design and operation of layouts, as it is the case of *uncertainty* or *safety* issues. The recent work of Amri et al. (2016) discusses the importance of *risk management* and control, during the design of production systems and of facility layouts – risks can be associated to the supply chain, production resources, quality, environmental and occupational health, or safety. The work by Caputo et al. (2015) considers a cost penalization when safe distances are not respected, during material transfer processes, as a way to reduce accidents, thus controlling *safety risks*. In our work we will take into consideration some safety issues, through the adjacency of departments, that in some cases, will force some types of departments or machines to stay away from each other.

Uncertainty is another type of risk commonly considered in this area. Production variety is commonly referred, as a way to account this type of uncertainty. The design of robust layouts is another way to deal with uncertainty. Creating multiple scenarios to evaluate different hypotheses or including *uncertainty* in a stochastic approach (with stochastic variables or data) have also been applied. Krishnan et al. (2009) developed an approach to deal with uncertainty of each product demand, in the design of a facility layout. Still on uncertainty, Snyder (2006) presents a rather comprehensive literature review.

To summarise, we might say that, depending on the adopted objectives and methods, we can combine several of these characteristics, to solve diverse types of FLP. Papers that considered these different characteristics are presented in Table 2.3 and in Table 2.2, with more detail. Some surveys in the literature review these characteristics, although the majority focus more on the problem formulation and on the adopted approaches (see some examples in Table 2.1). Benjaafar et al. (2002) and Drira et al. (2007) presented most of those important problem characteristics in their surveys.

2.2.2 Problem formulation

There are, in the literature, a large combination of formulations, used to mathematically represent the problems. These models use input parameters and variables to be quantified, and require the definition of one (or more) objective function(s) and constraints (Marcoux et al., 2005). Some of the most applied types of FLP formulations are presented in Table 2.4.

The main **formulations** used in the FLP are associated with the *Quadratic Assignment Problem (QAP)* and general *Mixed Integer Programming (MIP)*. The QAP is a combinatorial optimization model that assigns a number of activities (e.g. facilities, departments, machines) to the same number of locations (on the QAP see e.g. the survey by Loiola et al. (2007)).

The general *Mixed Integer Programming* models use linear objective functions with integer and non-integer decision variables, and linear equality and inequality constrains (see e.g. Moslemipour et al. (2011) and Drira et al. (2007)).

Table 2. 4 - Example of formulation of FLP in the literature.

Formulation		**This work**	**References**
Formulation	Quadratic assignment	x	(Loiola et al., 2007), (Balakrishnan, C.H. Cheng, et al., 2003)
	Mixed integer programming	x	(McKendall & Hakobyan, 2010), (Commander, 2005)
	Multi-criteria decision making		(Farahani et al., 2010), (Rao & Singh, 2012), (Zhou et al., 2011)
	Fuzzy logic		(Abedzadeh et al., 2013), (Azadeh et al., 2016)
	Multi-objective	x	(Kulturel-Konak, 2007), (Marler & Arora, 2004), (Zhou et al., 2011)
	Representation		
	Discrete	x	(Şahin et al., 2010), (Balakrishnan, C.H. Cheng, et al., 2003)
	Continuous – Flexible bay	x	(Davoudpour et al., 2010), (Chang & Lin, 2012)
	Continuous – Slicing tree		(Hernández, 2011), (Aiello et al., 2012), (Chang & Lin, 2012)
Objectives	**Minimization**		
	Transport time		(Saifallah Benjaafar & Sheikhzadeh, 2000), (Zhao & Tseng, 2007)
	Distance travel		(Koşucuoğlu & Bilge, 2012), (Azadeh et al., 2016)
	Traffic congestion		(Han et al., 2012), (Azadeh et al., 2016), (Zhang et al., 2011)
	Work in process		(Raman, 2011), (Hasan et al., 2012), (Xambre & Vilarinho, 2007)
	Material handling costs	x	(Bozorgi, Abedzadeh, & Zeinali, 2014), (Ulutas & Islier, 2015)
	Transport cost	x	(Chen & Rogers, 2009), (Gogi et al., 2014), (Hasan et al., 2012)
	Distance / space cost		(Koşucuoğlu & Bilge, 2012), (Krishnan et al., 2012)
	Reconfiguration cost	x	(Mazinani et al., 2013), (Sakhaii et al., 2016), (Kia et al., 2014)
	Maximization		
	Profit		(Şahin et al., 2010)
	Satisfaction		(Aiello et al., 2012), (Bonenberg, 2015), (Ho & Perng, 2006)
	Efficiency		(Bozorgi et al., 2014), (Neumann & Fogliatto, 2009)
	Adjacency/ closeness	x	(Chen & Rogers, 2009), (Emami & S. Nookabadi, 2013)
	Distance request		(Krishnan et al., 2012), (Bozorgi et al., 2014)
	Multi-objective	x	(Andersson, 2000), (Marler & Arora, 2004), (Zhou et al., 2011)
Constraints	Non-overlap	x	(Emami & S. Nookabadi, 2013), (Ulutas & Islier, 2015)
	Area	x	(Kulturel-Konak & Konak, 2011), (Arikaran et al., 2010)
	Volume	x	(Han et al., 2012), (Perera & Ratnayake, 2015), (Caputo et al. ,2015)
	Positioning	x	(Taghavi & Murat, 2011), (Kulturel-Konak & Konak, 2015)
	Budget		(Baykasoglu et al., 2006), (Şahin et al., 2010), (Amri et al., 2016)
	Orientation	x	(Abedzadeh et al., 2013), (Ficko et al., 2004), (Krishnan et al., 2012)
	Drop-off/on points		(Jaafari et al., 2009), (Hammad et al., 2016), (Krishnan et al., 2012)
	Security		(Vazquez-roman & Mannan, 2011), (Jung, 2016), (Bonenberg, 2015)
	Demand	x	(Shah et al., 2015), (Mallikarjuna et al., 2016), (Kia et al., 2012)
	Capacity	x	(Shah et al. ,2015), (Ulutas & Islier, 2015), (Zhang et al., 2009)

The FLP can be modelled using various **representations of the physical space of facilities**, that can be grouped into two main categories: the *continuous* or the *discrete representation*. In a *discrete representation* (see Figure 2. 4), the plant site is divided into rectangular blocks with the same area and shape, and each block is assigned to a facility (Drira et al., 2007).

1	1	2
1	1	2
3	3	4

Figure 2. 4 - Discrete representation of facility layout problem.

On the other hand, in a *continuous representation* (see Figure 2.5) facilities are located either by their centroid coordinates (x_i, y_i) in the plant, with half-length l_i, and half width w_i, or by the coordinates of bottom-left corner, length L_i and width W_i of the facility. This type of representation is frequently used with *Mixed Integer Programming* formulations.

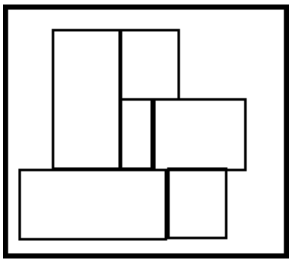

Figure 2. 5 - Continual representation of facility layout problem.

The generation of layouts requires defining one or several *objectives*, that can either be translated in terms of an objective function or in terms of layout evaluation criteria. The *minimization of costs* has been the most used **objective** in the models developed for the FLP (e.g., Bozorgi et al. (2014) *minimize material handling* and *reconfiguration costs*). Several extensions of these models have been proposed, such as the *minimization of distance travelled* (Koşucuoğlu & Bilge, 2012) or *time spend in travelling* (Benjaafar & Sheikhzadeh, 2000).

In terms of *maximization*, the most common objective functions are: *adjacency* (Chen & Rogers, 2009), *distance requested* (Krishnan et al., 2012) and *profit* (Şahin et al., 2010). Almost all the recent published works combine several objectives in *multi-*

objective approaches, thus trying to be more realistic (Drira et al., 2007). More recently, Emami and S. Nookabadi (2013) consider a multi-objective model, with the minimization of material handling costs and re-layout costs considered separately, plus an *adjacency* measure.

In a similar way, here we propose a multi-objective model to minimize MHC and the re-layout cost, and to maximize the adjacency between departments. Additionally, we consider a new objective function, designated here as the *unsuitability* between departments and locations, to measure the fitness between the characteristics of the existing locations and the requirements of the departments, that will be described in more detail, later in this work.

A careful definition of **constraints** is essential to find more accurate and realistic solutions. In layout problems, the most used constraints are naturally the *non overlapping* of departments or machines and guaranteeing all "objects" are placed somewhere. Some works consider *area constraints* on the plant site, especially with continuous representations, and unequal departments or machines. Good examples are Kulturel-Konak and Konak (2011), requiring the total area available to be larger or equal to the sum of all the facility area; or Arikaran et al. (2010), presenting an analysis of unequal area FLP.

There are few studies considering *budget constraint*s – Şahin et al. (2010) is an example, with budget values changing from period to period, to be considered in layout design or reconfiguration; Baykasoglu et al. (2006) is another example. *Security requirements* are another type of constraints that have not been very explored – this is a promising area, due to the growing concerns with safety certification and legal standards. Vazquez-roman and Mannan (2011) have considered constraints related with *security* in a facility, for a process unit that may release toxic gases, and more recently (Aven 2016) presented a review about risk assessment and management, in this area.

It is also important to note that research on the FLP is often concerned with specific industry or service areas, where special problem features directly constrain the design of layouts. For example, the design of hospitals (Arnolds & Nickel, 2013) or nursing units (Rashid, 2015), construction site layouts (Hammad et al., 2016), chemical industry (taking into account specific safety constraints, such as noise or pollution (Jung, 2016), or the process needs of an ethylene oxide process (Martinez-Gomez et al., 2015)).

Some papers deal with temporary layouts such as those of fairs (Fernandes Muritiba et al., 2013) or those of infrastructures to support construction works, as it is the case of a hydropower station (Xu & Song, 2015). Ulutas and Islier (2015) design the layout of a footwear manufacturing company, and Hasan et al. (2012) propose a decision tool for evaluating production flow layouts and enhancing agile manufacturing.

However, the great majority of papers propose and test new models and approaches on a limited number of previously published cases. But the need for more real case studies is referred by several authors (see for example the survey by Drira et al. (2007)). Our work is in fact inspired and validated in a real case of a first-tier supplier of the automotive industry, with all the most relevant features of complex products and *just-in-time* response.

Finally, in what concerns capacity constraints, typically only machine capacities are considered (see e.g. Taghavi and Murat (2011)). Some few works deal with the capacity constraint of the MHE (Shah et al., 2015), this being an important aspect to take into account for the MFLP, specially for the transport activities between companies. In our work we explicitly consider these constraints (for the transport capacities at each period), inside and between facilities.

2.2.3 Resolution approaches

There are several approaches to solve the FLP, according to the type of problem representation and adopted formulation. These approaches aim either at finding good, satisfactory solutions, or at searching for a global or local optimum, considering one or several performance objectives (Drira et al., 2007). One important aspect that should be taken into account at the moment of choosing the approach to apply, is the problem complexity. Layout problems are combinatorial and in general intrinsically hard – being *NP-hard problems*, they require an exponentially growing computational time to be solved to optimality (Talbi, 2009) – see Figure 2.6. In practical terms, this means that the success of the adopted approach will strongly depend on the number of departments or machines to allocate or reallocate, the variety of products implying more process routes or even the dynamics of the problems (with more periods of time to test).

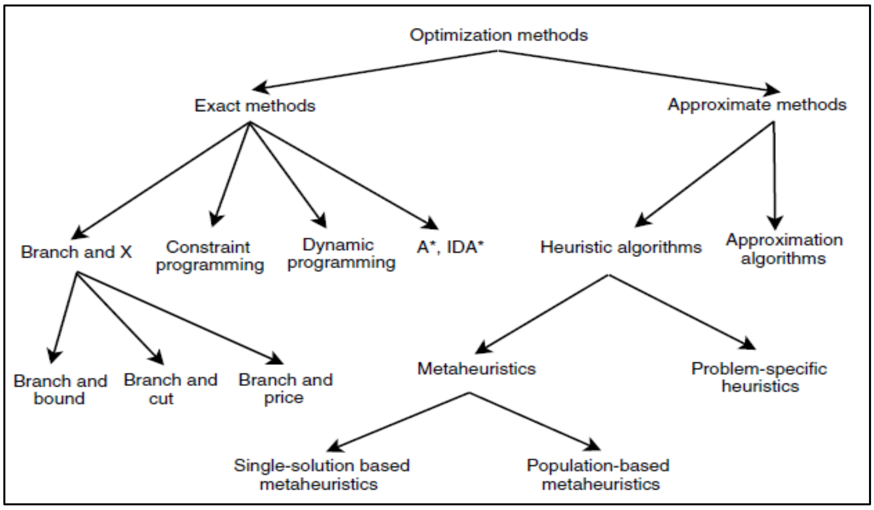

Figure 2. 6 - Classical optimization methods (Talbi, 2009).

Depending on the type of data and problem dimension, different approaches have been applied to solve the FLP – Table 2.5 lists the main approaches used in practice.

Table 2. 5 - Main approaches for FLP.

Type	Approach	References
Exact methods	Dynamic Programming	(Rosenblatt, 1986), (Mazinani et al., 2013), (Dunker et al., 2005)
	Branch-and-Bound	(Solimanpur & Jafari, 2008), (Lacksonen, 1997)
Heuristics	Simulated annealing	(Tuzkaya et al., 2013), (Kulturel-Konak & Konak, 2015)
	Genetic algorithm	(Hernández, 2011), (Negahban & Smith, 2014), (Tuzkaya et al., 2013)
	Ant colony optimization	(Mohan & Baskaran, 2012), (Chen & Rogers, 2009)
	Particle swarm optimization	(Derakhshan Asl et al., 2016), (Adrian et al., 2015)
	Pairwise exchange	(Balakrishnan et al. 2003), (Bozorgi et al., 2014)
	Tabu search	(Bozorgi et al., 2014), (Kulturel-Konak et al., 2004)
	Others	(Tuzkaya et al., 2013), (Krishnan et al., 2012), (Abedzadeh et al., 2013)
Other approaches	Simulation	(Negahban & Smith, 2014), (Baykasoğlu & Göçken, 2010)
	Artificial immune systems	(Ulutas & Kulturel-Konak, 2011), (Kulturel-Konak & Konak, 2011)
	Qualitative evaluation	(Raman et al., 2007), (Lin & Sharp, 1999), (Hasan et al., 2012)
	Others	(Jung, 2016), (Azadeh et al., 2016), (Drira et al., 2013)

Exact methods try to find optimal solutions, and are normally used in small, less complex problem instances. *Branch-and-Bound* is the natural approach in this class of methods – Solimanpur and Jafari (2008) proposed a *branch-and-bound* approach to solve a linear mixed integer model, and Lacksonen (1997) applied a revised *branch-and-bound* technique to solve a realistic size dynamic layout problem, with unequal department areas. Due to its intrinsic complexity, the FLP, is usually approached by **heuristics** or, more generally, by metaheuristics (Talbi, 2009) – see, e.g., Juan et al. (2015), Moslemipour et al. (2011) or Barsegar (2011).

To complement the use of heuristics or exact methods, **other methods** are usually applied in the evaluation or the design of layouts, such as *simulation* or the *definition of indices* to evaluate and select different layouts according to some given criteria. *Simulation* is more and more used to solve this kind of problems, allowing an explicit treatment of uncertainty – see Negahban and Smith (2014) with a literature review on the use of *simulation* in manufacturing systems design, and strong arguments to use discrete event simulation in the FLP.

Finally, a brief reference should be made to the more and more sophisticated optimization software’s, such as CPLEX, GUROBI, MATLAB, GAMS, or LINGO. In our work we have used CPLEX, currently viewed as probably one of the most advanced optimization software, integrating quite sophisticated features for dealing with complex integer, non-linear models. The CPLEX solver is an analytical decision support toolkit for rapid development and deployment of optimization models, using mathematical and constraint programming engines for automatically solving problems (Subhaa & Jawahar, 2013). Solving linear, mixed integer or quadratic problems, CPLEX has been applied in many problems and sectors. Sakhaii et al. (2016) is a recent example, applying CPLEX to solve small and medium dynamic cellular manufacturing problems, with dynamic cell formation, inter-cell layouts, machine reliability, operator assignment, alternative process routings and production planning concepts. Fischer et al. (2015) applied CPLEX to solve row layout problems. Other applications of CPLEX in the FLP can be found, e.g., in Kulturel-Konak and Konak (2015), Koşucuoğlu and Bilge (2012), or Taghavi and Murat (2011).

2.3 Layouts Reconfiguration

Currently, manufacturing companies require, more and more, a prompt change or adjustment of the facilities, as a way to respond to new customer needs and upcoming market demands. They are continually striving to use such resources or facilities, that not only produce their products with high productivity and lower costs, but also provide them with some degree of flexibility to cope with stochastic changes in market and in customers. In order to survive in this new manufacturing environment, companies need tools to react to changes rapidly and cost effectively. Reconfigurable Manufacturing Systems (RMS) are responsive systems whose production capacity is adjustable to market fluctuations and whose functionality is adaptable to a variety of new products (Hasan et al., 2014). The reconfiguration of layouts is therefore a constant need to face production adjustments and to deal with several types of problems, such as:

- performing some local layout optimizations, due to changes in the production process or in the production methods;
- increasing or reducing activities (departments or machines), that can imply finding additional space and guarantee the integration with existing spaces and flows;
- moving or exchanging the positions of departments, of different types and dimensions.

Most of the literature about the *reconfiguration of layouts* focus on layout optimization due to changes in process or production methods. Normally these problems consider that the total area of a facility is fixed, and change the location of these activities, with equal or unequal areas. In this line, McKendall and Hakobyan (2010) propose a heuristic to solve the layout problem in a dynamic way, with changes from period to period, and Xiaoting and Li (2011) present a model focusing on manufacturing cell formation and resources layout problems. Another example is the model by Guan et al. (2012), for layout design and reconfiguration of workstations, using AGV material handling systems. Recently the work of Ulutas and Islier (2015) consider the reconfiguration of layouts, with the relocation of machines with fixed dimensions and fixed number of machines. In reality, sometimes it can be necessary to add machines or departments, being different to find a location for those machines and to reconfigure the flows. This can imply changing the location of other machines (Zhang et al., 2009). The work of Dong et al. (2009) is another example of a dynamic layout with reconfigurations (adding and replacing machines), taking as an input the list of machines to be changed at each period, according to the changes in product demand. This is also a characteristic of our work – giving the decision-maker the possibility of adding and dropping departments and facilities.

All reconfigurations imply costs (re-layout costs) along with specific difficulties. Companies must operate within a given budget, and therefore a realistic problem must take budget limitations into consideration (Şahin et al., 2010).

The expansion or reduction of facilities is also a common need for companies. Monteraill (1991) study some scenarios of layouts changes, at different cycle time phases of manufacturing systems, and exploring the expansion and reduction of layouts. Nonetheless, these and other few works deal only with a single facility, and the reconfiguration of layouts considering multiple facilities is a quite unexplored field. So we propose a model with this flexibility of expanding the dimensions of the facilities, and also to increase or reduce the number of facilities at each period.

As referred before, there are several characteristics behind the reconfiguration of layouts, that are important to take into account, especially when considering multiple facilities, such as: the *dynamics* of systems and the *flexibility* to change and to adjust quickly to new realities; when we are considering a group of companies, *collaboration* can be an important aspect to take into account, especially in layout reconfigurations, with a possibility to exchange and share activities (e.g departments, machines, products, etc); *material handling* is another important aspect, mainly due to the transport activities between facilities; the *evaluation* of the impact of each configuration for each company and for the global network of companies has a great importance in multi-facility layout problems. These aspects will be discussed in the following sections.

2.3.1 Dynamics

Manufacturing facilities are dynamic systems, continuously evolving to ensure optimal performance, and layouts should also evolve based on the system changes, that may occur over time (McKendall & Liu, 2012). So the concept of *dynamic layouts* involve the design of an optimal layout for each period of a multiple period planning horizon (Meng et al., 2004). On the other hand, it is interesting to clarify that *robust layouts* are designed to be better over the entire planning horizon (Moslemipour et al., 2011). The dynamic approach has therefore the advantage of providing an “optimal” layout for each period, within facility rearrangement cost that may be quite high.

The first rigorous development of the *dynamic facility layout problem (DFLP)* was provided by Rosenblatt, (1986), who developed an optimal solution methodology and designed heuristic techniques. Since then, a lot of research has been done, with several techniques (such as simulated annealing by McKendall et al. (2006) or genetic algorithms (Hernández, 2011)) and with distinct manufacturing characteristics (multiple objectives (Emami & S. Nookabadi, 2013), cellular layouts (Sakhaii et al., 2016)), or from diverse industrial or services cases, as Ulutas and Islier (2015) with a DFLP for footwear manufacturing or hospital wards (Arnolds & Nickel, 2013)).

Designing layouts means dealing with volatile environments and as *uncertainty*. There are several different types of uncertainties that can differently affect the efficacy and efficiency of a manufacturing system. Sethi (1990) classified uncertainty in two types: external uncertainties, related with levels of demand, product prices or mix; and the internal constraints, such as equipment breakdowns, queuing delays, reworks, etc. In this work, we do not explicitly consider uncertainty, but we believe that it will be an important aspect to take into account in future works, at the multi-facility layout problem, especially due to the fact that considering several facilities can increse the uncertainty aspects that influence the design of layouts and operations between facilities (e.g. transport between facilities, sharing activities, etc).

Table 2.2 presents some, more aspects addressed by the literature on the DFLP and by the main surveys in the area Moslemipour et al. (2011) and Balakrishnan and Cheng (1998) (Table 2.1). The importance of dynamic layouts is clear, due to the diversity of characteristics (e.g. dimensions, quantities, capacities, etc.), that may vary, from period to period, and dynamic approaches clearly allow a greater approximation of the mathematical models to reality. In multi-facility layout problems, this is a crucial characteristic, with special application to our case study, when considering several projects and their lifetime, with flow adjustments with an impact in layout reconfigurations.

2.3.2 Flexibility

Flexibility can be defined as the manufacturing capability of an enterprise to meet the demand quickly and efficiently, with little effort and low cost. It provides the performance to deal with the changes and uncertainties of the customer needs (Blanco-Fernandez et al., 2014). A flexible facility is one that can readily adapt to changes without significant affecting performance (Kulturel-Konak & Konak, 2011).

There are several types of flexibility and quite different perspectives on this topic. Table 2.6 presents the so-called flexibility strategic levels. Given the qualitative nature of flexibility, many of its factors are also analysed by qualitative indices.

Table 2. 6 - Taxonomy of Flexibility (Narasimhan & Das, 1999).

Level	Manufacturing flexibility dimensions	Description
Operational flexibilities (machine/shop level)	Equipment flexibility	The ability of a machine to switch among different types of operations without prohibitive effort
	Material flexibility	The ability of equipment to handle variations in key dimensional and metallurgical properties of inputs
	Routing flexibility	The ability to vary machine visitation sequences for processing a part
	Material handling flexibility	The ability of a material handling system to move material effectively through the plant
	Program flexibility	The ability of equipment to run unattended for long periods of time
Tactical flexibilities (plant level)	Mix flexibility	The ability of a manufacturing system to switch between different products in the product mix
	Volume flexibility	The ability of the manufacturing system to vary aggregate production volume economically
	Expansion flexibility	The ability to expand capacity without prohibitive effort
	Modification flexibility	The ability of the manufacturing process to customise products through minor design modifications
Strategic flexibilities (firm level)	New product flexibility	The ability of the manufacturing system to introduce and manufacture new parts and products
	Market flexibility	The ability of the manufacturing system to adapt to or influence market changes

For example, El-Tamimi et al. (2012) consider *layouts flexibility* as a key factor in a manufacturing system, enabling companies to respond quickly to market needs. They define three levels of flexibility; basic, system and aggregate. At the basic level: *machine flexibility* is used to deal with, a variety of products; *material handling flexibility* to transport and position different part types in various places (machines / workstations, departments…); *operation flexibility* measures the adaptability to alternative operation sequences, for producing a part type. At the system level, flexibility is viewed as the capability to operate efficiently within different volumes of products, alternative paths, variations in volume, etc. At the aggregate level, flexibility is used to overcome the limitations in terms of time, products and market variety.

Neumann and Fogliatto (2009) consider the *flexibility of the layout* associated with manufacturing flexibility, proposing a systematic evaluation of layout flexibility improvements in dynamic environments, and considering internal and external uncertainties. A methodology is proposed for the evaluation of flexible layouts, based on matrices to balance the impact of factors such as proximity of departments, production area used, and the association with other types of manufacturing flexibility.

Kia (2012) views flexibility of layouts in terms of cells reconfigurations and routing flexibility. By routing flexibility, they consider having a large number of routes in which a part can be processed in different machines, and having a number of ways to form cells. Other layout flexibility type is considering the possibility of changing the departments area at each period (Zhao & Tseng, 2007).

Our work considers the possibility of adjusting the area of departments in each period as a flexibility characteristic. Transport capacity is, in our research, another factor of flexibility. Undoubtedly the possibility of moving departments of a factory to another factory, is in our view, another flexibility characteristic of this model, allowing companies to respond quickly to customer needs and at the same time to work more efficiently.

2.3.3 Collaboration

The concept of *Collaborative Network (CN)* is currently widely disseminated and recognized as an important instrument for the competitiveness and survival of organizations, specially in periods of turbulent socio-economic changes (Camarinha-Matos et al., 2009). A CN is a network of a variety of entities (e.g. organizations and people), largely autonomous, geographically distributed, and heterogeneous in terms of operating environment, culture, social capital and goals, but that collaborate to better achieve common or compatible goals, thus jointly generating value, with interactions supported by computer networks (Camarinha-Matos et al., 2009). In CNs, *Virtual Organizations (VOs)* are an important class, that can be characterized in four dimensions, as follows: space (physically dispersed), time (asynchronous), mode of interaction (electronic networks) and individual diversity (different) (Vartiainen, 2001). A particular case of VO is the *Virtual Enterprises (VE)*, representing a temporary alliance of enterprises that come together to share skills or core competences and resources, in order to better respond to business opportunities, and whose cooperation is supported by computer networks (Camarinha-Matos et al., 2009).

A rapid formation of VOs, when needed, and their adjustments to the specific requirements of a given emerging opportunity is of great importance and is frequently viewed as a requirement for agility, and used as a survival mechanism in face of market/society turbulence (Afsarmanesh et al., 2009).

Moreover, strategic agility is viewed in the literature from quite different managerial perspectives (e.g., operations, information systems, marketing, human resources) (Li et al., 2009). For example Yusuf et al. (1999) define agility as “a successful exploration of competitive bases (speed, flexibility, innovation proactivity, quality and profitability) thought the integration of reconfigurable resources and knowledge management, to provide customer driven products and services in a fast changing market environment”. Recently, Conforto et al. (2016) consider that agility is the project team’s ability to quickly change the project plan as a response to customer or stakeholders needs, market or technology demands, in order to achieve better project and product performance, in an innovative and dynamic project environment.

In fact, given today’s frequency of changes in business environments, it is more and more important for companies to be flexible, as a way to respond quickly and dynamically to those changes. This response capability should also exist at a higher, corporate level, combining a plant-level and a network-level analysis, that aims at understanding the continuous interaction between individual plants and their constituent networks (Cheng et al., 2015).

In the context of this work, we aim at applying these concepts to extended facility layout problems (FLP), and in particular to the MFLP, taking into account the collaboration existing between facilities, by sharing and exchanging resources (e.g. machines, departments or projects).

One of the characteristics of collaboration is sharing of resources. We believe that it can be an important aspect to consider when we are working with multiple facilities, as it is the case of the present work. However, there are very few research works, in this topic that are related to the FLP or to the MFLP or applied to a real-world factory (Ho & Perng, 2006), and (Benjaafar, 1995) explored the effect of machine sharing on the performance of cellular systems. Another example is the work of Ho and Perng, 2006), who use a simulation model to maximize the space utilization.

It is clear that there are other interesting aspects to explore, such as the use of optimization methods to solve this type of problems, considering multiple criteria (costs, times, etc.) or managing several facilities. To partially cover this gap, we explicitly consider the benefits of having departments of the same type at the same facility. In this way, companies can benefit from sharing some resources that otherwise would be duplicate. But there are several other sharing possibilities that can be taken into consideration and with real impact on design of layouts.

In fact, collaboration between companies and sharing of resources (e.g. machines, departments, space, or even workers or services) is a very promising area for research for the FLP and the MFLP. Extending the collaboration between companies and also inside companies, between departments of the same type can have an enormous positive impact.

2.3.4 Material handling

Material handling is a fundamental part of facility layouts (Figure 2.2). The purpose of material handling systems (MHS) is essentially to increase material flow efficiency, to provide the required materials where and when needed, to decrease their costs, increasing the usage rate vehicles, to improve safety and working conditions, to turn the manufacturing process ease and to increase productivity (Kilic et al., 2012).

According to Mitch (1968):

> "*A plant is actually nothing more than a great collection of machinery – receiving, assembling, shipping and storage areas linked together by materials handling devices of one kind or another. The building which surrounds them is merely a*

> *protective shell that must be designed to fit their requirements. No matter how handsome a plant may be from the outside, no matter how clean and functional it may look on the inside, no matter how thoroughly it is tooled, its production efficiency will depend upon the swift, smooth flow of materials throughout the plant*".

Today, MHS still have a great impact in company's efficiency, not only in production but also in services. MHS design should meet a set of basic requirements: *What* to move (materials and unit load); *When* and *Where* should be moved (layout); *How (method)* and *Who* should transport. The College Industry Council on Material Handling Education developed some **material handling principles** (see Table A.2.2), based on good practices that are very useful for designing and evaluating MHS.

MHS design and operation is frequently considered in the literature as part of *logistics.* For this work we are interested in *industrial logistics*, covering the procurement (with the transportation of raw materials or components to intermediate storage, also called "order-picking" or "commissioning"), production (raw and semi-finished products are moved and stored along the process of manufacturing and assembly), distribution (responsible for supplying product to customer - storing, picking, packaging and transport) and disposal logistics (depending on the type of product).

In the literature MHS have been covered from several perspectives: determining routes, transportation systems or planning and managing both. Within the FLP, the determination of routes can have distinct meanings: the sequence of production, defining the best sequence of machines to produce the products (for example with less cost, or faster); or defining where machines should be positioned in a plant. (Wang, 2011) developed two models: one for re-layouts, and another to find routes with AGV transport systems. On the other hand, there are research works considering the routes in terms of logistics, designing MHS and defining the type of transport to use, or what should be the best sequence to distribute materials and collect products. The work of (Kilic et al., 2012) is an interesting example, presenting a model for the design of material flow from storages to cells, from cells to cells, and from cells to assembly areas and storages.

In a lean manufacturing environment where the pull system is applied, we typically have a transportation vehicle (the milk-run train) periodically moving on a predetermined route. The milk-run train system aims to minimize the WIP and the transportation costs, and requires an optimization of the routes and frequencies. A similar approach can be applied to organize transports between facilities and be combined with the transport inside facilities in multi-facility layout problems, as we propose in this work.

Layouts with rows (single or multi-rows) are common when the transport is made by automated vehicles or trains, and in this case we need to have enough space for the vehicles to pass between cells or machines (Wang & Chang, 2015). MHS are often viewed as a constraint of the problem, as it is the case of multi-floor layouts with the determination of the location of *elevators* and their number (Lee et al., 2005). Others design the layout configuration of each floor, with a constraint of capacity or location of each elevator (Kia et al., 2014).

Other works focus on the MHS type, determining for example the optimal number of material handling vehicles (Raman, et al., 2009). Others combine these aspects with the FLP considering specific material handling vehicles, such as trains (Kilic et al., 2012), robots (Wang, 2011), or elevators (Neghabi & Ghassemi Tari, 2015). We believe that there are many other combinations and more characteristics to explore in this area. Real problems that many companies have to solve, can surely be better handled by optimization models and decision support systems.

Additionally, warehouse layout optimization has received some attention for a few decades (Rakesh & Adil, 2015), specially on design and operation of warehouses (see the review by (Gu et al., 2010)). The design and selection of handling systems also uses optimization methods, specially combined with layout design (see (Asef-Vaziri & Laporte, 2005)). For Row Layouts, Ficko et al. (2004) apply genetic algorithms (GA) to design a Flexible Manufacturing System (FMS) in multi-rows layouts. The integration of facility layout design and flow assignment, applying heuristics is proposed by Taghavi & Murat (2011). And Shah et al. (2015) try to minimize total costs, taking into account the possibility of adding production and material handling capacity.

2.3.5 Layout evaluation

The configuration of a layout in a manufacturing system has a direct impact in their efficiency, allowing a quick and flexible flow of products and materials, as well as their storage. A good layout hopefully ensures high production levels, allowing quick and efficient responses to changes in demand and product mix (McKendall & Shang, 2006). The evaluation of layouts becomes therefore an important tool to control layout effectiveness.

Layout evaluation can be done at different moments and in distinct ways. It can be performed in a more **qualitative** way or in a **quantitative** form (Table 2.2 reviews the literature on these approaches). On the other hand, the evaluations of a layout can take place in 2 distinct **moments** during the life cycle of a manufacturing system (see Figure 2.7). A first moment is at the design phase or in a maturity phase, if we want to extend this phase with a re-layout process. Layouts can also be object of a **systematic evaluation**, for controlling layout performance, to verify and decide if the current physical arrangement is the best or if it is time to change and reconfigure.

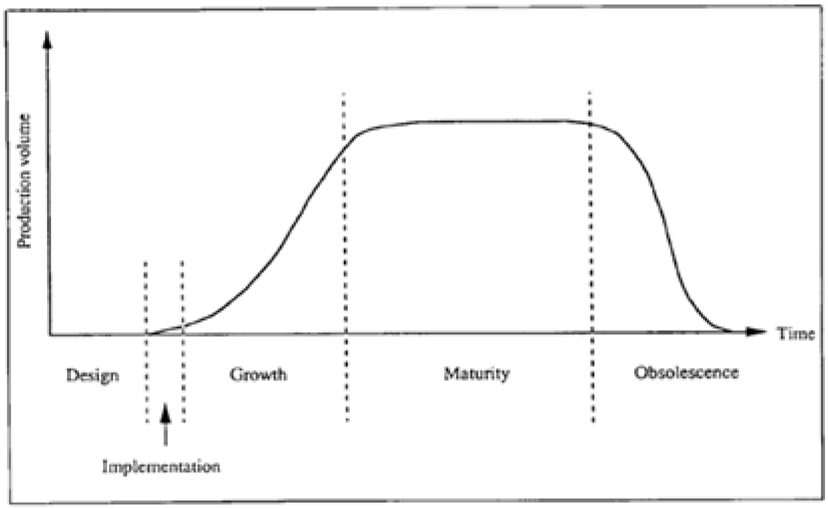

Figure 2. 7 - Manufacturing system cycle (Leung & Suri 1990).

The main criteria used to evaluate layouts can be gathered in 3 main groups in Table 2.7 (see some references in Table A.2.1). **Costs** (c1 and c2) are naturally the main criteria used to evaluate layouts (operations and rearrangement costs). The **physical characteristics** of a layout are also often taken into account: distances (c3); material flows (c4); volumes (c5) of existing space or material moved; closeness (c6) between facilities, departments or machines; space utilization (c7); building expansion (c8) possibilities; non material flows (c9) such as people flows; and process time (c10) particularly the make span. There are also **other** characteristics used to evaluate the layout performance such as: the flexibility (c11) that a layout can enable; transportation system characteristics (c12), such as the type of transportation system available; and the environment (13) characteristics, that can be influenced by the building features; or human safety.

Table 2. 7 - Layout evaluation criteria, applied in the literature.

Layout evaluation criteria		
Costs	**C1 - Inventory costs / Material handling costs** raw material inventory holding costs WIP inventory holding costs MHC inter-cell MHC intra-cell MHC finished goods inventory holding costs	**C2 - Non-inventory costs** initial cost (land, building, product machinery, material handling equipment) overhead cost of machines operating cost of machines annual operation and maintenance cost (labour, utility, maintenance) rearrangement cost (rearrange machines and departments, stop/start departments work) future salvage costs budget constraint
Physical characteristics	**C3 – Distance** distance for frequent facility maintenance distance travelled time spend to move the material	**C4 - Material flow** loaded travel of material handling equipment empty travel of material handling equipment
	C5 - Volume density volume of material moved through the aisle/departments volume of the bounding box, that contain all the facilities volume of design space	**C6 – Closeness** contact perimeter between departments closeness ration
	C7 - Space utilization space for production machinery space for people needs space for storage aisle space for material and people movement space utilization productive area used (value adding – machine, tool, storage, transportation, inactive) (non-value adding – machine, tool, storage, transportation, inactive) clearness (partition/wall, column, stair/elevator) free space aisle (area served by the aisle, ease of access, alternative routes, intersections, department share, straight aisle) aspect ratio	**C8 - Building expansion** building a new facility or move to another factory rearrange the area and location of free space rearrangement in the existing layout adding a new facility near the existing one expending the existing building space in some direction
	C9 - Non-material flow information flow people flow other equipment flow	**C10 – Time spending** Makespan

Others	**C11 - Layout flexibility** ease of expansion free space availability demand volume variation demand violations variation in material handling cost routing flexibility flexibility in volume capacity flexibility in change production capacity flexibility in mix of products flexibility of workers in tasks range flexibility in range of machines	**C12 – Transportation system characteristics** variety of material handling equipment (MHE) sufficiency of MHE number of MHE subsystems capacity of each MHE subsystem capability of each MHE subsystem
	C13 – Environment topography (natural site conditions, truck access and circulation pattern, connection with external MHE and methods) community (traffic congestion, waste management and pollution control, appearance of external or viewable feature) human safety (human-building accidents, human-machine / material interfaces, lighting, noise, ventilation/heating, ergonomics, handicapped access) property (theft from outside the building, theft from within the building, special caution for dangerous areas) access for maintenance (compatibility of building construction and MHE, space for maintenance work, location of maintenance activities, complexity of MHE)	

The quantification of most of these criteria is not an easy task. As referred before, it implies the collection of a large amount of data and a significant additional computational effort (for applying the associated mathematical models).

A rather common approach used for this quantification is to implement a set of **quantitative** procedures to be applied during the layout process. The work of Aiello, La Scalia, and Enea (2012) is a good example, as they propose a multi objective GA for solving unequal area facility layout problems, minimizing operating costs (MHC) and maximizing system efficiency (satisfaction of weighted adjacency, distance requirements, and aspect ratio requirements).

On a somehow different line, Raman (2011) proposes an integrated methodology that incorporates manufacturing variability and concurrently optimizes the layout design and material handling system, applying a GA. With this approach, the production systems were significantly improved concerning the total travelling time, the total work in process

(WIP) in the system, the utilization and quantity of material handling equipment, and the required area.

The **qualitative evaluation** involves defining the criteria to evaluate the layout, and assigning weights to the criteria, reflecting their relative importance. This kind of evaluation can be done at different times, as a way to check if changes are necessary (and a re-configuration process started). In these situations, normally rules or indices are defined, mainly when the objective is to evaluate the layout in several aspects, applying multiple-attributes, such as *layout flexibility*, *robustness,* or *agility*. These models normally require detailed information, oversimplifying assumptions, and request a longer computational effort, not acceptable in practice. Lin and Sharp (1999), Neumann and Fogliatto (2009) have defined several criteria and evaluated the situation of a company in all those parameters. To evaluate the performance of a layout (Raman, Nagalingam & Lin, 2009), considered three layout effectiveness factors: *facilities layout flexibility*, *productive area utilization* and *closeness gap*.

Separating the layout evaluation from the layout design, Jiang and Nee (2013) allow the decision maker to customize the planning criteria and constraints to suit specific requirements of different FLP tasks, and then use an AHP multiple criteria approach with Genetic Algorithm. Shen and Yu (2009) propose a fuzzy multiple attribute decision making method, helping managers to link selection criteria with the requirements of operations strategies for facility location selection.

Based on this survey and on the above observations, we believe that layout evaluation, has a vital importance, but has been a practice somehow overlooked, even by many companies that claim to be flexible and agile but often forget the importance of a good layout. As Figure 2.2 shows, the majority of the 96 works reviewed on the FLP (75) focus on layout design, and only 17 are dedicated to layout evaluation. Moreover it seems useful to design new tools to evaluate the case of multiple facilities, and the way they can collaborate. With our work we start in some way this research path, but for sure there is still a lot to be done.

In our work, the evaluation of layouts takes into account the objectives specified for each situation (*small* and *large changes* (Azevedo et al., 2013)) and is based on a layout evaluation model, to control layout efficiency and to identify potential needs of layout reconfigurations. A quantitative evaluation, is used during layout design to select the configuration that better fits the established objectives. A qualitative evaluation takes place every moment there is a need to control the real effectiveness of the layouts.

2.4 Conclusions

Despite the vast literature on the FLP, it is interesting to verify that the majority of the published works are currently more focused on applying and combining different resolution approaches, then adding new characteristics to the standard FLP. They can vary from static or dynamic problems, but in general new models are only tested with randomly generated instances or benchmark examples. However, more recently, some case studies are presented, from quite different areas such as hospitals design (Arnolds & Nickel, 2013) or nursing units (Rashid, 2015), or even construction site layouts (Hammad et al., 2016). If we have a look at Table 2.2, half of the works are validated with data from other works, and only around 20% use real cases. That is in fact highlighted in the literature by several authors ((Drira, 2007), (Kulturel-Konak, 2007), (Singh & Sharma, 2006), (Benjaafar et al., 2002), etc.). With our work we intend to contribute to minimize this gap, by developing models inspired in the real problems of a first tier supplier of the automotive industry.

Nowadays, companies operate more and more as part of larger networks, or they have multiple facilities located worldwide, this creating a need for tools to support the integration of operations in a flexible and efficient way. Combining plant-level and a network-level analyses could contribute to this goal, even if there is still a lot to do to understand and to evaluate the continuous interaction between individual plants and their constituent networks (Cheng et al., 2015). On the other hand, as far as we know, there are no references in the FLP literature to problems involving physically separated facilities (see Figure 2.2). Naturally the MFLP can be a response to some of these needs (Figure 2.8), by combining *large changes* and *small changes* (Azevedo et al., 2013) in a set of several facilities.

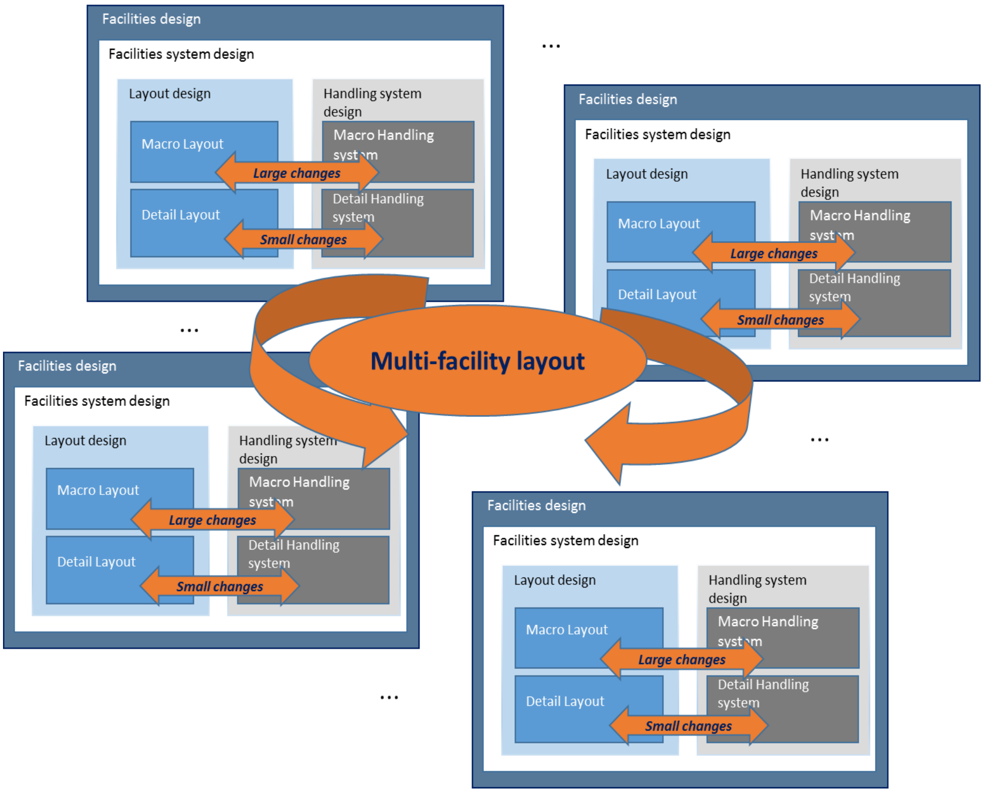

Figure 2. 8 - Multi-facility layout design.

As Drira et al. (2007) noted, models are still missing to solve problems in an integrated way. For example, it would be interesting to have models considering macro-layouts with detailed layouts, or the design of layouts with material handling systems, as proposed in this work (by *small* and *large changes*). These integrated models would probably allow the combination of automated guided vehicles, along with other transportation systems.

On the other hand, there are few works considering the expansion of facilities, the majority reflecting the possibility of changing department areas, but with a fixed size of the facility. Adding and removing departments and facilities, as the MFLP allows is surely a very promising area, due to the increase needs of flexibly in response to changes in the market.

The minimization of costs has been the most used objective in FLP models (e.g. Bozorgi et al (2014). However, several extensions of these models have been proposed such as the minimization of distance travelled, time spent in travelling, adjacency, distance requirements, or multiple-objectives. But when we focus on layout reconfiguration, it can be important to evaluate other objectives, for example to take advantage of the characteristics of each location (e.g. location with adequate height for the machines, reinforced floor to receive specific types of machines). In this work we propose the *unsuitability* objective, to find good matchings between the characteristics of each department and those of each location.

The FLP is frequently formulated as a Quadratic Assignment Problem (QAP), this was also the choice for our model, essentially because we are assigning departments to locations of facilities (and this may be especially important for reconfigurations), taking into account the characteristics of each location, and the requirements of the departments.

In the literature, for these problems, there are a great variety of approaches, and due to the intrinsic difficulty of the problems, the majority of published works applies heuristics to find near optimal solutions. However, there are more and more software tools, such as CPLEX, that can be used to solve small to medium size problems to optimally. We have, therefore, applied CPLEX to solve our MFLP.

In summary, with this chapter we have tried to explore the main published literature on the FLP, identifying areas for research and opportunities for minimizing the gap between academic results and the practical world. One of the most exciting findings is the need for a new extension of the FLP, due to the fact that existing works have only focused on a single facility. We strongly believe, that, with this new extension, we are opening several interesting paths for future research.

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3. CASE STUDY

This chapter presents the real case used in this dissertation. The complex problem of the company shared here, improved our research and then developed models were applied and tested in this company.

Contents of the chapter:

- *Introduction*
- *Case description*
- *Particularities of the automotive industry*
- *Production process and physical characteristics of facilities*
- *Type of flows*
- *Layout design and reconfiguration.*

3.1 Introduction

This research work was inspired by a real case study, *SIMOLDES Plastic Group*, an industrial company that is a first-tier supplier of the automotive industry.

This dissertation was partially the result of a collaboration with the company, to solve some of their problems related with facilities reconfiguration. To better understand their reality and main problems, we made an internship in the Portuguese factories of the group (*SIMOLDES Plásticos* (Figure 3.1), *INPLAS* and *PLASTAZE*). During this period, direct observation and interviews were made to workers and managers of several departments of the facilities, as a way to collect data and define the requirements of the problem. Throughout this research project, we had some brainstorming meetings with the main actors of the processes, to analyse the collected information, and to validate and refine the models.

Figure 3. 1 – SIMOLDES Plastic facility.

In this chapter, we briefly present *SIMOLDES Plastic*, with special focus on the Portuguese factories. Since the main customers are from the automotive industry, the company has to be organized and aligned with this industry. The layout design process is subject to specific constraints that strongly influence the problem solutions. Then we describe how this company actually works and how it does the layout design and reconfiguration. At the end of the chapter, the main conclusions are summarized.

3.2 Case description

SIMOLDES Group was founded in 1959 and has been working for the automotive industry since 1968. The group is constituted by the *Plastics division* and the *Tools division*. This dissertation was developed with the Plastics division, composed by 8 companies, as presented in Figure 3.2, in particular, with the Portuguese companies (*SIMOLDES Plásticos*, *INPLAS* and *PLASTAZE).*

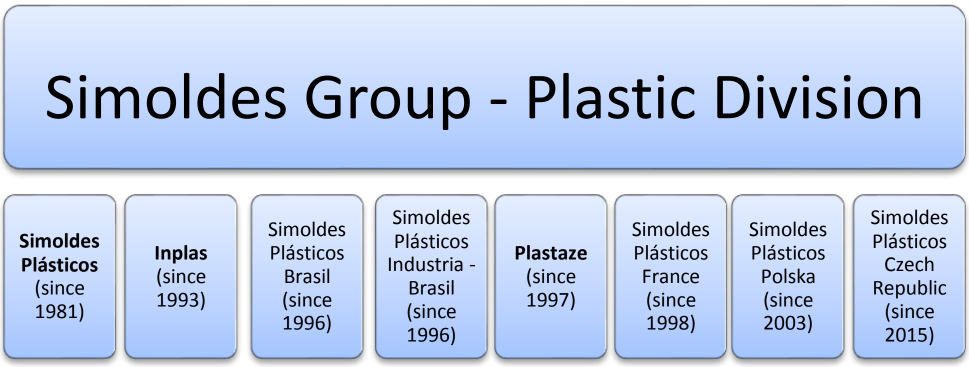

Figure 3. 2 – SIMOLDES Plastic Group.

The group has their headquarters in Portugal, more specifically in Oliveira de Azeméis, at *SIMOLDES Plastics* facilities, the first company of the group. The Portuguese companies have different locations in a relatively small region (see Figure3.3).

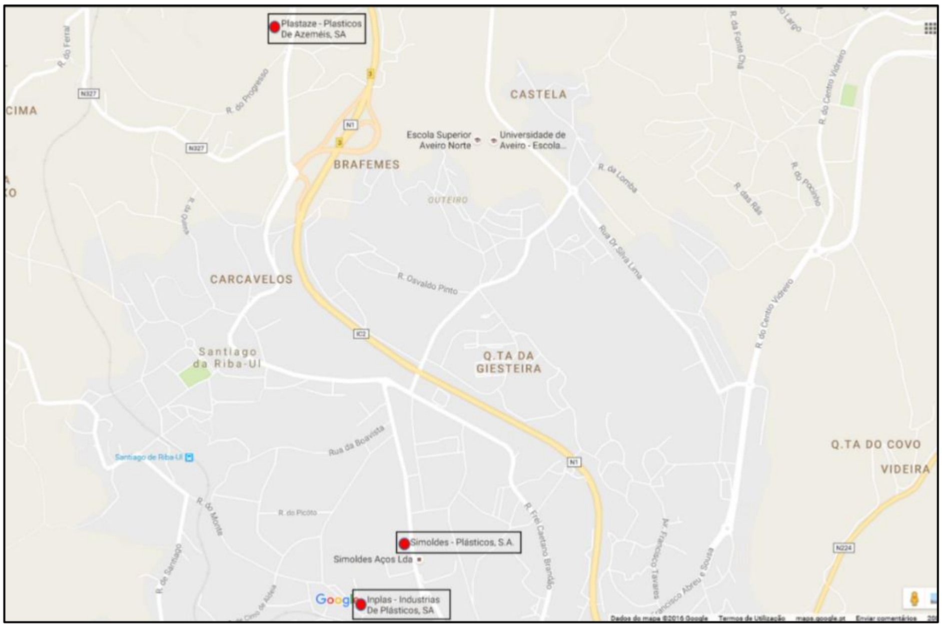

Figure 3. 3 - Localization of the Portuguese companies of the SIMOLDES Plastic group.

The main activity of *SIMOLDES Plastic Group* is produce plastic parts for automotive industry, such as dashboards and consoles, door panels, and seats parts. (see Figure 3.4).

Figure 3. 4 - Products of SIMOLDES Plastics Group for automotive industry.

They supply directly to the major automotive OEMs, such as PSA, Volkswagen, General Motors, among others, as represented in Figure 3.5.

Figure 3. 5 - Automotive brands supplied by *SIMOLDES*.

All the facilities can produce the same products, in what concerns the automotive industry, but PLASTAZE is the only company of the group that also produces plastics for other industries, such as shopping carts, gas bottles, babies' seats, etc. However, the production of this type of products is negligible, when compared with the automotive production, and therefore in this work, it will be not considered.

SIMOLDES, works in fact, like a corporate group. Each company has almost all types of departments, to produce all parts of a product, even if in some cases they share the production among the companies. Specific departments, such as logistics, innovation, recycling, are centralized. These departments take decisions for all the companies of the group, for example, concerning the negotiation with customers and suppliers, or the development teams for new products and technologies.

The company has a *transport operations centre*, responsible for transporting the semi-finished products and final products between the factories. For this purpose, they have trucks, that pass every day through each factory. As the main production of SIMOLDES is for the automotive industry, they have some advanced warehouses, near to the more important customers. Transport for those warehouses is frequently made by subcontracted logistics companies. For SIMOLDES the environmental issues are also important, and therefore they have a *Recycling plastic centr*e, at SIMOLDES Plastics factory, to recycle all the non-conforming products of the 3 factories. This obviously creates additional transport needs. In general, all the factories of the company work with the same type of rules and certification.

3.3 Particularities of the automotive industry

The automotive industry is one of the world´s more important economic sectors. A car is composed by many plastic parts. Depending on the specific *project*, SIMOLDES can produce more or less plastic parts for each car model. For SIMOLDES each model of a car is viewed as a *project*, or a “kit” (see, for example Figure 3.6).

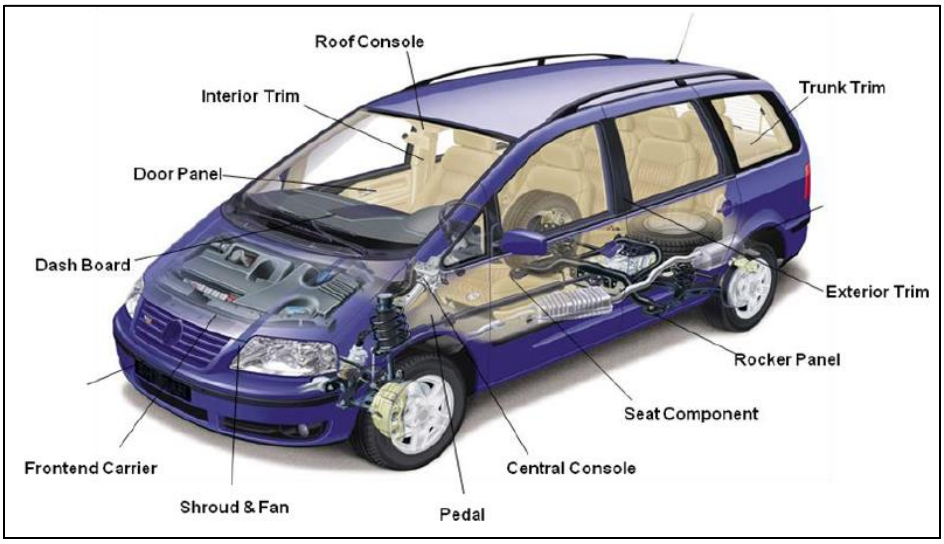

Figure 3. 6 - Parts of a car, produced at SIMOLDES.

Thus, a *project* comprises several parts that are themselves composed by various materials or a set of components (see Figure 3.7). Although a *project* refers to a specific car model, this car can have multiple versions. Often what changes from one version to another are the "finishings" or some materials, as is the case of some interior parts, this leading to a large variety of references for the same part of the same car. For instance, the coating of doors, can be leather, or tissue, or even plastics; the injected plastic piece is the same, but with different materials application of the finishing. Another example is the production of models that are sold in countries with the steering wheel on the left, this meaning having parts for the same local car with inverted formats, but belonging to the same *project*.

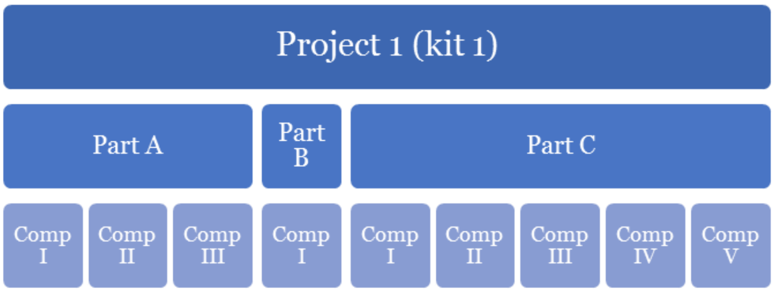

Figure 3. 7 - Product complexity.

The duration of a *project* is identical to the life time of the car model. When a model is new, every time SIMOLDES receives a customer order, a complete kit for that model must be produced and delivered. On the other hand, for old or for new models, it will always be necessary to produce separated components, to be used as spare parts. Obviously, the quantities are very different if we are producing complete kits or individual parts (see Figure 3.8). Moreover the requirements of synchronisation of production of each part and component, will also be different.

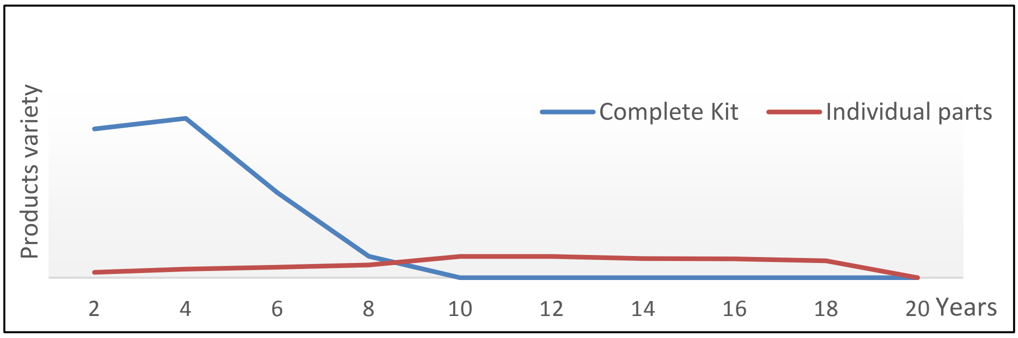

Figure 3. 8 - Example of demand along the life cycle of a *project*.

Consequently, a *project* can have three phases in its life time (see Figure 3.9):

- Phase 1 – Produce complete kits (all components and parts) - the quantities increase along time, and the diversity of components also grows.
- Phase 2 – Produce complete kits, normally in very large quantities. At the same time, produce individual parts - some components in smaller quantities.
- Phase 3 – The production of new cars has stopped. Now only separated parts are produced, until the end of the car life-time. These quantities are reduced but still they must be produced.

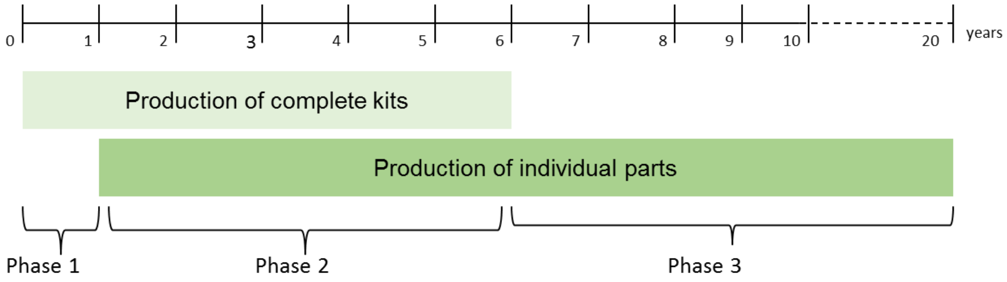

Figure 3. 9 - Phases of production of a *project*.

SIMOLDES has simultaneously in production several *projects* at different phases, this significantly increasing complexity. If we look at several facilities, this complexity grows further. Given the high complexity of products, and the variety requested from customers, in general collaboration between facilities is needed, with the formation of networks that are dynamically changed for each *project*.

The development of products and the design of cars is a strong collaborative process between SIMOLDES, as a first tier supplier, and the OEMs. In this stage, they have to decide which facility will produce the project. This implies that every order of this project will always be delivered from this facility, during the life time of the project. So the allocation of projects to facilities is not only a decision of SIMOLDES, but a joint decision with the customer.

The customer has, in fact, a great decision power on the process of facilities selection, and if during the project life, SIMOLDES want to change the project to other facility, it will probably be difficult to have the customer's agreement. If this agreement is not possible, SIMOLDES will have the costs of transporting the products between facilities. So, during this negotiation process, SIMOLDES need tools to rapidly evaluate different scenarios and production allocation possibilities in their factories network, to obtain the most profitable and competitive proposal.

Regardless of the facility chosen to produce a given project, the final products can be supplied directly from the factory or from advanced warehouses. SIMOLDES have some advanced warehouses, strategically positioned near some costumers, to ensure a synchronized supply to the assembly lines. Normally those advanced warehouses only have storage areas and picking areas. However, sometimes, it is possible to enlarge those advanced warehouses, by transferring some departments from other facilities. But the question is *what could be more advantageous to transfer, and from which facility?* Recently SIMOLDES have built new facilities near some important customers, such as the new facility at the Czech Republic, to directly supply Skoda plants. But this facility can move part of its production to other facilities of the company. The current problem of SIMOLDES is where could it be more profitable to have the production, taking into consideration the constraints of customers' locations, *project* characteristics (dimension, technologies, duration, etc.) and the existing facilities and employees. The exchange of departments and machines between facilities is sometimes the answer, and this dissertation hopes to be a contribution for making this process more agile, and allows the analysis of more scenarios and possibilities to make these changes easy, profitable and efficient. That is why our model will allow the decision maker to try different solutions, in order to make successful contract negotiations.

3.4 Production process and physical characteristics of facilities

The production process at SIMOLDES is, in general, organized by departments. All products are produced in the injection machines, typically located in the injection departments. Then, depending on the product characteristics, some finishing operations, may be required, such as painting and assembling (see Figure 3.10).

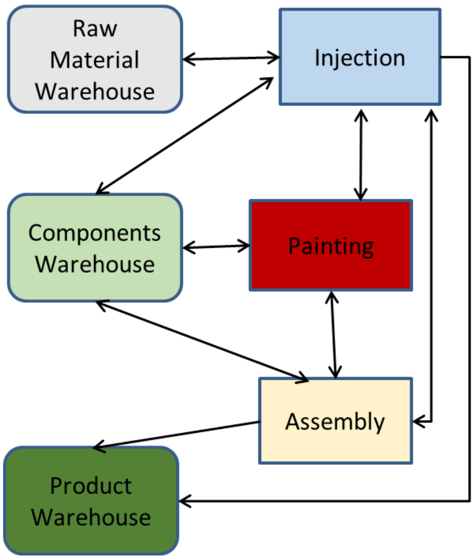

Figure 3. 10 - Production of plastics.

Due to their physical characteristics and sizes, the Portuguese factories have several departments of the same type in the same facility, as Table 3. 1 presents.

Table 3. 1 - Number of departments types, at each facility of SIMOLDES.

Department type	**Number of departments**		
	SIMOLDES	**INPLAS**	**PLASTAZE**
Injection (Inj)	2	3	2
Assembly (Ass)	1	3	1
Painting (Paint)	0	1	0
Raw material warehouse (Wr)	6	4	1
Components warehouse (Wc)	4	4	2
Product warehouse (Wp)	3	3	1
Others	3	6	5
6	19	19	12

3.4.1 Injection

Injection moulding is the main manufacturing process used at SIMOLDES, for producing plastic parts by injecting some material into a mould. This is the more critical department (or section), in what concerns the layout reconfiguration process. The injection machines are normally large, especially those of higher tonnage, used for the production of large parts, such as front cars or dashboards with front panels. The installation and the operation of these machines imply strict place requirements, such as the preparation of the soil to support their weight or the existence of air bridges to transport the moulds (with large dimensions, in high tonnage machines). In practice, this makes the re-location of those machines unfeasible or very difficult to do, wishing light costs and acommodable amount of time. In total SIMOLDES has currently 133 injection moulding machines in the Portuguese facilities, (see Table 3.2).

Table 3. 2 - Number of Injection machines currently on each facility, per capacity.

Injection moulding machines				
Power (ton)	**SIMOLDES**	**INPLAS**	**PLASTAZE**	**Total**
< 400	18	24	21	63
> 400 - 800	16	13	14	43
> 800	17	2	8	27
Total number of machines	**51**	**39**	**43**	**133**
Capacity installed (ton)	**36.710**	**15.010**	**23.135**	**74.855**

Due to the variety of plastic parts, in general, the big parts take more time to produce, than the small ones. Frequently it is not easy to synchronize the production, with the assembly of small parts (for example a tail-spin) in the big ones, to complete the final product (see Figure 3.11).

Figure 3. 11 - Example of a big complex product.

To minimize these problems, injection machines are put together in the same department (see Figure 3.12), and the output of these machines goes to the component warehouse. Then, only when these components are needed, they are distributed, in the needed quantities, to the required machines or assembly lines. In practice, there are no direct flows between injection machines or between the assembly lines. To optimize all these movements, a train is used to collect and distribute materials and components, as well as to collect the products. With this organization, it is also possible to optimize the space utilization of injection departments, as there is no space for warehousing. Near to each machine, there are only materials for one hour of production and products from one production hour. Of course, if the products are large or if they have a high production frequency, it may be necessary to make intermediate collections, at these machines.

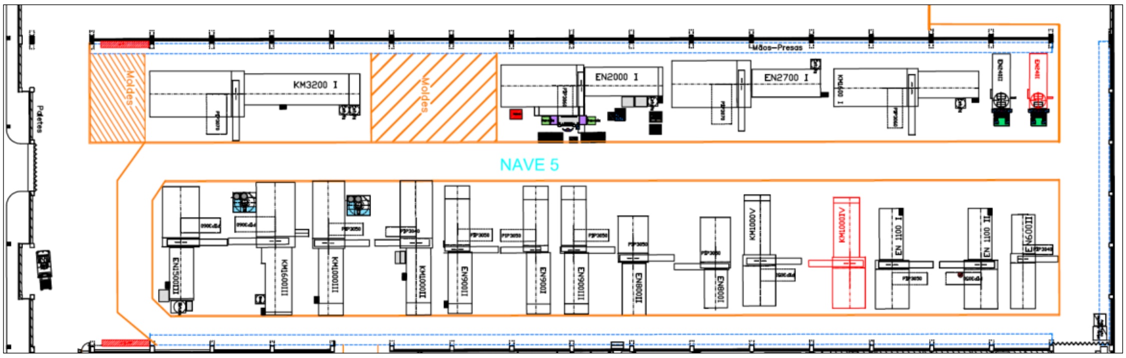

Figure 3. 12 - Injection department layout of one facility.

3.4.2 Assembly

Injection molded parts can be assembled together with other components or parts, and finished with some other components such as leather or textiles. These operations are carried out in the assembly department.

SIMOLDES can produce a wide range of products with varying needs of finishing and assembly. This production phase may need only one mounting position, with a simple assembly involving one or more components, or some gluing or welding operations. This may require assembly lines with multiple jobs, and machines (see Figure 3.13 for example of an assembly department configuration).

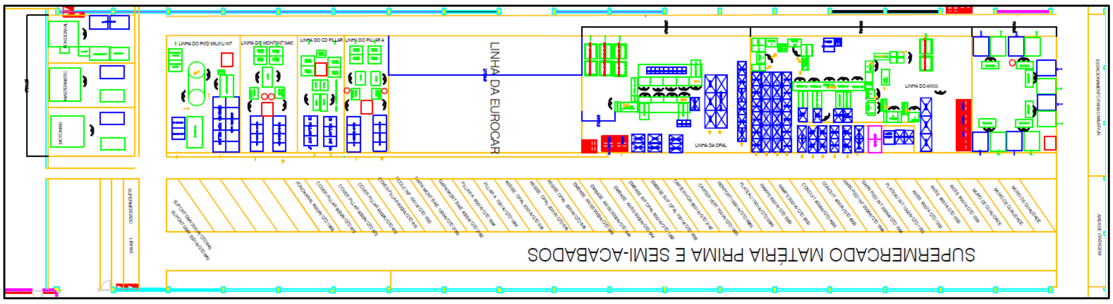

Figure 3. 13 - Assembly department layout of one facility.

The factories are essentially organized by departments. However, due to the characteristics, size and life stage of a specific *project*, production can be organized in manufacturing cells. Some of these cells can be located in the injection department, if they include injection machines. Due to soil preparation and to specific requirements of the moulds, these cells can include one or more injection moulding machines (located in the injection department or in the assembly), along with the injection machines that are producing the parts for that product. These cells can also include other finishing and assembly operations, such as riveting or welding (see Figure 3.14).

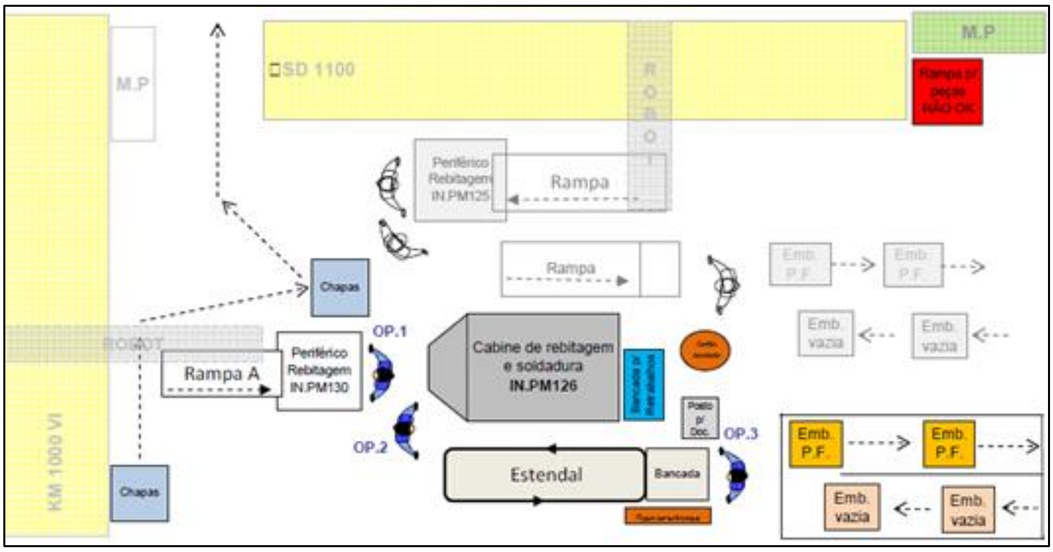

Figure 3. 14 - Example of a cell configuration.

So, the main flows inside these departments are essentially between the workstations, lines or cells and the “supermarket”, to collect components. Flows can also exist between workstations and some machines specialized in some operations (such as riveting, welding, etc.). The majority of the flows are done by the “train”, that collects products and supplies “supermarkets”. In some situations, when products are very large, the collection and supply to the lines or cells can be done directly with the lift-truck.

3.4.3 Painting

SIMOLDES has only one painting department, to supply the three Portuguese facilities. This department is a complete line that, for this study, was considered as a single block. The layout optimization of this department was out of scope of this work, due to the high reconfiguration costs involved.

3.4.4 Warehouses

One of the main objectives of the company with this work is, in fact, to optimize the space of factories, since currently warehouses occupy about 50% of the facilities (see Figure 3.15).

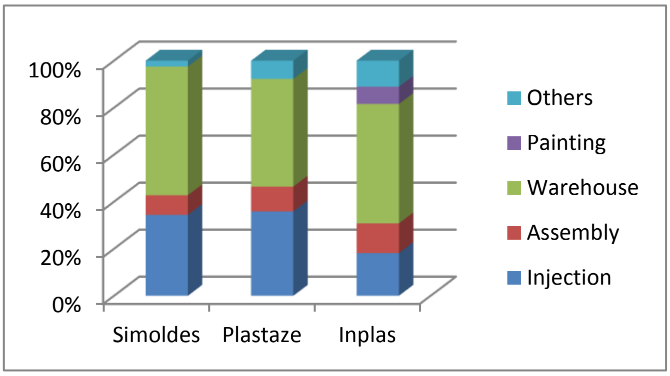

Figure 3. 15 - Area of the main departments of the facilities.

SIMOLDES has six main types of storage areas, as presented in (Figure 3.16).

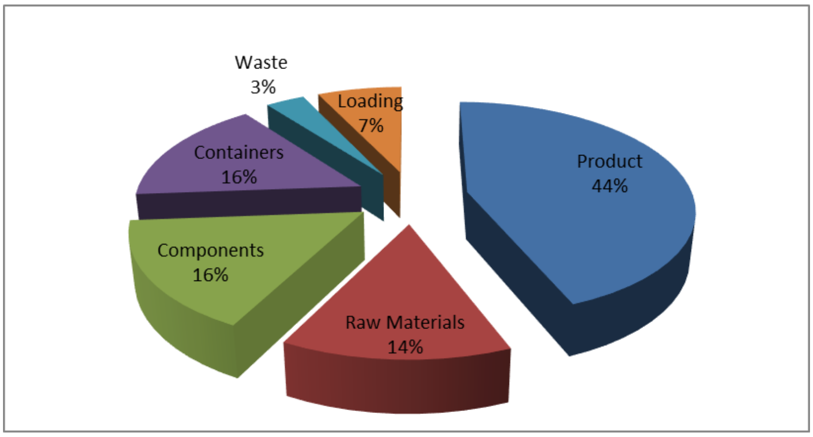

Figure 3. 16 - Total area of the warehouse types of the facilities.

Product storage occupies a lot of space, mainly due to the fact that, during the production of complete kits (Figure 3.9), for each order, all parts of the kits must be simultaneously available for delivery. The loading area represents around 7% of the total storage area, and is used to organize the loading of the trucks, leaving to customers, advanced warehouses, or to other facilities of the company. Those two storage areas are considered as part of the *product warehouse*.

Components storage areas are mainly located near or in the assembly departments, and are frequently organized as "supermarkets". All these areas together are considered as the *Components Warehouse*. This warehouse receives components from suppliers, and from the injection, painting and assembly departments. Then, when they are needed they are sent to the "supermarket", at the required quantities (e.g. for a work day). Components with large dimensions are stored at specific areas in the assembly departments. This warehouse can send components to the assembly departments, to painting and sometimes to injection, to be put together with other injected parts, just produced at that moment.

The main raw material is granulate for injection machines. It can be stored, in several forms: silos, bags, or octabinas, (see Figure 3.17). Two of the Portuguese facilities have in total 11 silos to store granulate. Some of these silos are connected by pipes that supply directly the raw material to the injection machine, thus requiring less space for storage and transport. The raw material can have different compositions or colours. Those that are used more frequently are stored in silos, the others being stored in bags. When needed, Raw materials are mixed in a "beater" (located inside the warehouse) and them the resulting material is transported to a specific injection machine. These *Raw Material Warehouses* receive raw materials from suppliers and from a centralized department, that recycles the plastic waste of all facilities.

Figure 3. 17 - Raw material and storage forms.

The majority of the customers use containers (see Figure 3.18), with fixed dimensions, to transport products (these containers normally belong to the customers). Therefore SIMOLDES needs to have a safety stock of empty containers. When they deliver an order to a customer, they receive back the same quantity of empty containers. These containers can have various sizes and forms, according to the product dimensions and characteristics. In total, they occupy around 16% of the total area. Currently these containers are stored outside the facilities, so they are not considered in this study (the same happing with the waste storage).

Figure 3. 18 – Containers to transport products to OEMs.

Other factor that makes these warehouses so large is the size of some products. Obviously, the moulds used to produce the parts, in the injection machines, also occupy a considerable area, because, some of them have big dimensions, and they have to be maintained in perfect conditions, to be used during the total life of the *project* (around 15 to 20 years). Every time these parts have to be produced, on injection machine (a mould is only made for a specific part, and cannot be used to produce other parts) moulds that are being used are stored inside the injection department. Those that are used occasionally are stored at a specific warehouse, that is not considered in this study.

Thus, SIMOLDES have essentially three types of warehouses (Figure 3.10): raw materials, components, and products.

3.5 Type of Flows

As stated before, there are several types of flows (materials, equipment and people) between facilities and inside facilities (between departments) (see Figure 3.19). However, for this work, the main focus is on the flows of materials (raw materials, components, and products), as described in the following sections.

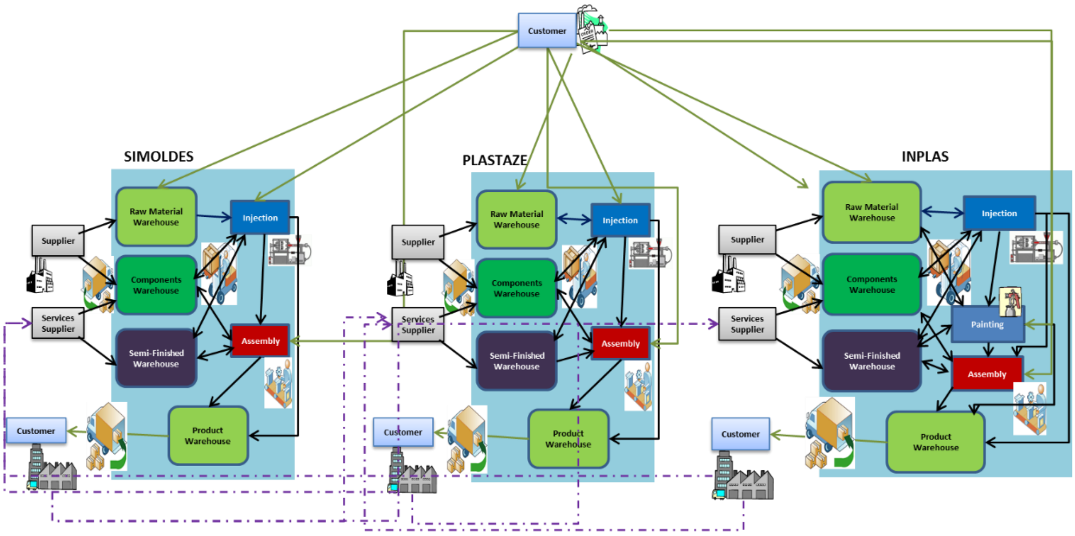

Figure 3. 19 - Different types of flows.

3.5.1 Flows between facilities

As mentioned above, the different facilities exchange raw materials, semi-finish products (mainly from painting to assembly), final products, and containers. This transportation is made by trucks owned by SIMOLDES, and daily scheduled for this purpose.

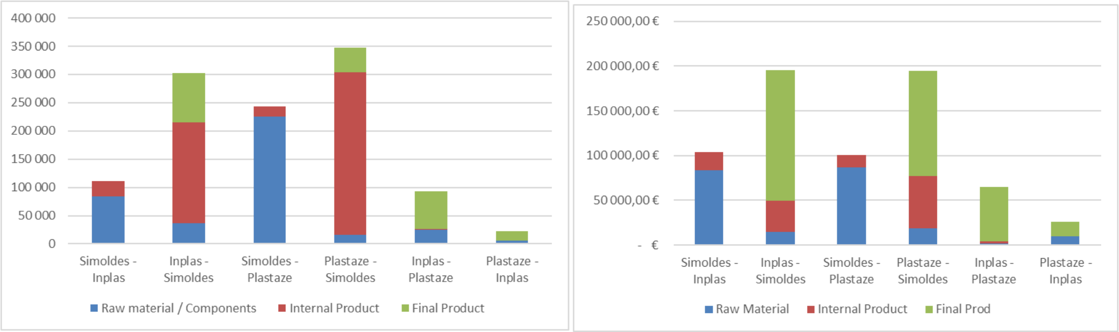

Figure 3. 20 - Flows (quantity and cost) between facilities, in one month.

The flows that are more frequent (Figure 3.20) are for; *Internal products*, to be finished at other facility. PLASTAZE, in this case, is the facility that sends larger quantities to SIMOLDES. On the other hand, in terms of costs, the more expensive transports are those for final products. SIMOLDES essentially sends raw materials to PLASTAZE, and INPLAS, mainly due to the fact that the recycle center of the group is at SIMOLDES facility.

INPLAS mainly sends, final products to SIMOLDES and PLASTAZE, because these products are finished in the painting department, located at INPLAS facility.

3.5.2 Flows inside facilities

Inside facilities, most flows are between departments, for raw materials; components and semi-finished products are moved between warehouses and other departments; and products and semi-finished products, are sent from manufacturing departments to product warehouses (see Figure 3.21).

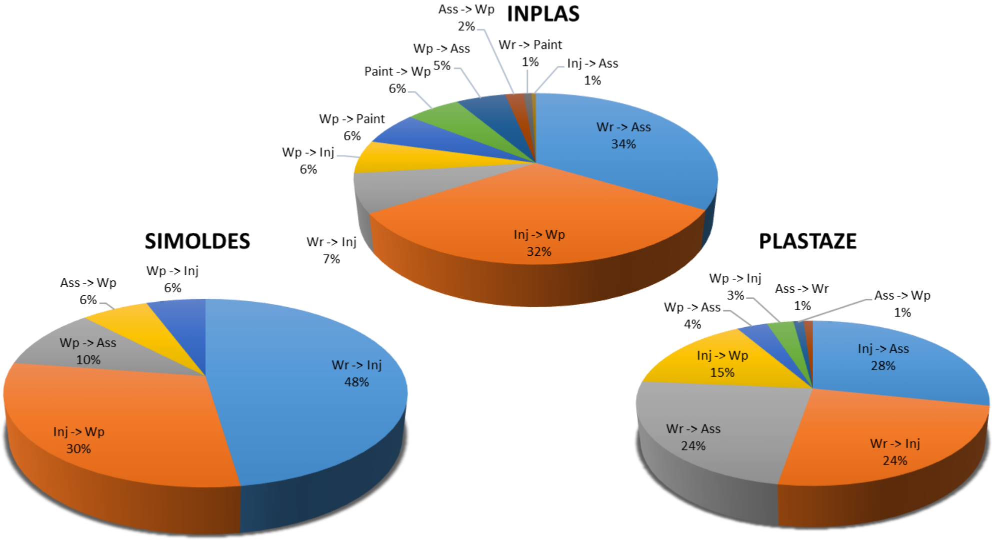

Figure 3. 21 - Flows between departments, inside each facility.

As referred above, trains are used to transport the materials inside facilities, between departments, and inside the injection and assembly departments. Due to the products variety and sizes, manufacturing is not synchronized. There are therefore few movements between machines, at the facilities. Frequently, products are injected, and then they go to the component warehouse, and only when needed, they are sent in the right quantities to the assembly departments, painting or even again back to injection, to be joined with other components. Frequently the transport of products with large sizes is made with a lift-truck. Lift-trucks are also used to transport materials and products inside warehouses.

3.6 Layout design and reconfiguration

Reconfigurations of layouts can be made for different reasons, and in various ways. The more frequent layout changes are due to the introduction of new *projects*, as explained in Figure 3.22. In these situations, new and existing flows need to be adjusted. For example, it can be useful to put machines that are producing products of identical (large) size or at high cadences, near the exits, so that they can be quickly supplied and products can be collected by forklifts.

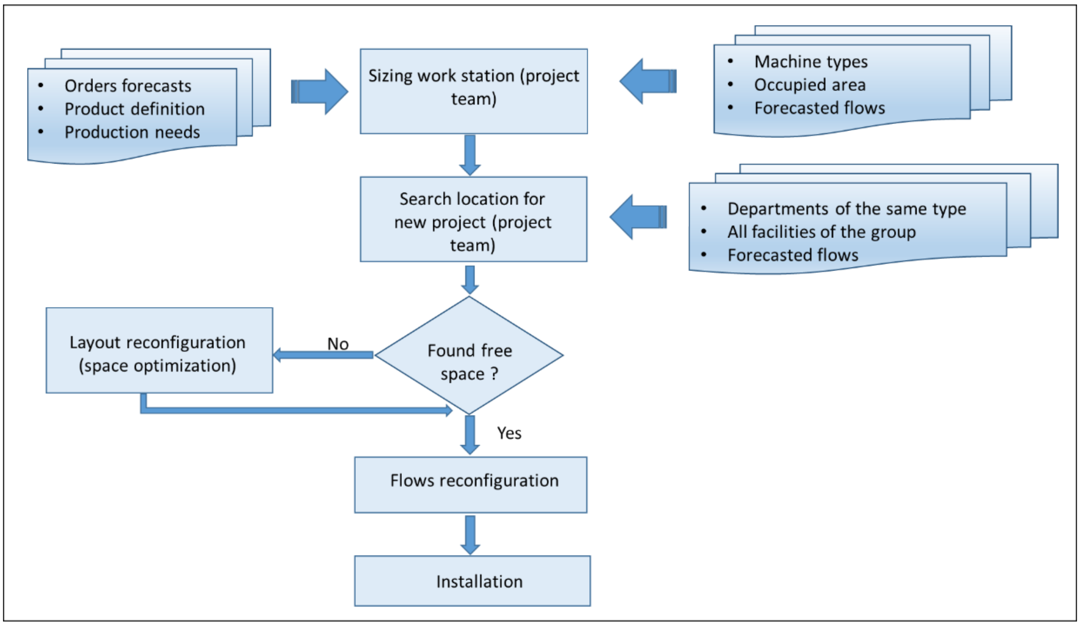

Figure 3. 22 - Currently layout reconfiguration process, due to the introduction of a new *project*.

These reconfigurations can involve exchanging machines between facilities, for example, to optimize mould utilization. In fact, one of the main objectives of SIMOLDES, in terms of production, is to minimize mould exchanges, trying to fix them at the machines. This means that an injection machine with a fixed mould, can only produces a specific product. Setup times can be very large (in the order of several hours), due to the moulds dimensions and to the need of production adjustments.

Setting moulds to machines occurs only in the early years of a *project*, for the production of complete kits (phase 1 and phase 2 – see Figure 3.9). Then the required quantities become smaller and more spaced in time, and therefore it is not interesting to have a machine full time dedicated to a given product. At that time, moulds are only fixed on the machines for the needed products (a minimum lot), and then they are removed.

Sometimes these products can be manufactured in another facility, where it is easier to fix the mould, but these decisions have often to be taken where the *project* starts.

A systematic evaluation of the performance of each department and each facility, can allow the identification of some problematic situations and critical processes. Frequently, the solution is a simple reconfiguration of the layouts or relocation of machines. Essentially the factors that can lead to changes in the layouts are dysfunctionalities such as: less productivity; production delays; high number of exchanges of moulds; space disorganization; high number of workers, loss of capacity; customer dissatisfaction; increase of defects; etc.

Layout reconfigurations can be suggested by the workers, resulting from "kaizen moments" (meetings between workers to discuss and propose ideas to improve workplace conditions and performance). The majority of the suggestions have been related to, routing reconfigurations, or simplification of working tasks (allowing the elimination of some assembly workplaces, by combining tasks at the injection machine, thus freeing up more space in the assembly). Some warehousing optimization, has also been suggested by those meetings. Figure 3.23 shows the main steps and components of a layout reconfiguration process, due to a systematic evaluation process.

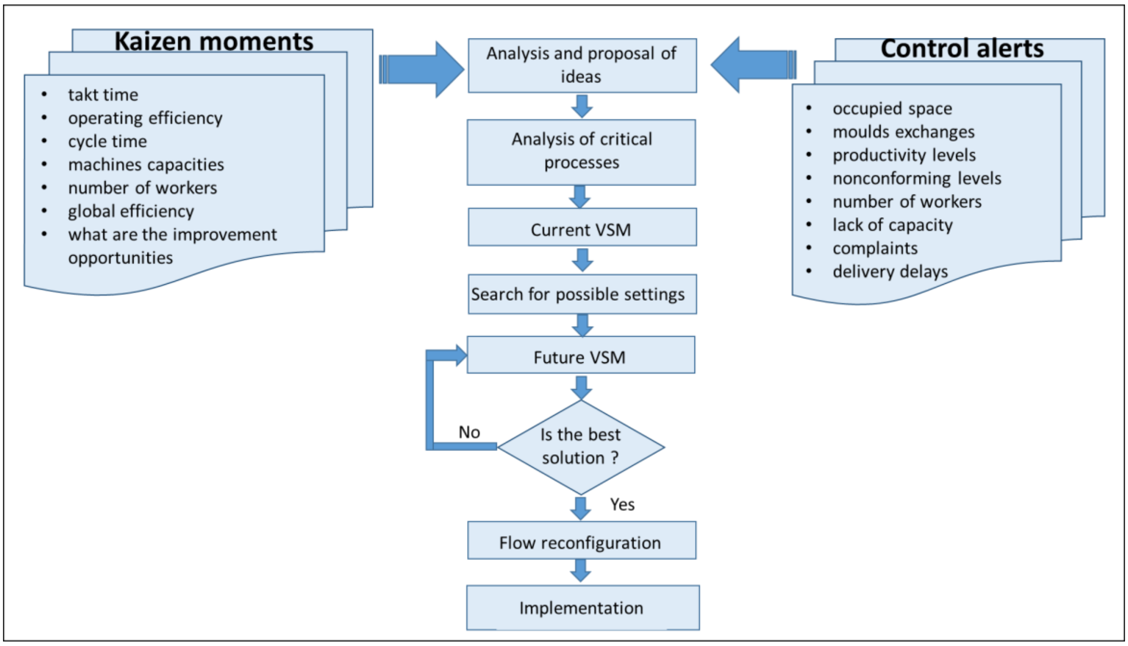

Figure 3. 23 - Currently layout reconfiguration process due to systematic evaluation.

Some of these reconfigurations can result on moving a *project*, from one facility to another, or just moving the production or assembly of some components.

The methodology for reconfiguration of facilities currently used by SIMOLDES does not give any idea on how far is the new solution from the optimum, and it cannot be applied to a set of facilities, at the same time. Our approach is therefore justified by these weaknesses of the current procedures.

3.6.1 Changing departments between facilities

To change layouts, we need to take into account several aspects, such as:

1) *Changing assembly departments can imply changes in components warehouses.* It is critical to safeguard assembly supply, frequently done at a high cadence. And transport between facilities can lead to delays or increase stocks at the assembly departments, suggesting the duplication of storage sites.
2) *Changing injection, needs to take into account the location of silos.* Some of the injection machines are directly connected to silos by pipes. Changing injection departments requires therefore checking the need of changing pipes and silos.
3) *Changing injection involves significant changes in maintenance activities* - the maintenance department is essentially dedicated to injection machines and mold maintenance. Therefore, most of the maintenance area is occupied by molds and parts of injection machines and tools. So if injection changes to another facility, it will be better to create also a maintenance site near the injection or, at least, at the same facility. Maintenance for other departments does not require too much space, and it is not so frequent as the injection maintenance.
4) *Changing silos of raw materials, it* can be very expensive, and this possibility should not be considered.
5) *Taking into account the stage of the project life, when change department to other facility* - that can imply more transport, during the rest of the project life

3.6.2 Changing departments inside facilities

The main points to be taken into account when changing the department locations inside the same facility obviously depend on the type of department under consideration:

- *Warehouses.* Changes in locations should try to minimize the negative impacts. In general, they only imply the time to dismantle and assemble the shelves and then, the time to transfer materials. In reality, these changes can be made gradually, without too much impact on departments operations, if there are available spaces for the transition, or if the changes can be made during a weekend.
- *Injection.* Due to the dimension of machines and the fact that these are the main productive departments, their change can imply stopping their production and the production of some other departments, that receive materials and components from injection, such as painting or assembly. These changes should therefore take place during large break periods (e.g. holidays periods). Of course, it is important to guarantee if the new location has the required infrastructure, or if it has to be changed, that the changes are as small as possible. Since there is no flow between the injection machines, moving the machines to another location, can be carried out machine by machine, thus reducing the production stops.
- *Assembly.* Changing the location of these departments can be made without much impact, except for the workplaces, lines or cells, that are being transferred.
- *Painting.* These departments are very difficult to transfer, because they are formed by several inter-connected stations, therefore these stations have to be moved simultaneously, this implying the need to stop the painting lines, and possibly affecting the three facilities.

3.6.3 Changing machines inside departments

Depending the type of departments and the type of machine to be relocated, we will need to take into account some important aspects, as described below.

Injection

- it is important to ensure that injection machines are assigned to places that are covered by bridges to transport moulds;
- machines should be aligned so that the *train* can pass, to collect and supply materials and products;
- there must be a zone in the injection department, for temporary storage of moulds being used;
- only some injection machines have pipes connecting them with silos, that need to be re-configured when machines are moved to new locations;
- each machine need to have an input area (for the storage of small material quantities) and an output area (for product storage);
- machines with higher cadence, should be located near doors, to be quickly supplied;
- there are no flows between machines, only inside cells or lines;
- it may be interesting to put together assembly workplaces and injection machines, therefore forming new cells, reducing space of both and transports between injection and warehouse, and warehouse and assembly.

Assembly

Reconfigurations inside these departments do not have any special requirement. However, the corridors should have enough space to allow the movements of the "train" that supplies and collects materials and products. As there are no flows between cells or production lines, machines can be changed without affecting the work of other machines.

Warehouses

Reconfigurations inside warehouses can be made without stopping production or the operation of other departments. However, moving shelves and "beater" (at the raw material warehouse) can be more painful, as they need to be dismounted and mounted again. Moving the beater also implies to change the pipes that directly supply some injection machines. Arranges in the remaining areas do not involve any major inconvenience.

3.7 Conclusions

In this chapter we have briefly presented the case study supporting this research project. Some of the main findings presented here are results of the direct observation and information analysis made by the author in the different facilities. The main problems of SIMOLDES seem to be in the articulation of activities and in the connection between facilities, with delays that often result on tasks and resources duplication. Another problematic situation is the use of around 50% of the area of facilities for stocks. In fact, this is a problem, especially when they need to increase the production area and do not have enough available space in the facilities. Layout reconfigurations, can be an important way to handle these problems. Optimizing layout configuration more often (for example, not only when a new project comes, but in a systematic way) would increase the flexibility in controlling layouts efficiency and resource utilization. As the complexity of products and of manufacturing systems is always increasing, tools are needed to support decision-making, and optimizing this process, and giving the possibility of analysing new and more complex evolution scenarios. There tools should help SIMOLDES maintaining the levels of efficiency and flexibility, to cover increasing market changes and more demanding production requirements.

4. PROPOSED APPROACH

The research gaps identified in our comprehensive literature review and the practical needs recognized in the case study led us to formulate a new extension of traditional FLPs – the Multi-Facility Layout Problem (MFLP). In this chapter, we describe the approach we have developed to address this new problem.

Contents of this chapter:

- *Introduction*
- *The multi-facility layout problem*
- *The model*
- *Adopted methodology*
- *Layout evaluation criteria*
- *Conclusions*

4.1 Introduction

The reconfiguration and continuous optimization of resources and production processes can be viewed as a natural way to reduce costs and increase business opportunities and profit (Afsarmanesh et al., 2009). The integration in Collaborative Networks (CN) can also be an important step to make organizations more effective and agile, as part of broader manufacturing systems, and this may be especially important for SMEs, due to their reduced dimensions and high vulnerability. In this context, one of the current big challenges for industry is the permanent need for rapid reconfiguration of manufacturing enterprises, in response to changing requirements and opportunities (Camarinha-Matos et al., 2009). This response capability should also exist at a higher, corporate level, combining a plant-level and a network-level analysis, as a way to understand the continuous interaction between individual plants and their constituent networks (Cheng et al., 2015).

To cover these needs and taking into account the fact that the wide variety of literature about *Facility Layout Problems* only focus on the design of single facilities, we propose a new extension of these models - the *Multi-Facility Layout Problem* (MFLP).

In this chapter, we present this new problem, and show its applicability, this model is inspired on the case study, that supports and justifies this research work. Then, the proposed approach is explained, as well as the evaluation criteria proposed for assessing the quality of solutions. Finally, the main conclusions on the developed research are presented.

4.2 The multi-facility layout problem

As referred before (see chapter 2), companies operate more and more as parts of larger networks independently of their particular ownership. We may have quite different configurations such as networks of companies, generally SMEs, or a large company with several facilities located worldwide. This new reality creates a need for tools to support the integration of operations, in a flexible and efficient way.

The classic facility layout problem (FLP) involves the physical organization of the resources needed for the production of goods or delivery of services. This is an intensively investigated area, due to the large impact that a layout configuration has in the performance of an industrial company (Drira et al.,2007). Layout reconfiguration can be a key tool to achieve more flexible and efficient operations in response to market changes, increasing companies’ competitiveness. This may be specially relevant for groups of facilities that are physically separated from each other, but have the possibility of exchanging and sharing departments.

The Facility Layout Problem (FLP) has been studied from many different perspectives, considering: the types of layout configuration (single row, multi-rows, multi-floor, etc.); the types of problem (facility location, department allocation, routing, etc.); the objectives and constraints; the static or dynamic nature of the problem; the large variety and combination of resolution approaches (exact methods, heuristics, etc.). There are in the literature several surveys related with the FLP, such as Keller and Buscher (2015), Chen et al. (2014), Moslemipour et al. (2012), Arabani and Farahani (2012) and Drira et al. (2007), but in general, the described approaches focus only on the case of single facilities.

The multi-floor layout problem is a particular case of the FLP (Neghabi and Tari, 2015) that has some similarities with the *multi-facility layout problem*. The multi-floor layout problem allocates resources to different floors of a single building, with horizontal and vertical material flows. These vertical flows are a strong constraint, associated to the existence of a single place to enter and exit the floor (generally through elevators). The *multi-facility layout problem* assigns resources to different buildings / facilities, involving internal and external flows (see Figure 4.1). *Internal flows* occur inside each facility, and are normally performed by the transportation systems existing in the facility. Depending on the type of manufacturing process, some internal transportation tasks could even be performed *continuously* (e.g. with conducts, carpets). On the other hand, there are *external flows*, between facilities, that are often quite critical, as they are dependent on external transportation means (e.g. trucks, trains), being therefore subject to several uncontrollable factors. These factors clearly justify the development of an integrated model for the problem (Azevedo et al., 2017).

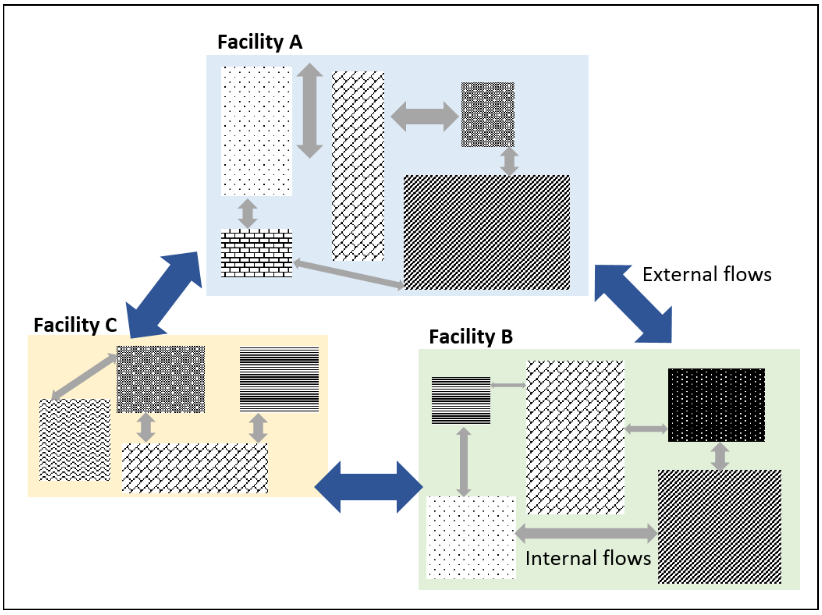

Figure 4. 1 – Multi-facility layout.

Our work involves the allocation of departments (with unequal areas) to multiple facilities that behave as a single, integrated production system, in a discretized time planning horizon (e.g. each period can be a couple of years, normally ranging from 2 to 4 years). In each time period it is possible to change the area of the departments, as a way to respond to variations of the demand (due to new products, seasonality, etc.) or to emerging strategic adjustments. The model also considers the possibility of capacity changes along time, with the possibility of changing the area of departments and transport capacities, as well as changes in the mode of transport between facilities.

The *multi-facility layout problem* deals with companies owning several facilities physically separated from each other, with departments to be allocated to the facilities, in order to achieve more flexible and efficient operations. In this study, the developed model was applied to the automotive industry, but it can be easily adapted to other industrial sectors, in cases where there are a set of geographically separated facilities or where companies are organized in a collaborative network The MFLP is meant for the simultaneous design of the layout of a group of facilities, with the allocation of products, considering the whole network. In our model, this network can have different topologies along time, by adding or reducing the number of facilities and departments, according to market needs, for each period and for each product.

4.3 The model

As stated above, the MFLP allows several layout analysis and reconfigurations, that can take place at three levels: 1) globally, taking into consideration all the facilities; 2) locally, for each facility, trying to fit its characteristics and specific features to the needs of departments at each planning period; and 3) operationally, at the machine level, organizing the machines inside each department according to the production characteristics and to the needs of each product, at each time window (see Figure 4.2).

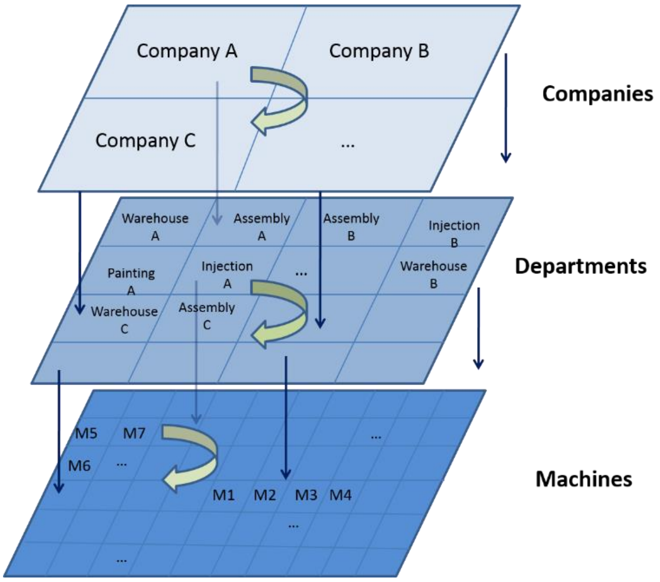

Figure 4. 2 – Multi-facility layout analysis levels.

Given the high variety and complexity of products, as it is the case in the automotive industry, the need for adjustments in layouts is also higher. Quite often, machines are large and difficult to move, and therefore most of the times, interesting changes in the layouts are not performed or they are continuously postponed. Frequently, new machines are located in unplanned places, creating difficult material flows, and thus decreasing efficiency. In reality a layout is efficient if the materials flow in a rapid way, without waste of time and resources, and it is flexible when it allows fast, cheap and easy to do reconfigurations (Azevedo et al., 2013). Depending on the level of analysis, our model handles two types of reconfigurations: "*small*" and "*large*" *changes* (see Figure 4.3).

Large changes are required when departments need to be moved from one facility to another, or change their position in the same facility, possibly as a result of the arrival of new projects. However, there is not always a need to change the whole department; frequently some adjustments inside departments are enough to get significant operational efficiency gains. These interventions are called here *small changes* - they are naturally more frequent and consist of reconfigurations inside a department, by adding / dropping machines, or by redirecting the flows of materials and products in progress. Typically, this type of change does not interfere with the normal operation of the other departments and may even not affect all the machines in the department that is being reconfigured. However, if needed, these changes at the machines level can be applied to design a complete facility.

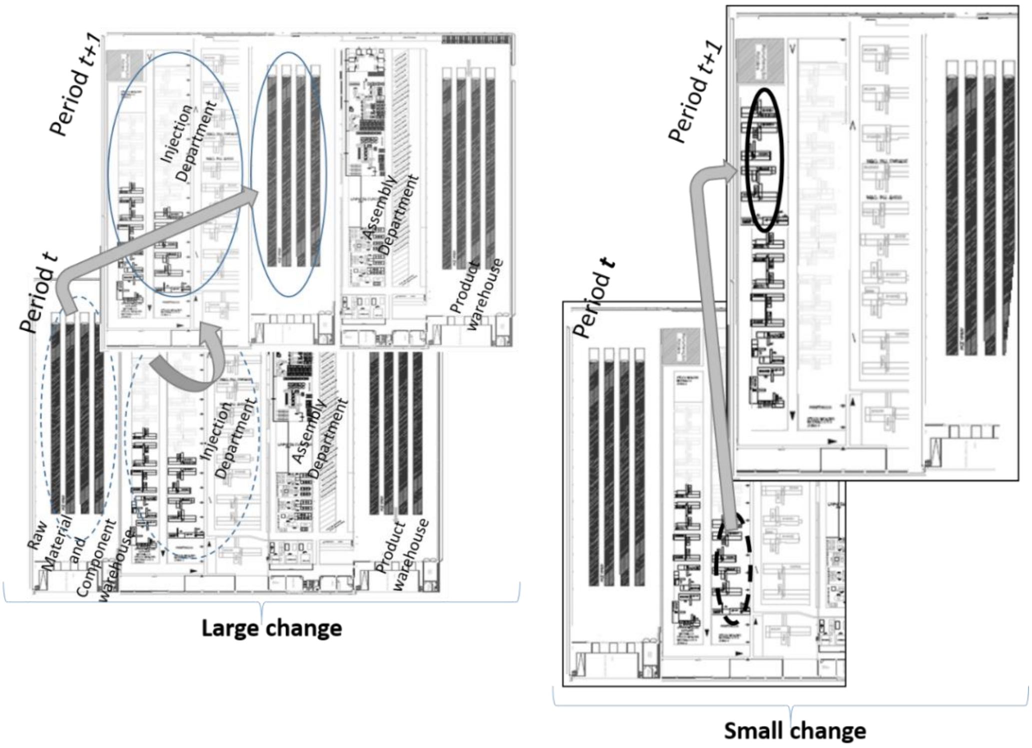

Figure 4. 3 – *Large* and *small* changes in a layout (example).

Based on these concepts and principles, we propose a new approach for layout design – see Figure 4.4. This approach was developed inspired on our real life case study, and consists in a set of 7 steps. It starts with a characterization of the current situation, in terms of layout configuration. Then, this current layout is evaluated taking into account a set of pre-established criteria. With the results of this evaluation, it is possible to check if the layout is efficient enough or if it has to be reconfigured. At this step, it is also possible to identify the type of reconfiguration needed, and what are the departments that need to be optimized.

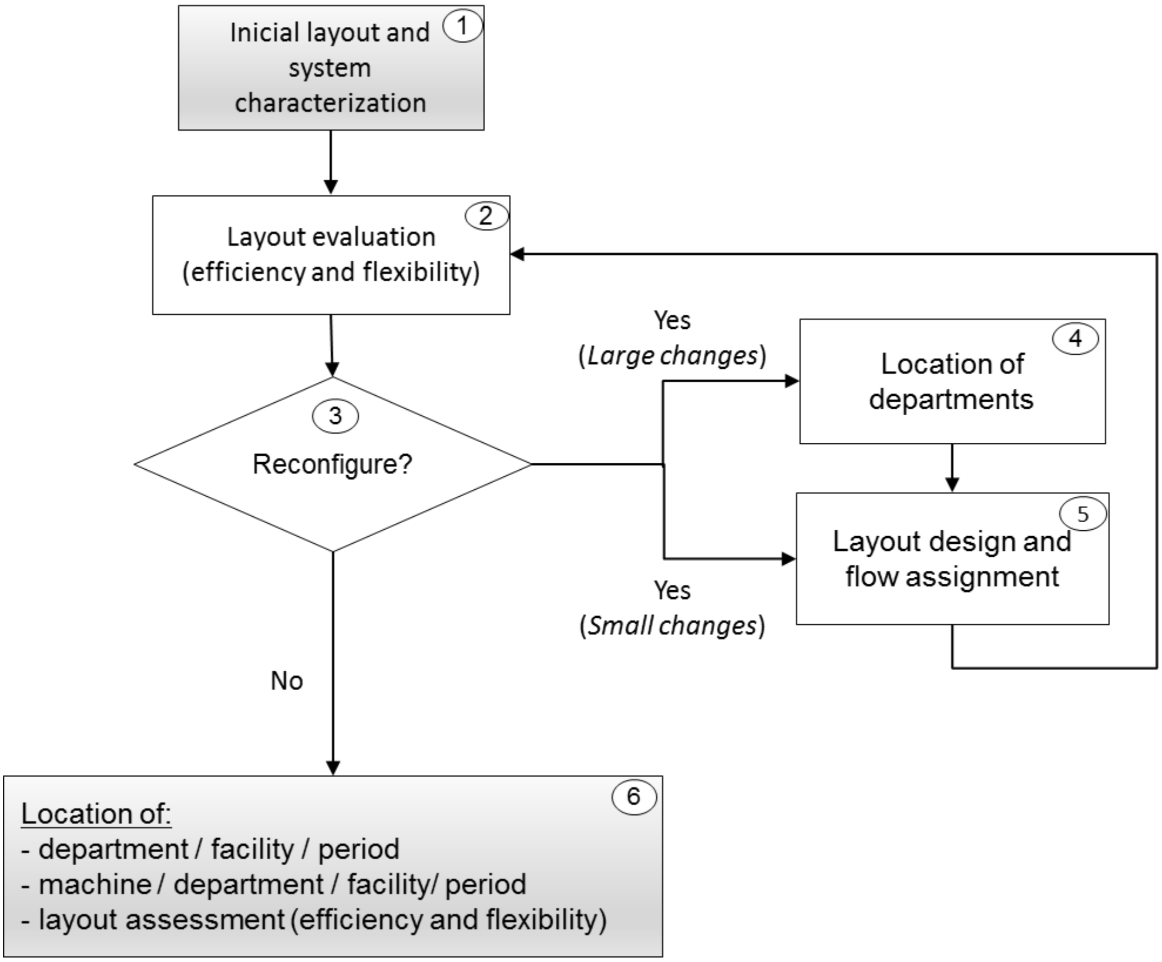

Figure 4. 4 – Proposed approach.

This approach consists of the following 7 phases:

Phase 1 – The system is described and characterized by a set of parameters.

Phase 2 – With this information the system is evaluated in a multi-criteria perspective.

Phase 3 - The results of this evaluation are compared with predefined layout efficiency and flexibility targets. If the levels of efficiency are satisfactory, the current layout is not changed. Otherwise, depending on the level of achieved efficiency, the required reconfiguration of the layout can be classified as “large” or “small”. For example, if only one department has low efficiency, only this department needs to be reconfigured, this consisting in a *small change* (phase 5). On the other end, if the whole system has low efficiency, the reconfiguration is considered to be *large* (phase 4).

Phase 4 – Using several criteria (costs, unsuitability and adjacency requirements), the model determines the new locations for the departments.

Phase 5 - With several criteria (costs, unsuitability and adjacency requirements), the model determines the position of machines inside each department and the respective flow assignment.

Phase 6 - Finally, a complete solution is presented, with the layout configuration of the system, organized in different levels: facilities, departments, machines, and the assignment of products to the different machines.

This "framework" allows the decision maker to experiment different perspectives, at different situations of the life cycle of a manufacturing system (as previously explained in section 2.3.5 (Figure 2.7) and exemplified in section 3.6), namely:

i) for a group of key departments of a facility, with enough space to receive a new production system, with new technology and new machines;

ii) for a complete facility, only to assess how it is operating, or even to increase the production capacity or portfolio and to re-design the layout accordingly;

iii) for a group of facilities that collaborate in the manufacturing of certain products, and that can share resources.

These are just some examples, but many other situations can be analysed with this type of tool. For the layout reconfiguration and design (at phases 4 and 5) we have applied operational research methods, in particular by developing a mathematical programming model for the *Multi-Facility Layout Problem*.

4.4 Adopted methodology

In this work, we have followed the classical approach for decision-making process, composed by four main steps, Figure 4.5.

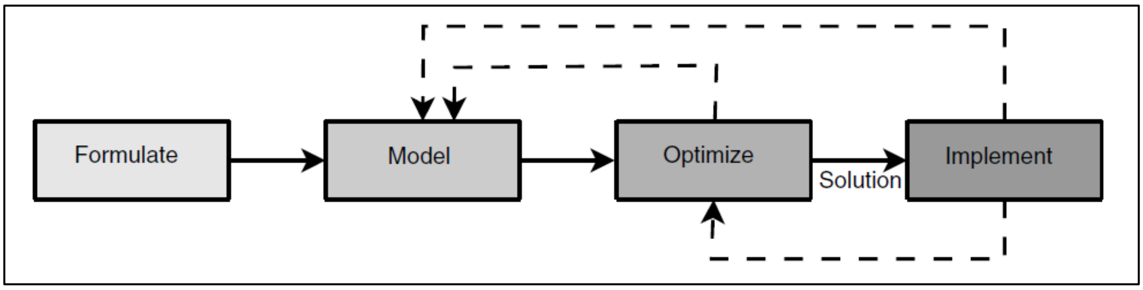

Figure 4. 5 – Classical process in decision making (Talbi, 2009).

Problem formulation. With an initial statement of the problematic situation under analysis, the problem is formulated, by defining its scope and by considering its internal and external factors, and the objectives. The result of this phase is a statement of the *objectives*, to be achieved by solving the problem; the *constraints* (bounds to be respected) in the overall system and the *relations* and interdependence of all the components of the system.

Problem modelling. A model is a simplified representation of the reality. It reflects the essence of the problem, representing the existing interdependence relations between all the components of the system under analysis. A mathematical model is defined by a set of equations (inequalities) limiting the values of a set of decisions to be taken, represented as *decision variables*. They are interrelated by a mathematical function, the *objective function*, which represents the measure of advantage (disadvantage) associated with the decision represented (this function is either to be maximized or minimized). In many situations, there are state-of-the-art mathematical models, previously used, that can be adapted to the problem under analysis. That is the case of this research, where we are extending the well-known FLP to a MFLP.

Model optimization. At this phase, a solving procedure is used to generate a solution for the model, that in fact is a simplified representation of the real-life problem. As presented in section 2 (Figure 2.6 and Table 2.5), the FLP has been solved with several optimization methods. Exact methods look for the optimal solution but can only be based in small problems or in problems with less complexity (to be solved in reasonable time, as these combinatorial problems are NP-hard). On the other hand, approximate methods (heuristics) are able to find satisfactory (non-optimal) solutions in an efficient way, i.e. with a low computational time.

As we are starting to explore a new extension of the FLP (the MFLP), developing the basis for a new research line, it is important to find optimal solutions, to establish and prove the importance of this new model. We therefore use an *exact method* to solve the MFL models. To illustrate the application of the proposed models, we have develop instances, based on the case study, for which we can find optimal solutions in reasonable time (seconds), as presented in the next chapters. Moreover, in practice, this kind of decision (changing a complete department, from a facility to another), is not taken in one or two days, being subject to discussions and adjustments. So if a problem instance needs two or more hours to reach the optimal solution, this is not critical. And in practice, an "optimal" solution can never be completely implemented – rather being used to provide insights and guidelines to the real solution.

On the other hand, there are more and more sophisticated software tools, such as CPLEX, that can be used to efficiently solve to optimality medium or even large size real problems. CPLEX is currently viewed as probably the most advanced optimization software, integrating quite sophisticated features for dealing with complex integer, non-linear models, and was recently upgraded with interesting developments to solve quadratic problems. We have therefore used CPLEX to solve our MFLP.

Implementation. Finally, the obtained solution is analysed and assessed by the decision maker. When approved, it is implemented, frequently with adjustments and refinements imposed by practical reasons. While the solution is not practically "acceptable", the model and/or the optimization procedure should be improved, and the decision-making process repeated.

4.5 Layout evaluation criteria

As previously mentioned, in section 2.3.5, layouts can be evaluated at different moments and in various ways. Based on the list of the main criteria used in the literature about the FLP (Table 2.7 and Table A.2.1), we have selected a set of criteria to be used in our work, as presented in Table 4.1. Those criteria are the more representative for the case study, but the model can support other combinations of criteria, we adopted to the specific situation under analysis.

Table 4. 1 – Layout evaluation criteria.

	***Large changes* model**	***Small changes* model**
COSTS	**C1 - Material handling costs / Inventory costs**	
	transport cost inside facilities transport cost between facilities internal MHC (inside facilities) external MHC (between facilities)	transport cost inside facilities MHC
	C2 - Non-inventory costs	
	cost of shifting departments operating cost of departments cost penalization for suppling from a facility	cost of shifting machines operating cost of machines total production cost
PHYSICAL characteristics	**C3 – Distance**	
	distance between locations distance travelled	distance between locations distance travelled
	C4 - Material flow	
	production sequence of each product (project) flows between departments, each period total flows, each period	production sequence of each product flows between machines demand of products per period
	C5 – Capacity (volume density)	
	transport capacity (between facilities)	machine capacity machine capabilities
	C6 – Closeness	
	closeness ratio between departments adjacency between departments	closeness ratio between machines adjacency between machines
	C7 - Space utilization	
	area of locations area of departments	area of locations area of machines
	C8 - Building expansion	
	adding and reducing facilities and departments changing area of departments	adding and reducing machines and departments changing area of machines and departments
	Others	
	department rating requirements rating of location characteristics	machine rating requirements rating of location characteristics
Others	**C12 – Transportation system**	
	transport capacity	

4.5.1 Layout Costs

Layout costs are the main criteria used in the literature for layout evaluation, (Table 2.2, Table 2.7, and Table A.2.1), especially the material handling costs (MHC). Naturally, our model also takes into account costs to evaluate layouts (even if other criteria are also considered).

As mentioned above, layout costs here are composed by: the operational cost, the transportation cost, and the reconfiguration cost. The operation and transportation costs are mainly related with the daily operation of the system.

The **Transportation cost (*ct*),** is the cost of moving one unit (of materials or products) one unit of distance. This cost depends on the transportation equipment used and may be significantly different if it is inside a department, between departments, or between facilities. With the quantity (q) to transport and the distance travelled (r) we have the **material handling cost (*Ct*)**, frequently used as the main objective to be minimized in the layout design process.

$$Ct = q * r * ct \tag{4.1}$$

The **re-layout cost (C_r)** will reflect all the costs of moving a part of a system from one place to another, and has the following components:

$$C_r = c_{stop} + c_{desM} + c_{prep} + c_{restart} \tag{4.2}$$

Stopping (or closing) a department (c_{stop}) could imply closing not only departments that will move, but also others, that are related and near, or because other machines and equipment in the neighborhood have to be moved. To reflect this cost, we will consider a fixed cost, depending on the type of department and machine to be moved.

Dismantling and mounting a department or a machine (c_{desM}) these two costs are essentially the same, as dismantling normally requires the same tasks and time as mounting again. This cost depends on the type of department (and its machines) and includes the transportation cost, from the initial place to the final place.

Preparing the new place to receive a department (c_{prep}) involves costs for installing or changing the power grid, the compressed air network, the floor to support some specific machines and all related works. So, this cost depends on the type of department and machines.

Restarting operations ($c_{restart}$) has a cost that includes the production lost, during the initial test until a normal level of production is reached. It, also depends on the type of department and machine.

The **Operation cost (*Co*)** is a fixed cost that depends on the type of department or machine. It includes costs for maintenance, power, and workers. For instance, a warehouse may have operation costs that are quite different from those of a production department.

4.5.2 Physical characteristics

The configuration of facilities is influenced / constrained by a set of physical characteristics of the location to be configured. The most commonly considered aspects are:

- **Distance** between departments or machines. Some departments or machines should be as close as possible. When we are considering several facilities, departments may even be located in different countries or cities.
- **Material flows** are related to the production sequence of a product, in terms of machines or layouts, and to the quantities (of materials, components, products, etc.) that will be moved from one department to another or between machines, or even facilities. Depending on the model, these flows may be represented in a more or less aggregated way (detailed by product or project, or considered on the whole).
- **Capacity**, that reflects the physical capacity and capabilities to process a product. It is applied only in the "*small changes*" model for the machines.
- **Closeness**. Depending on the characteristics of some departments and machines, they can have some closeness requirements. For example, some departments need to be isolated, to not contaminate the other departments, or due to the continuality of the process they have to be together. In our case, due to the existence of departments with different importances, and to the fact that we are considering several facilities physically separated, we consider the *adjacency* between departments and machines, as an objective to be maximized. Here, we use on a closeness rating (in a [0 to 5] scale), defining the importance of proximity between departments (for this purpose we have adopted the classification by (Jaafari et al., 2009). Due to market changes, the production sequences and needs, in terms of proximity between departments and machines, may also change, from period to period. We therefore take this into account, by considering that the needs for closeness can change along time (Abedzadeh et al., 2013).

The fact that departments are allocated to different buildings can constraint, in different ways, the relationships between departments, e.g. by imposing constraints on sharing the same specialized equipment or workers. To cope with these situations, the model considers a *proximity* rating (with values from 0 to 5) between the locations where the departments are positioned (see Table 4.2).

Table 4. 2 – Proximity rating between locations, and closeness rating between departments.

Value	Proximity rating	Closeness rating
5	At the same building, at adjacent locations	Absolutely necessary
4	At the same building, at close locations	Especially important
3	At the same building, at relatively near locations	Important
2	At buildings relatively close	Ordinary
1	At buildings relatively far	Unimportant
0	At buildings far from each other	Undesirable

For example, if we consider the layout of Figure 4.6, and the information about proximity between locations and department closeness, in Table 4.3, the total adjacency value is computed as explained in Table 4.4.

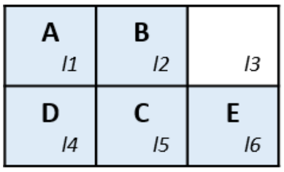

Figure 4. 6 – Layout configuration (example).

Table 4. 3 – Adjacency information (example).

Location proximity						
	l1	***l2***	***l3***	***l4***	***l5***	***l6***
l1	-	5	3	5	4	3
l2	5	-	5	4	5	4
l3	3	5	-	3	4	5
l4	5	4	3	-	5	3
l5	4	5	4	5	-	5
l6	3	4	5	3	5	-

Department closeness					
	A	**B**	**C**	**D**	**E**
A	-	5	1	3	0
B	5	-	1	1	1
C	1	1	-	5	1
D	3	1	1	-	1
E	0	1	1	1	-

Table 4. 4 – Computation of the total adjacency value (example).

				Adjacency
A*l1* x B*l2*	A*l1* x C*l5*	A*l1* x D*l4*	A*l1* x E*l6*	44
(5 x 5)	(1 x 4)	(3 x 5)	(0 x 3)	
B*l2* x A*l1*	B*l2* x C*l5*	B*l2* x D*l4*	B*l2* x E*l6*	38
(5 x 5)	(1 x 5)	(1 x 4)	(1 x 4)	
C*l5* x A*l1*	C*l5* x B*l2*	C*l5* x D*l4*	C*l5* x E*l6*	39
(1 x 4)	(1 x 5)	(5 x 5)	(1 x 5)	
D*l4* x A*l1*	D*l4* x B*l2*	D*l4* x C*l5*	D*l4* x E*l6*	27
(3 x 5)	(1 x 4)	(1 x 5)	(1 x 3)	
E*l6* x A*l1*	E*l6* x B*l2*	E*l6* x C*l5*	E*l6* x D*l4*	12
(0 x 3)	(1 x 4)	(1 x 5)	(1 x 3)	
				160

According to these computations (Table 4.3), department A must be near to department B, with a value of closeness of 5; and the same, for departments C and D. They are, therefore, positioned at adjacent locations, as shown in Figure 4.6.

- **Space utilization**. The space available must be able to accommodate the areas of the various departments, and machines. This aspect has a great impact in our model, since we allow the possibility of having distinct areas in each period.
- **Building expansion**. In this work, we have explored the possibility of increasing and reducing the number of departments and facilities at each period, to cope with fluctuations in demand.
- **Space suitability**. This factor comprises other physical characteristics that make a space more suitable than another. During the design of a layout, mainly in layout reconfiguration, there are some characteristics that are specific requirements of some departments. On the other hand, there are the existing characteristics of each place, which should fit with the characteristics of the department. As an example, consider the resistance of the floor (injection departments need sturdy, smooth surfaces). Therefore, the model should take this into consideration, when selecting the place. In case there is no place with the required characteristics, there is a cost related to the preparation of the surface. Taking into account these other physical characteristics allows us to perform a more adequate reconfiguration, and to estimate times and costs for the preparation of the space. Other characteristics, that could also be interesting to take into consideration are:

- existence of boarding wharfs for loading trucks;
- existence of cranes, or other equipment to facilitate vertical movements of materials;
- existence of specific containers to store materials;
- day light existence or absence.

The minimization of *unsuitability*, for facility layout problems, is a new point of view, and a way to give layout stability, extending its lifetime, and taking advantage of the existing conditions. This may also be a tool to decrease costs in adapting the place to the required characteristics, reducing the local reconfiguration time and working with more efficiency.

These characteristics can be represented in a "1 to 5" scale, reflecting the *fitness level* between the requirements of each department and the characteristics of each location (see Table 4.5). If a department is assigned to a location with a lower level them required, some kind of penalty (or cost) is incurred or the assignment is infeasible. Here we have assumed that a department cannot be allocated to a location with lower assigned value than the required by the department.

Table 4. 5 – Linguistic set for the departments requirements and locations features.

Value	Department requirements	Location features
1	department without requirements	place without these features
2	department with a few requirements	large effort needed to implement these features
3	department with some requirements	moderate effort needed to implement these features
4	department need most of these features	easy implementation of these features
5	department must have these features	place with these features

To better understand this new concept, we can look, in more detail, to an illustrative example, considering two "characteristics":

Characteristic C1 - floor resistance, denoting the level of floor preparation required to support heavy machines (this is especially important in injection departments);

Characteristic C2 - cranes required, this characteristic being important, for example, for moving "molds" at injection departments (a mold, can be considered as a tool of injection machines, with large dimensions and heavy weight, that could be changed any time that the product changes).

$$\boldsymbol{Uns} = \frac{C1_{local}}{C1_{department}} + \frac{C2_{local}}{C2_{department}} + \cdots + \frac{Cn_{local}}{Cn_{department}} \tag{4.4}$$

Considering the layout presented on Figure 4. 6, with the characteristics detailed on Table 4.6, the *unsuitability* score of this configuration, applying equation (4.4) is 7 (2+3+2). More than the global value of unsuitability, the most important is how its location can fit the allocated department, on each characteristic, with diverse levels of importance for each department. In this example, department A fits totally in both characteristics, with different levels (5 for C1 and 1 for C2). But department B only fits totally in characteristic C2 (2/2); however if it is on position *l1*, it will be more unsuitable in both characteristics (c1 = 5/2 and c2 = 1/2), so position *l2* is a better location.

Table 4. 6 – Unsuitability example.

Department	C1	C2	Location	C1	C2	Unsuitability	Observation
A	5	1	***l1***	5	1	5/5 + 1/1 = 2	C1 and C2 fit totally
B	2	2	***l2***	4	2	4/2 + 2/2 = 3	only C2 fits totally
C	1	1	***l5***	1	1	1/1 + 1/1 = 2	C1 and C2 fit totally
Total						**7**	

Discussions with practitioners suggest that this new “measure” (objective) can be very important in the reconfiguration of facilities that are currently not operating. These facilities can be prepared to accommodate new manufacturing areas in the future, thus making a better use of available spaces (Azevedo et al., 2017).

4.5.3 Transportation system

Transportation is extremely important when we allow the existence of geographically dispersed facilities. The choice of a mode for transport influences speed, capacity, cost and reliability. In this study, we only focus on cost and capacity (being possible to explore different transport capacities at each period). Based on these features, the DM can experiment and assess the use of different transport systems.

4.6 Conclusions

In general terms, the approach proposed here was developed, based on the case study, to solve multi-facility layout problems (MFLP). However, it can be applied to any facility layout problem (FLP). Other important characteristic of this approach is the possibility of integrating the "*small* and *large*" changes, or even to apply them separately.

One of the main contributions of this research work is the design of a decision-making procedure based on two types of reconfigurations that differ in the deepness and frequency of the modifications (the concept of "small" and "large" changes), making the manufacturing system more dynamic and flexible. This is a dynamic model, not only because we can, at any time, change the position of departments and machines, but also because it allows changing networks, by adding or eliminating facilities, departments or machines.

The layout evaluation criteria (characteristics) presented in the previous sections were incorporated in the proposed models, as objectives or as constraints. The proposed models for the MFLP are multi-objective, based on the *minimization of costs*: (material handling costs (*Ct*); reconfiguration costs (*Cr*); and operation costs (*Co*)); the *minimization of unsuitability* between locations and departments or machines, depending on the model ("*large changes*" or "*small changes*"); and the *maximization of adjacency* between departments or machines. The remaining criteria will be applied by defining additional constraints (or goals), for example: ensuring that the area of a department or a machine should always be less than or equal to the area of the location to where it will be assigned; ensuring that the existing capacity for transportation between facilities is never exceeded; guaranteeing that a department is only assigned to locations with suitable characteristic values; ensuring that, at the flow allocation of the "small changes" model, each operation of each product only takes place in compatible machines; checking that the capacity of each machine is never exceeded; and guaranteeing that all operations of each product are assigned to one machine in each period.

In summary, we might say that this model can be efficiently used to support the design and deployment of new configurations and layouts, for advanced forms of collaboration, and thus promote the strategic agility of a corporate group. This will allow a higher adaptability to customer requirements (better handling demand fluctuations or changing the location of facilities to be closer to customers) certainly improving global performance. On the other hand, the MFLP can also be applied to a group of companies with the same owner, for sharing departments and machines.

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5. MODEL FOR *LARGE CHANGES*

This presents and assesses a mathematical model for the multi facility layout problem for departments allocation (large changes).

Contents of this chapter:

- *Introduction*
- *Mathematical model*
- *Illustrative example*
- *Computational assessment of the model*
- *Conclusions*

5.1 Introduction

In this chapter, we present and computationally assess a mathematical model for the *multi facility layout problem* (MFLP) proposed in chapter 4. As referred, this work studies the *facility layout problem* (FLP) in a new perspective, considering a group of facilities and two different concerns: to optimize the location of departments within a group of facilities; and to optimize the location of departments inside each facility, itself. So there are two types of flows: *Internal flows* occur normally inside a facility; and the *external flows,* between facilities, that are more critical as they depend on external transportation means.

The problem is formulated as a Quadratic Programming Problem, with multiple objectives and unequal areas, allowing layout reconfigurations in each planning period. The objectives of the model are: the minimization of costs (material handling inside facilities and between facilities, and re-layout); the maximization of adjacency between departments; and the minimization of the "unsuitability" of department positions and locations. This *unsuitability* measure is a new objective proposed in this research project, to combine the characteristics of existing locations with the requirements of departments. The constraints considered in the model are those usually applied to the FLP: no department overlapping; each department is assigned only to one position; and the department size fits into the location area. Moreover, a new constraint has been considered, to bound the transportation capacity between facilities, in each planning period; and another constraint to guarantee that departments are only assigned to positions with the required characteristics.

The model was tested with data from the literature, as well as with two illustrative instances, inspired in a first-tier supplier in the automotive industry. The first instance intends to perform a sensitivity analysis of the model on several key features: problem dimension, multiple objectives, transport capacity, and cost outcomes. Then, we also performed testes with a large instance (with 30 departments) to demonstrate the applicability of the model on real problems. The model presented in this chapter has already been published (Azevedo et al., 2017).

5.2 Mathematical model

The formulation presented here is based on the Quadratic Assignment Problem (QAP), commonly used for dynamic layout problems (Drira et al., 2007) with multiple objectives. We started with the mathematical model introduced by Balakrishnan and Cheng (2000) and adapted it for the MFLP with multiple objectives (see expressions below). We now introduce the concepts and notation used in the model.

Indices	
T	number of periods
F	number of facilities
I	number of departments
L	number of locations inside facilities
N	number of characteristics to evaluate the *suitability* between departments and locations
Parameters	
a_l	area of position *l*
a_{it}	area of department *i*, in period *t*
$r_{(f1,l)(f2,k)}$	distance between position *l* at facility *f1*, and position *k* at facility *f2*
q_{ijt}	flow (product quantity) to move between department *i* and *j*, in period *t*
$ctInt_t$	transport cost of a unit of material per unit of distance in period t, inside facilities
$ctExt_t$	transport cost of a unit of material per unit of distance in period t, between facilities
cr_i	cost of shifting department *i*
Ct	total material handling cost
$CtInt$	total material handling cost, inside facilities
$CtExt$	total material handling cost, between facilities
Cr	total reconfiguration cost
e_t	transportation capacity between facilities, in period *t*
Chd_{ni}	rating of requirements of department *i*, for characteristic *n*
$Chl_{n\,(f,l)}$	rating of characteristic *n* of location *l* of facility *f*
Uns	total unsuitability value
cl_{ijt}	closeness rating between departments *i* and *j, in* period *t*
$Prox_{(f1,l)(f2,k)}$	proximity rating between locations *(f1,l)* and *(f2,k)*
Adj	total adjacency value
α, β, γ *and* δ	weights for the multi-objective function
Decision variables	
$x_{i(f,l)t}$	1, if department *i* is placed at position *l*, in facility *f*, in period *t*; 0 otherwise

In order to duly capture the multi-objective nature of the problem, four different objectives have been considered. They are described here in some detail, and they were aggregated, for computational purposes, in a single weighted function (see equation (5.4)).

- *Minimize total material handling costs* (MHC) – this is commonly applied in the literature of the unequal area FLP ((Abedzadeh et al., 2013), (Bozorgi et al., 2014), (Emami & S. Nookabadi, 2013)). Like Wong (2010), we assume fixed dimensions for facilities and the existence of several departments to be located inside facilities. For the MFLP we consider the total MHC as the sum of internal MHC (equation (5.1.1)) and external MHC (equation (5.1.2)).

$$Ct = CtInt_t + CtExt_t \tag{5.1}$$

$$CtInt_t = \sum_{t=1}^{T} \sum_{f=1,(f1=f2)}^{F} \sum_{l,k=1}^{L} \sum_{i,j=1}^{I} \left[q_{ijt}\, r_{(f1,l),(f2,k)}\, ctInt_t\, x_{i(f1,l)t}\, x_{j(f2,k)t} \right]$$

(5.1.1)

$$CtExt_t = \sum_{t=1}^{T} \sum_{f=1,(f1 \neq f2)}^{F} \sum_{l,k=1}^{L} \sum_{i,j=1}^{I} \left[q_{ijt}\, r_{(f1,l),(f2,k)}\, ctInt_t\, x_{i(f1,l)t}\, x_{j(f2,k)t} \right]$$

(5.1.2)

- *Minimize reconfiguration costs (RC)* - the model will reflect the total cost of reconfiguring a layout, according to equation (5.2), as usually used for layout reconfigurations (see e.g. Shahin and Poormostafa (2011) or McKendall and Hakobyan (2010)).

$$\boldsymbol{Cr = \sum_{t=2}^{T} \sum_{f=1}^{F} \sum_{l,k=1}^{L} \sum_{i=1}^{I} \left[cr_i\, x_{i(f1,l)t}\, x_{i(f2,k)t-1} \right]} \tag{5.2}$$

- *Minimize unsuitability between departments and locations (UC)* - unsuitability is used to measure (for a department positioned in a given location of a facility) the gap (to be minimized) between the actual characteristics of the existing location ($Chl_{n\,(f,l)}$) and the ideal characteristics of departments (Chd_{ni}), as defined by equation (5.3).

$$\boldsymbol{Uns = \sum_{t=1}^{T} \sum_{f=1}^{F} \sum_{l=1}^{L} \sum_{n=1}^{N} \left[\frac{Chl_{n(f,l)}}{Chd_{ni}} * x_{i,(f,l)} \right]} \tag{5.3}$$

As explained in the previous chapter, those characteristics can be defined in a "1 to 5" scale, reflecting the fitness level between requirements of each department and the characteristics of each location.

This new objective can be very important in the selection and reconfiguration of facilities that are currently not operating. These facilities can be prepared to accommodate new manufacturing areas, thus making a better use of available spaces.

- *Maximize adjacency between departments (ADJ)* – as previously explained, this measure is based on a *closeness* rating (cl_{ijt}) and a *proximity* rating (in a “0 to 5” scale), defining the importance of proximity between locations *(f1,l)* and *(f2,k)* where the departments are positioned ($Prox_{(f1,l),(f2,k)}$)(see Table 4.2).

  The adjacency of a pair of departments (department *i*, located at facility *f*, at location *l*; and department *j*, located at facility *f1*, at position *k)*, is determined by equation (5.4).

$$\boldsymbol{Adj = \sum_{t=1}^{T}\sum_{i,j=1}^{I}\sum_{f=1}^{F}\sum_{l,k=1}^{L}\left[cl_{ijt}\ Prox_{(f1,l)(f2,k)}\ \left(x_{i(f1,l)t}\ x_{j(f2,k)t}\right)\right]} \tag{5.4}$$

The components for the individual objectives have been duly normalized[1] (e.g. Ct_{Norm} is the normalized value for Ct, the total material handling costs).

Adopting this notation, the model can now be written as follows.

$$Min\ Z = \alpha\ Ct_{Norm} + \beta\ Cr_{Norm} + \gamma\ Uns_{Norm} - \delta\ Adj_{Norm} \tag{5.5}$$

Subject to:

$$\sum_{i=1}^{I} x_{i(f,l)t} \leq 1 \quad \forall l,f,t \tag{5.6}$$

$$\boldsymbol{\sum_{f=1}^{F}\sum_{l=1}^{L} x_{i(f,l)t} = 1 \quad \forall i,t} \tag{5.7}$$

$$\boldsymbol{\left[\left(a_{it} - a_l\right) x_{\,i(f,l)t}\right] \leq 0 \quad \forall\, i,l,t,f} \tag{5.8}$$

$$\sum_{f=1,(f1\neq f2)}^{F}\sum_{l,k=1}^{L}\left[q_{ijt}\quad x_{i(f1,l)t}\quad x_{j(f2,k)t}\right] \leq e_t \quad \forall t \tag{5.9}$$

$$\left[\left(Chd_{ni} - Chl_{n(f,l)}\right)\ x_{i(f,l)t}\right] \leq 0 \quad \forall t,f,l,i,n \tag{5.10}$$

$$\alpha + \beta + \gamma + \delta = 1 \tag{5.11}$$

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[1] Normalized according to uniform distribution, e.g. $Ct_{Norm} = \frac{Ct - Ct_{min}}{Ct_{max} - Ct_{min}}$

The constraints in the model are those usually applied in unequal areas FLPs (Wang et al., 2005), adapted to this multi-facility dynamic layout problem. Constraints (5.6) ensure that each position in a facility has at most one department, in each period. Constraints (5.7) guarantee that each department is assigned only to one position, in each period. Constraints (5.8) ensure that the area of a department (*i*) in period (*t*) should always be less than or equal to the area of location (a_l) to where the department is assigned (Lacksonen, 1997). Constraints (5.9) ensure that the existing capacity for transportation between facilities is not exceeded in any period. Constraint (5.10) guarantee that a department is only assigned to locations with values for characteristics that are higher or equal to the values required by that department. Finally constraint (5.11) guarantees that the total value of the weights of each objective is equal to 1 (Singh & Singh, 2010).

5.3 Illustrative example

To better understand how the model can be applied, we have designed this illustrative example, inspired in the case studied in this work, previously presented in chapter 3.

Facilities

With 3 facilities (*facility1*, *facility2*, *and facility3*) geographically apart, the company has, in total, 13 locations to position the departments (see Figure 5.1).

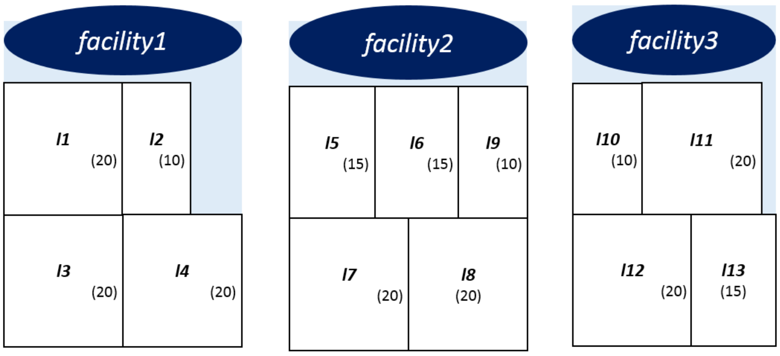

Figure 5. 1 – Location areas for the different facilities (e.g. location *l1* has an area of 20 units).

A distribution system (with trucks) is used to move raw materials, components and/or (final) products between facilities. This system has capacity constraints that can change from period to period. We consider distinct transportation costs, inside and between facilities, that can also change depending on the period (see Table 5.1).

Table 5. 1 – Data on facilities and locations.

		facility1				facility2					facility3			
Location		*l1*	*l2*	*l3*	*l4*	*l5*	*l6*	*l7*	*l8*	*l9*	*l10*	*l11*	*l12*	*l13*
Location characteristic	*Chl_1 - floor*	5	5	4	3	5	3	5	5	1	5	5	4	5
	Chl_2 - cranes	5	4	5	4	3	5	2	2	5	5	4	4	2
Distance	facility1	0				30					50			
	facility2	30				0					30			
	facility3	50				30					0			
Transportation data		**period1**				**period2**					**period3**			
Internal cost		5				5					5			
External cost		8				10					15			
External capacity		1500				1800					2000			

Departments

The company has 5 different types of departments: raw material warehousing, injection, assembly, painting, and product warehousing (Figure 5.2). The area for each department depends on the requirements of each period (i.e. on the estimated flows for the period). We consider that there are some advantages in having departments of the same type (e.g. injection – I1, I2, I3) together in the same facility. So, for closeness rating, we use the value of 5 (absolutely necessary) for any pair of departments of the same type, and the value 1 (unimportant) for any other pair of departments (Table 5.2).

Table 5. 2 - Departments characteristics.

Departments		**Area**			**Departments characteristics**		**Re-layout cost**
		Period1	Period2	Period3	*Chd$_1$-floor*	*Chd$_2$-cranes*	
Raw Material Warehouse	**Wr1**	15	20	15	1	4	5 000
	Wr2	20	20	20	1	4	
	Wr3	20	20	20	1	4	
Injection	**I1**	10	10	10	5	3	20 000
	I2	10	10	10	5	3	
	I3	20	15	20	5	2	
Assembly	**A1**	20	20	20	1	1	10 000
	A2	15	15	15	1	1	
	A3	15	15	15	1	1	
Painting	**Paint**	20	20	20	4	2	80 000
Product Warehouse	**Wp1**	20	20	20	1	5	5 000
	Wp2	10	10	20	1	5	
	Wp3	20	20	20	1	5	

Products

The company manufactures several types of products, with different production processes, quantities and components (e.g. a product can first be injected, then assembled with other components and painted, and later go through another assembly process, leading to a more complex product). The global flows between departments change according to the planning periods. In the example, we have assumed there is a 28% increment of these flows, from period1 (t1) to period 2 (t2), and an increment of 4%, from t2 to t3 (Figure 5.2).

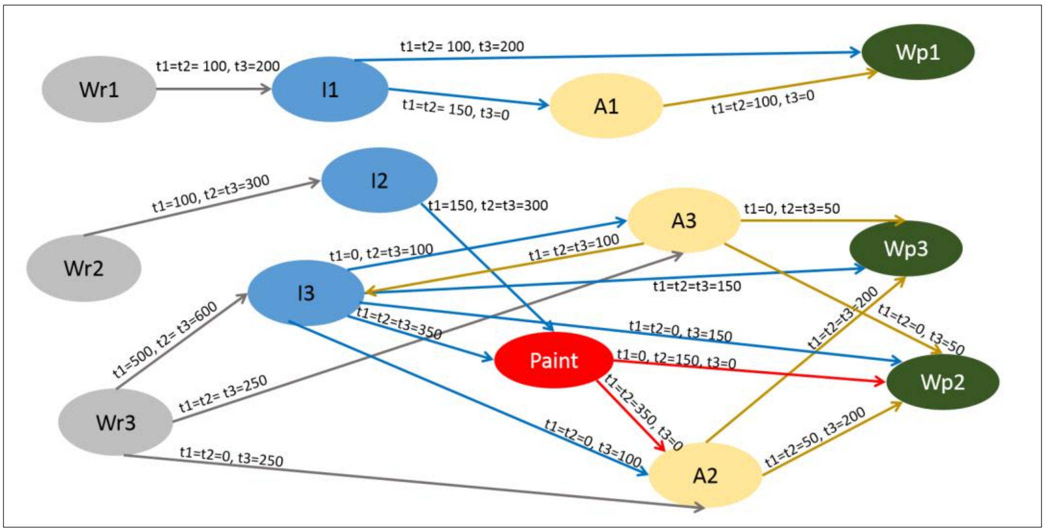

Figure 5. 2 - Flows between departments.

Considering that all the objectives have the same importance, the optimal configuration found by CPLEX is the one represented in Figure 5.3. We can observe that there are some departments that never change their positions – this is the case of departments Wp that are allocated to facilities 1 and 2. Other departments exchange positions between facilities (such as A1 and Wr1). These changes are due to the changes in the material flows between departments. Being larger, these flows can require area adjustments and, therefore, the algorithm suggests new configurations. For example, in period t2, the flows between departments Wr2 and I3 increased significantly, this implying that Wr2 moves from facility 1 to facility 3, to be near to I3.

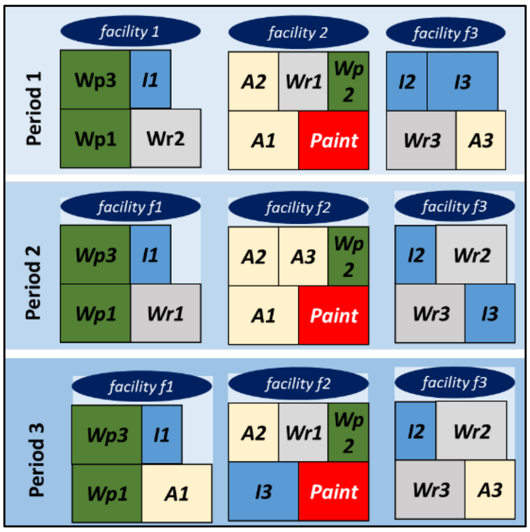

Figure 5. 3 – Optimal layout configuration (objectives with the same weights).

The model can also be used to manage material flows. This is useful when, in a given situation, it is not possible to guarantee the flow level proposed by the solution of the initial model (due, for example, to transport limitations between facilities), this forcing the model to be re-run with new adequate constraints. Figure 5.4 shows the global flows, that are larger inside facilities than between facilities. In order to illustrate the importance of analyzing flows, the following situations highlighted: a) in the solution, there is no flow between facilities 1 and 2; b) facilities 3 and 2 are those more dedicated to "production", with at least one department per type; c) facility 2, in period 2, gets together the three departments of type "A", and in the next period, it can work independently of the other facilities, having one department of each type.

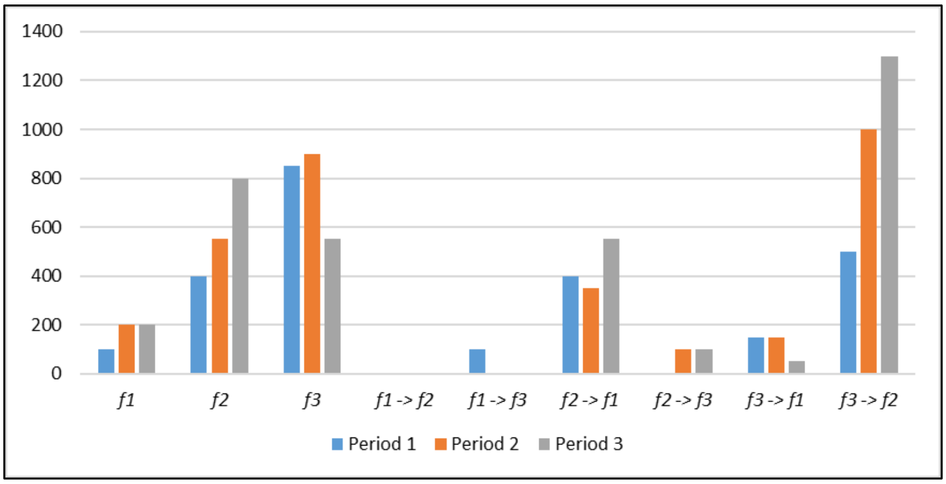

Figure 5. 4 – Flows inside and between facilities, (objectives with the same weights).

If we only consider the adjacency objective (with a weight of 1), the resulting layout is the one represented in Figure 5.5. We can observe here a greater concentration of, at least, two departments of the same type in each facility, in every period. In period 2, facility 2 merges the three departments of type A. It should be noted that the concentration of all departments of the same type in one facility is not totally possible as, in some situations, the location does not have enough space.

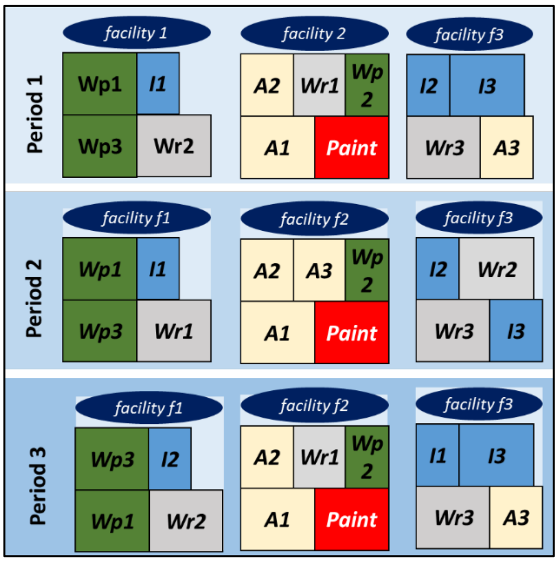

Figure 5. 5 – Layout configuration, considering only the adjacency objective.

On the other, in Figure 5.6 the *unsuitability* effect is very clear – here we are considering it as the main objective (with a weight of 1). This figure shows the resulting layout configuration and the values of each characteristic considered (in each small box, the upper numbers refer to characteristic 1, and those in the bottom refer to characteristic 2; the values on the left are for the location, and on the right for the department).

For example, department Wp2 needs the value 1 for characteristic c1, and the value 5 for characteristic c2. The department is positioned in a location with both c1 and c2 equal to 5. So, this location for Wp 1 is totally fit in terms of characteristic c2.

With this type of analysis, we can see that there are some departments, such as Wp2, that do never change their positions, probably because they are positioned in very suitable locations for both characteristics.

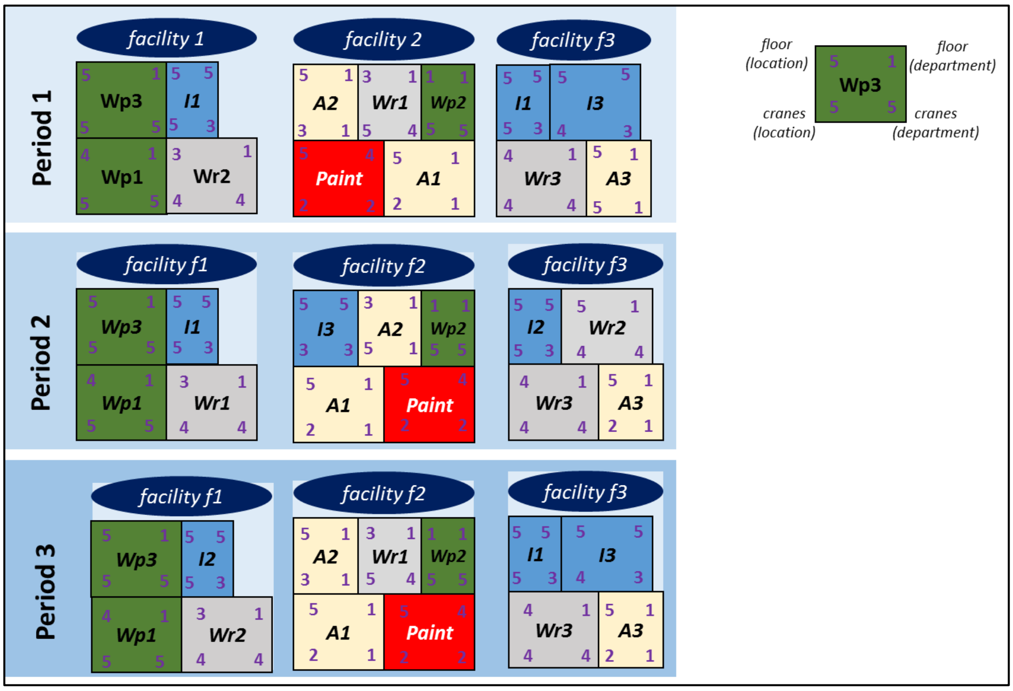

Figure 5. 6 – Layout configuration, considering only the unsuitability objective.

5.4 Computational assessment of the model

The performance of the proposed model was assessed in instances from the literature, and by comparing the obtained results with the results reported in those works (Rosenblatt (1986), Chen (2007) and Singh and Singh (2010)). Moreover, the case study was used to further assess the model. All the tests were made with the IBM ILOG CPLEX V12.6.1 optimization software, using the default pre-process values, at a portable computer (16 Gb RAM, and 2,6Ghz CPU Intel Core). As referred in chapter 2, CPLEX is currently viewed as probably the most advanced optimization software, integrating quite sophisticated features for dealing with complex integer, and non-linear models, and more recently with interesting developments to solve quadratic problems.

5.4.1 Model performance (literature instances)

The multi-facility layout model proposed in this work covers a reality that, to our best knowledge, has never been fully taken into consideration in the literature. There are no detailed examples that can be used for comparison purposes and, therefore, we have tested and compared the model in simplified versions of the problem. In this line, we have used the data instances from Rosenblatt (1986), one of the first works in the DFLP. However, as they only consider the minimization of material handling costs (MHC), we have used a simplified version of our model (only with these costs) to allow the comparison. The results on Table5.3 show that the model always finds layouts as good as, or better than those found by Rosenblatt.

We also tested the model with the data of case study #1 from Chen (2007), considering the same weights for both objectives (minimize cost and maximize adjacency). Our model found an alternative layout configuration, with better results in terms of workflow and closeness rating (Table 5.3).

Finally, we have applied the model to data sets from Singh and Singh (2010), just for 1 period, and considering only two objectives: the minimization of work flow, and the maximization of the closeness rating. For 6 departments, our model found one configuration with the same value of closeness, and a better adjacency value. For an example with 8 departments, we found one configuration with the same values for the workflow and for the adjacency (closeness).

These results show, therefore, the model developed in this work can be usefully used in designing and assessing new layout configurations, adopting a multi-criteria perspective.

Table 5. 3 - Results with instances from the literature.

Author	Objectives	Problem size	Instance	Literature solutions		Solution of the proposed method	
				layout	value	layout	value
(Rosenblatt 1986)	- min total cost	6 departments 1 period	t1	A1,C2,E3,F4,D5,B6	12.399	F1,D2,B3,A4,C5,E6	12.399
			t2	A1,D2,B3,E4,C5,F6	15.784	A1,D2,B3,E4,C5,F6	15.784
			t3	A1,E2,C3,B4,D5,F6	13.172	A4,B1,C6,D2,E5,F3	12.984
			t4	A1,F2,D3,B4,E5,C6	13.032	A6,B3,C1,D4,E2,F5	13.032
			t5	C1,B2,F3,D4,A5,E6	12.821	F1,B2,C3,E4,A5,D6	12.821
		6 departments 5 periods	t1	B1,D2,F3,A4,C5,E6	71.187	B1,D2,E3,A4,C5,F6	68.847
			t2	B1,D2,F3,A4,C5,E6		B1,D2,E3,A4,C5,F6	
			t3	B1,D2,F3,A4,E5,C6		B1,D2,E3,A4,C5,F6	
			t4	B1,F2,D3,A4,E5,C6		B1,D2,F3,A4,E5,C6	
			t5	B1,A2,D3,F4,E5,C6		B1,F2,D3,A4,E5,C6	
(Chen 2007)	- min MHC	6 departments	Case study #1	t1=t2=t3	MHC=532	t1=t2=t3	MHC=520
	- max adjacency	3 periods		(A5,B6,C3,D2,E4,F1)	Adj=138	(A5,B6,C3,D4,E2,F1)	Adj=142
(Singh & Singh 2010)		6 departments	n=6	B1,F2,E3,A4,C5,D6	Work flow=184	D1,B2,C3,E4,F5,A6	Work flow=184
	- min work flow	1 period			Closeness=40		Closeness=42
	- max closeness	8 departments	n=8	D1,F2,G3,B4,D5,H6,E7, A8	Work flow=358	C1,H2,E3,A4,D5,F6,G7,B8	Work flow=358
		1 period			Closeness=104		Closeness =104

5.4.2 Model performance (case study – instance 1)

Based on the case study described above, we have constructed a realistic illustrative example, previously presented (section 5.3), for which computational tests were performed to assess the impact of several key features on the model performance: problem dimension, multiple-objectives, transport capacity, and costs. We also performed tests with a larger instance of the illustrative example (with 30 departments) – see section 5.4.3.

5.4.2.1 Instance size

As the FLP is a NP-hard combinatorial optimization problem (Singh & Sharma, 2006), naturally the MFLP is also an intrinsically difficult problem. In Table 5.4, we can see how size of the proposed *large changes* model increases (in terms of constraints and variables) with the number of departments, locations and periods.

Table 5. 4 – Problem size of the *large change*s model.

Departments	Locations	Periods	Constraints	Variables	binary variables
13	13	1	195 + 1 quadratic	170	169
		2	390 + 2 quadratic	339	338
		3	585 + 3 quadratic	508	507
24	24	1	624 + 1 quadratic	577	576
		2	1248 + 2 quadratic	1153	1152
30	30	1	960 + 1 quadratic	901	900
		2	1920 + 2 quadratic	1801	1800

5.4.2.2 Impacts of multiple objectives

In order to illustrate the impacts of combining the various objectives (with different weights), we have made 29 tests with instance #1 (13 departments, 13 locations, and 3 periods). The results are presented in Table 5.5. With these tests, we get 6 different optimal layout combinations (see Figure 5.7). *Configuration 5* has the smallest total cost, but *configuration 6*, is quite interesting in terms of objectives balance.

Table 5. 5 – Tests for the *large changes* model (instance 1).

Layout configuration	Total cost	Total MHC (α)	Internal MHC	External MHC	RC (β)	Adj (δ)	Uns (γ)	Tests (weights)			
								α	β	δ	γ
1	2 215 750	**1 935 750**	**29 250**	**1 906 500**	280 000	820	179,75	100%			
2	2 123 600	2 038 600	31 500	2 007 100	**85 000**	890	179,25		100%		
3	2 366 200	2 146 200	32 500	2 113 700	220 000	865	**177,75**				100%
4	2 287 700	2 157 700	34 000	2 123 700	130 000	**950**	178,25			100%	
5	**2 052 100**	1 962 100	32 500	1 929 600	90 000	890	180 25	40%	30%	10%	20%
								40%	30%	20%	10%
								40%	10%	20%	30%
								40%	10%	30%	20%
								40%	20%	30%	10%
								40%	20%	10%	30%
								30%	40%	10%	20%
6	2 118 300	2 033 300	34 500	1 998 800	**85 000**	920	179,25	25%	25%	25%	25%
								30%	40%	20%	10%
								30%	10%	20%	40%
								30%	10%	40%	20%
								30%	20%	40%	10%
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								10%	40%	20%	30%
								10%	40%	30%	20%
								10%	20%	30%	40%
								10%	20%	40%	30%
								10%	30%	40%	20%
								10%	30%	20%	40%

It is interesting to note that facility 1 is often dedicated to warehousing of products, and normally with the same departments (Wp1 and WP3). In fact, these departments are frequently in the same positions, probably due to the *unsuitability* characteristics. On the other hand, facilities 3 and 2 are the more "active" in terms of exchanges. In particular, facility 2 frequently has all types of departments or concentrates the *assembly* departments. Facilities 2 and 3 have therefore more flows exchanges between them, than they have with facility 1.

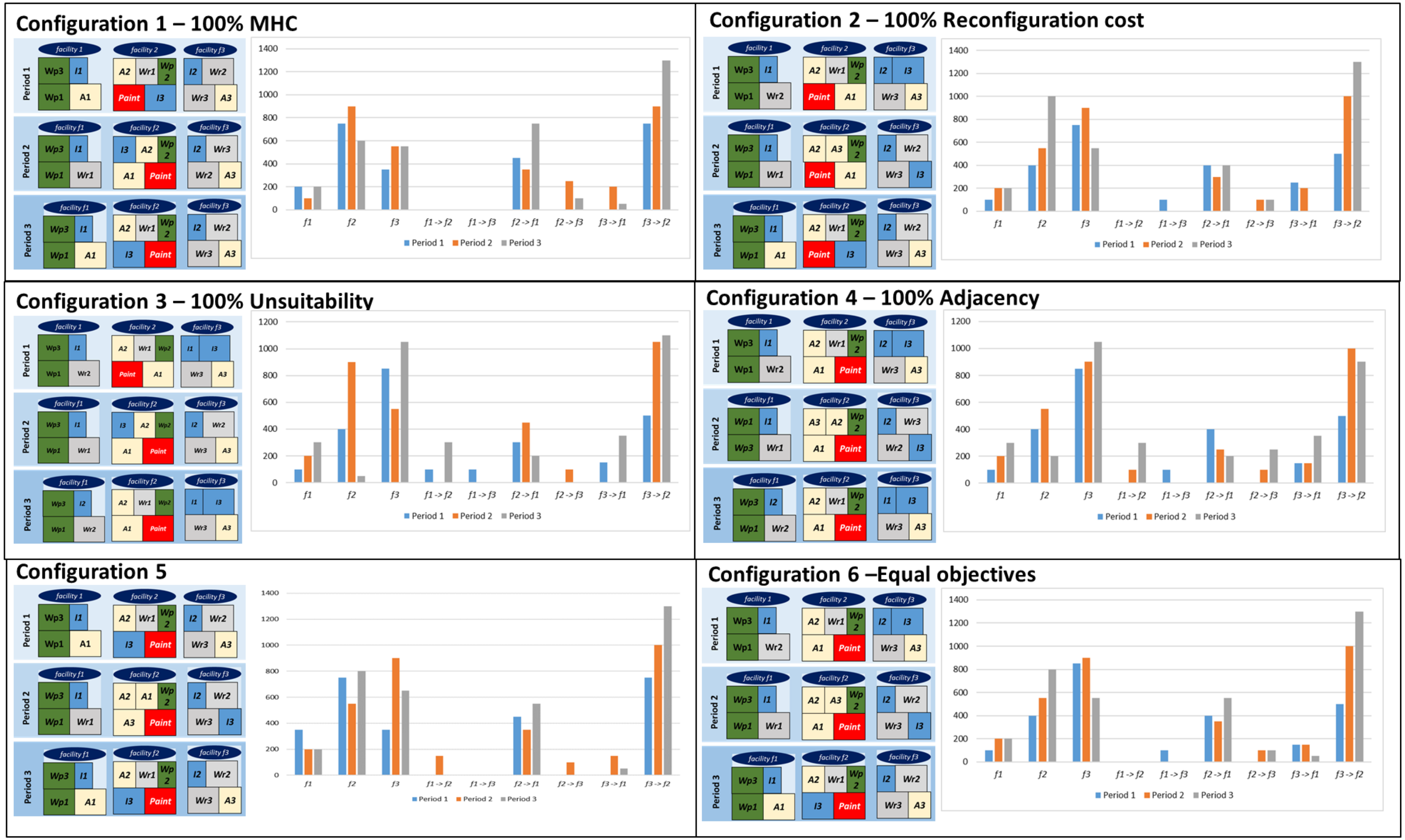

Figure 5. 7 – Configurations obtained by the *large changes* model (instance 1, 13 departments).

5.4.2.3 Impact of transport capacity

The transport capacity, as explained before, is a key characteristic of a MFLP, due to the dependence on external transportation means, subject to several uncontrollable factors. It is, therefore interesting to simulate different transport capacities. We made a set of tests combining different capacities, at each period. Table 5.6 shows that, for this data, the model does not find any solution if we consider there is no external transport capacity, at any of the 3 periods.

Table 5. 6 – Results of testing different transport capacities (instance with 13 departments).

Transport capacity (t1, t2, t3)	Configuration number	Total cost	Total MHC	Internal MHC	External MHC	RC	Adj	Uns
(1200, 1750, 2000)	5	2 052 100	1 962 100	32 500	1 929 600	90 000	890	180,25
(1 400, 1 750, 2 000) (1 400, 1 800, 2 000) (1 500, 1 800, 2 000) (1 500, 1 800, 2 500)	6	2 118 300	2 033 300	34 500	1 998 800	85 000	920	179,25
(2 000, 2 000, 2 000)	7	2 121 900	2 36 900	32 500	2 004 400	85 000	920	179,25
(0, 0, 0) (1400, 1800, 1950) (1500, 0, 2000) (1500, 1700, 2000) (1500, 1800, 1900)	No solutions							

The optimal solutions found are essentially the same for the different transport capacities (*configuration 6*). If we consider a capacity of 2000 for all periods, the model proposes *configuration 7*, that is essentially the same as *configuration 6*, by only exchanging the positions of Wp1 and Wp3. That solution has a smaller internal MHC, but a larger external MHC. If we decrease the capacity to 1200 in period 1, 1750 in period 2, and 2000 in period 3, the optimal solution is *configuration 5*, the one with less total cost. Figure 5.8 presents the flows distribution of *configurations 5* and *6*. In fact, they are very similar, and equal in periods 2 and 3. In period 1, they have different configurations for all facilities, and the flows between facilities are lower in *configuration 5* (700), then in *configuration 6* (1150).

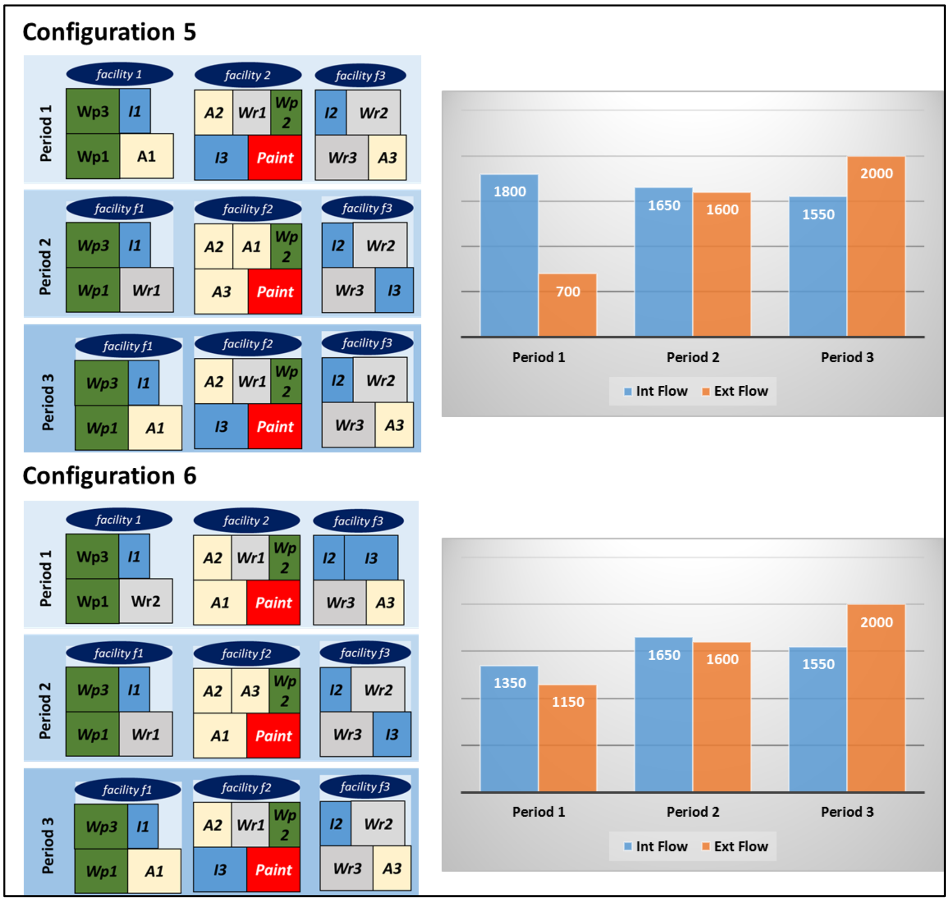

Figure 5. 8 – Flows inside and between facilities at *configuration 5* and *6* (instance 1, 13 departments).

5.4.2.4 Transport cost effect

Transport cost and capacities can have a great impact on the layout configurations this is particularly critical for costs. If, for example, there is an extraordinary increase in the price of fuel, directly reflected in an increase in transportation costs, the model proposes new configurations to minimize this impact - *configurations 9*, *10*, *11* and *12* (see Table 5.7). This table presents the results of 12 tests of the *large changes* (with weights of: 40% for MHC, 30% for the reconfiguration cost, 10% for unsuitability, and 20% for adjacency). With these results we can verify that, if we have the same *internal transport cost* and an *external transport cost* stable, the optimal configuration is *configuration 5*, the same found in the previous analysis. On the other hand, if the *internal transport cost* changes along time, and the *external transport cost* changes suddenly, the model suggests new solutions, exchanging some key departments, such as departments I3 or A3, see Figure 5.9.

Table 5. 7 – Testes for the *large changes* model, with different transport cost (instance 1, 13 departments).

Transport costs (t1, t2, t3)	Configuration number	Total cost	Total MHC	Internal MHC	External MHC	RC	Adj	Unc
Intern(5,5,5) / Extern(5,8,10) Intern(5,5,5) / Extern(8,10,15) Intern(5,5,5) / Extern(20,20,20) Intern (5,8,10) / Extern (20,20,20)	5	1 460 100	1 370 100	32 500	1 337 600	90 000	890	180,25
Intern (5,8,10) / Extern (50,10,15) Intern (5,8,10) / Extern (8,10,50)	10	3 700 100 4 402100	3 610 100 4 32100	46 800 44 000	3 563 300 4 268 100	90 000	875	180,25
Intern (5,8,10) / Extern (8,50,15) Intern (5,5,5) / Extern (8,50,15)	9	4 431 850 4 413 850	3 341 850 4 323 900	50 250 32 250	4 191 600 4 291 600	90 000	820	179,75
Intern (5,8,10) / Extern (8,8,8) Intern (5,8,10) / Extern (8,10,15)	11	1 477 450 2 069 850	1 387 450 1 979 850	47 850 47 850	1 339 600 1 932 000	90 000	890	180,25
Intern (5,5,5) / Extern (50,10,15) Intern (5,5,5) / Extern (8,10,50)	12	3 682 800 4 385 200	3 592 800 4 295 200	29 500 29 500	3 563 300 4 265 700	90 000	875	180,25

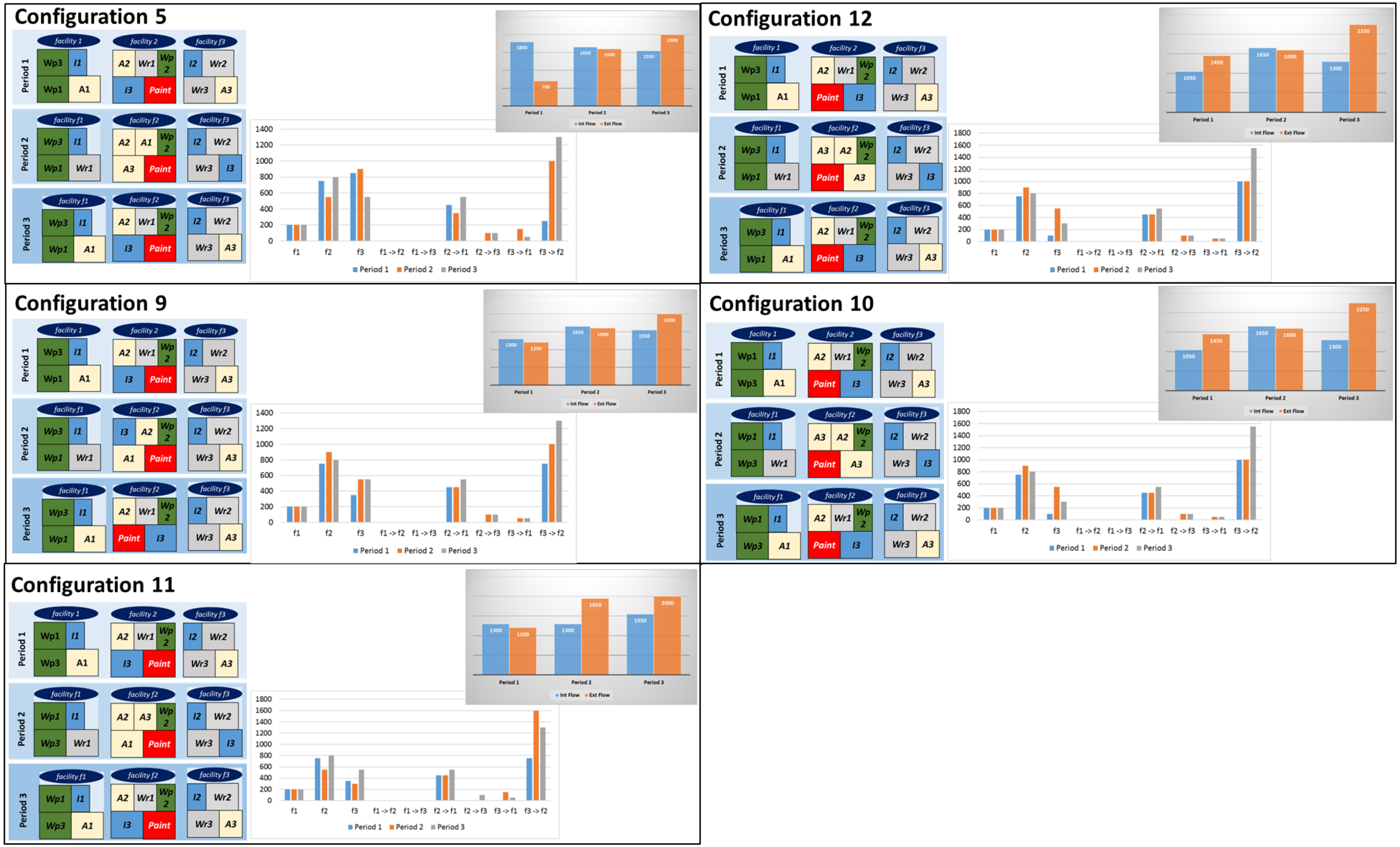

Figure 5. 9 – Layout configuration found with changing transport cost (instance with 13 departments)

5.4.3 Model performance (case study – instance 2)

A large problem instance also based on the case study was designed, by considering 30 departments, 30 locations, and 2 periods. With this test, we intended to show the model can solve larger instances, close to reality. The size of this instance is in line with the largest instances from the literature that have been solved by exact models (e.g., Sakhaii et al. (2016) or Fischer et al. (2015)).

In this instance, we have a group of companies, with two facilities (9 positions each), and another with 12 positions, in a total of 30 positions – the complete data is available in Appendix B (Table B.5.1, Table B.5.2, and Figure B.5.1). We consider here the transportation costs of the previously described tests, and a capacity constraint of 8000 units, for both periods. The results are presented in Figure 5.10 and Table 5.8.

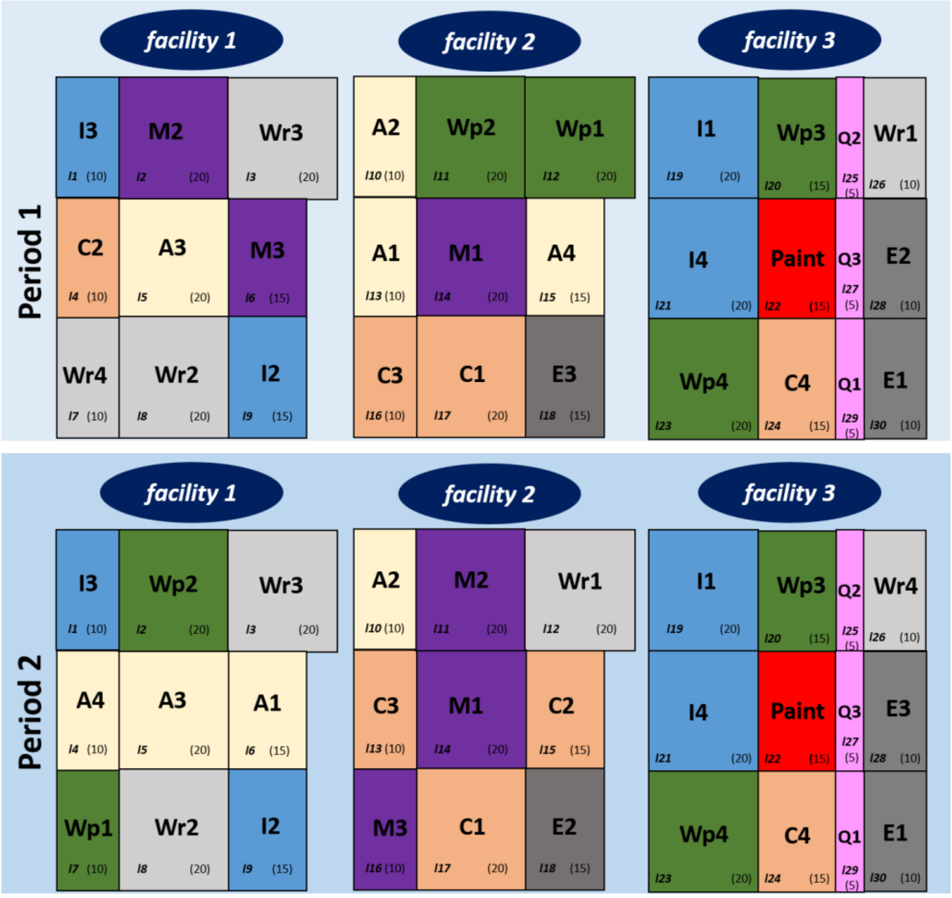

Figure 5. 10 - Facilities configuration for the instance 2.

Table 5. 8 – Results for instance 2 (30 departments, 2 periods).

Binary variables	1 800
Constraints	5 520 + 2 quadratic
Feasible solutions	17
Iterations	691 530
computational time (seconds)	7200
Objectives weights	**0.25 MHC** **0.25 Relayout cost** **0.5 Adjacency** **0.25 Unsuitability**
Total cost	1 767 100
MHC total	**1 719 300**
Internal MHC	94 500
External MHC	1 624 800
Relayout cost	**47 800**
Adjacency	**2150**
Unsuitability	**197,67**

In this large instance, the algorithm concentrates departments of the same type in a single facility (according to the closeness requirements), naturally respecting the area constraints and the characteristics of each location (reflected in the "suitability" of the departments). With this configuration, flows inside facilities are larger than the flows between facilities, in both periods (see Figure 5.11 and Figure 5.12).

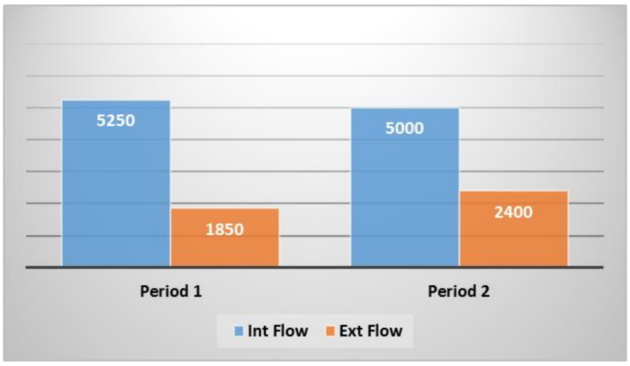

Figure 5. 11 – Total flows at each period, for instance 2.

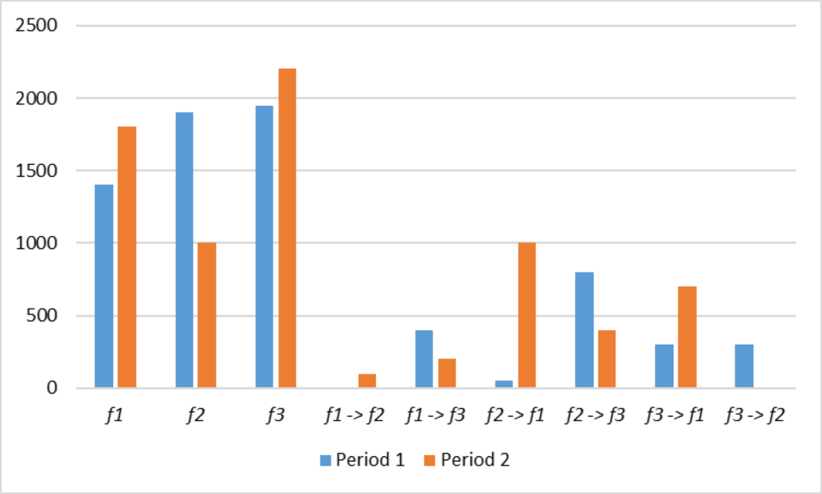

Figure 5. 12 – Flows inside and between facilities, for instance 02.

In both periods, all facilities have intense flows. However, the flows of *f2* in period 2 decrease significantly because they only have one productive department (A2). But at the same time, they increase their flows with facility *f1*.

These experiments show how the model can dynamically deal with the *multi-facility layout problem*, by adjusting solutions in each period, considering the production requirements, the physical constraints, and taking into account the transport costs and capacities.

5.5 Conclusions

In this chapter, we have proposed a mathematical model for the resolution of *multi facility layout problems*, for what we have called "*large changes*", this is an innovative extension of the traditional facility layout problem, with a significant practical potential. The MFLP simultaneously allocates departments at different facilities, taking into consideration transportation costs and operational constraints between facilities. The model can be viewed as dynamic, in the sense that layouts are reconfigured along time, with the additional flexibility that the area required for each department can change, as well as the transportation costs and capacities between facilities.

To be more realistic, the model considers four objectives (minimize total *material handling costs,* minimize *re-layout costs*, minimize *unsuitability* between departments and locations, and maximize the *adjacency* between departments) giving the decision maker the possibility to weight the objectives, according to his own strategy. The *unsuitability* objective, to be minimized, is proposed in this work to help finding a good matching between the characteristics of each department and those of each location. This is especially important for layout reconfigurations and also for facility conversion, even for the layout problems with one single facility.

The model proposed in this work was implemented and assessed in the CPLEX solver, comparing very positively with some well-known approaches from the literature. To prove the practical applicability of this model, we also tested it with two problem instances inspired on the case study. These preliminary results were very promising.

The main contributions of this work can be seen from two perspectives. For the industry, a model has been developed that can be used as a decision support tool to help the decision maker in testing several scenarios and in developing a set of alternative solutions that best suit his objectives and practical constraints. In this study, the model was applied to the automotive industry, but it can be easily adapted to many other sectors, in cases where there are a set of geographically separated facilities. For the FLP literature, we have contributed with a new problem perspective, by modelling the complexity of dynamically and simultaneously designing several facilities, considering multiple objectives.

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6. MODEL FOR *SMALL CHANGES*

This chapter presents the mathematical model we have developed for solving the "small changes" problem in a layout. This problem consists in selecting the machines to manufacture each product, and in choosing their location inside a facility or a department.

Contents of this chapter:

- *Introduction*
- *Mathematical model*
- *Illustrative example*
- *Computational assessment of the model*
- *Conclusions*

6.1 Introduction

After having defined the location of departments inside each facility, as presented in the previous chapter, we will now go down at the operational level, to the machine layout design (Figure 4.2). As previously explained (section 4.3 of chapter 4), the "*small changes*" model intends to look inside a department, and design a detailed layout configuration, by making the allocation of products to machines, and the allocation of machines to positions inside departments (see Figure 6.1).

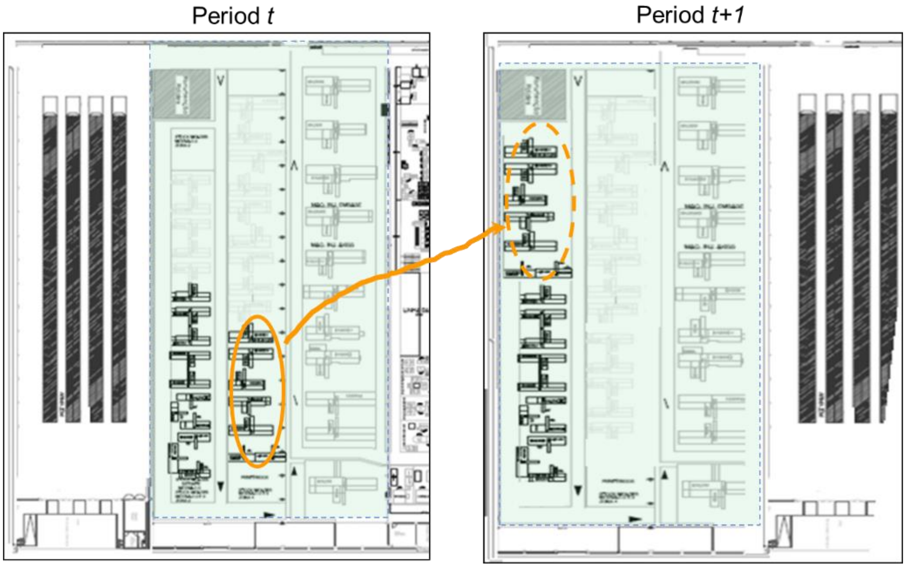

Figure 6. 1 – "*Small changes*" example.

In fact, these "*small changes*" can occur in several situations, for example:

i) when a department has been moved to another location inside a facility, or from another facility, requiring a re-arrangement of machines and other resources;
ii) when a department is new, and resources need to be located inside that department, or even inside the whole facility;
iii) to improve the operations inside a specific department or a facility, due to a previous identification of some problematic situations or inefficiencies (productivity levels, quality nonconforming levels, delivery delays, etc.);
iv) to reduce or to increase the number of machines or other resources in a department;
v) when a department changes its dimensions, enlarging or reducing, leading to a re-arrangement of all or parts of the resources;

vi) when a specific product must be manufactured immediately, or when there is a need to increase the production of a specific product during a limited time windows, to satisfy a special demand of an important customer.

A "*small change*" can be a simple change of the location of a machine, leading to significant gains in the production efficiency, with a relatively quick reconfiguration and without major disruptions in the overall operation of the company or the remaining machines (see Figure 6.2). Or it can arise each time a "*large change*" is made, depending on the type of department, and the characteristics of the resources involved.

"*Small changes*" can also happen on several periods inside a larger period of a "*large change*", with different impacts in the manufacturing system. For example, "*large changes*" can occur every 3 or 5 years, and "*small changes*" in every 3 or 6 months. They are, therefore, a flexibility instrument.

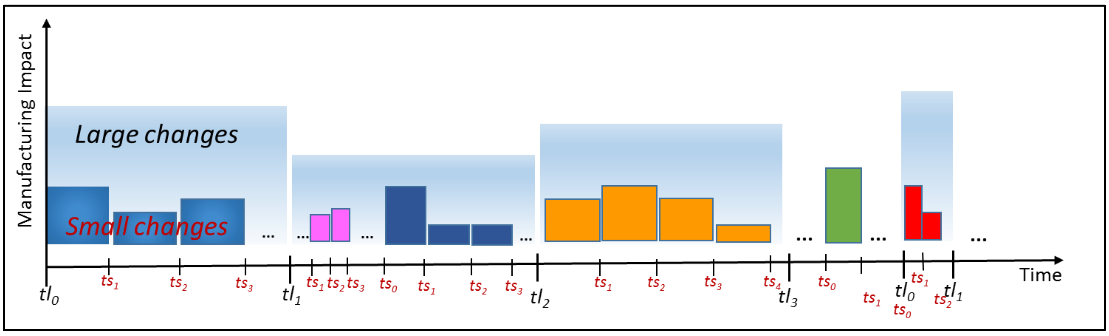

Figure 6. 2 - Layout *large* and *small* changes (*tl* – *large change* period; *ts* – *small change* period).

Although the "*small changes*" model can be used to organize a facility, in a way similar to the "*large change*" model, these models are different, as they are used to analyse the manufacturing system at different levels. *Large changes* focus on departments and strategic levels, taking into account the group of facilities, and thus being able to exchange departments between facilities. On the other hand, the small changes model is only used in a single facility, to organize either an entire facility or a specific department.

This model can be usefully applied to Reconfigurable Manufacturing Systems (RMS), allowing rapid and cost-effective reconfigurations in their modular structure (Goyal & Jain, 2016). It also allows adding, removing or modifying specific process capabilities, controls, software or machines, in order to adjust the production capacity to respond to changing market demands or technologies (Mehrabi et al., 2000).

Most of these circumstances require great flexibility and agility in terms of response, this surely being a differentiating factor in the company's competitiveness. Therefore, the need for reconfigurations and adjustments in the layout configurations can occur more frequently than the changes of entire departments ("*large changes*").

The problem was modelled mathematically as a distributed layout (Benjaafar et al., 2002), with two phases: first, production assignment – selecting the machines that will produce each product at each moment; and then, machine allocation – selecting the machines locations inside facilities, at each period.

The model proposed in this work for machine layout design is a Quadratic Programming model, with multiple objectives and unequal areas, allowing layout reconfigurations in each planning period. This multi-objective model is designed to *minimize costs* (production, material handling and reconfiguration), *maximize adjacency* between machines, and to *minimize unsuitability* (as a way to combine the characteristics of machines and the existing locations). The constraints are those usually applied to the FLP with product allocation: a) no machines overlapping; b) each machine is assigned only to one position; c) machine size fits into the location area; d) machine compatibility with product operations; e) machines capacity; and f) each operation is made only at one machine. Similarly to the "*large changes*" model, a new constraint has been considered, to guarantee that machines will only be positioned in places with the same or higher level of the characteristic defined as important for "*unsuitability*".

In this work, and for illustrative purposes, the model is applied to some small examples inspired in the case study, namely: the design of an entire facility, and the design of a specific department.

6.2 Mathematical model

This model is based on the concept of distributed layouts presented by Benjaafar et al. (2002), Lahmar and Benjaafar (2005) or Jaramillo and McKendall (2010). As previously explained (chapter 2), in a distributed layout, machines are strategically distributed through the plant floor, increasing material handling flexibility, under fluctuations in product mix and product volume. As the "*small changes*" model can be applied to the design of several types of departments that can be located in various facilities, flexible reconfigurations can be achieved. We are, in this way, distributing products by machines, and allocating machines to locations in a facility or a department, for a single period, or dynamically, for several periods. This model has two sequential phases, (see Figure 6.3), as already used in the literature ((Jaramillo & McKendall, 2010), (Sakhaii et al., 2016)). First, the operations of products are allocated to machines, then the location of machines is chosen, taking into account the flows between machines, obtained in the first phase.

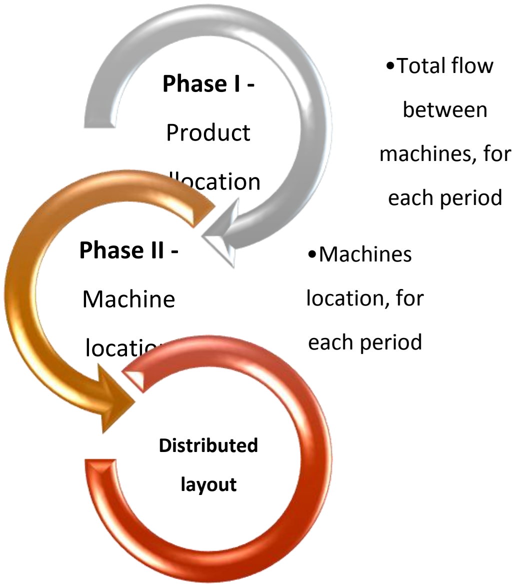

Figure 6. 3 – Proposed "*small changes*" model, based on a distributed layout.

The formulation presented here is based on the Quadratic Assignment Problem (QAP), commonly used for dynamic layout problems (Drira et al., 2007) and for distributed layout problems with multiple objectives. The formulation is adapted from Jaramillo and McKendall, 2010), with multiple objective functions: minimizing *costs*, minimizing *unsuitability*, and maximizing *adjacencies*. Similarly to the "*large changes*" model (chapter 5), the "*small changes*" model also considers the *unsuitability* and *adjacency* objectives.

The reality of manufacturing systems is so complex, that we need to make some general assumptions, for modally purposes. In this work, the assumptions considered are the following:

- the cost of moving machines is known, but it depends on the type of machine;

- a machine transforms an input into an output (a product), but it can also be a workstation, that assembles a product or performs other kind of function;
- all machines can be moved to any location inside the department or the facility;
- each operation can only be made at one machine, at a time;
- a product can have operations made in different facilities, but each operation of the product can only be made in a factory;
- each period, for small changes, can represent the total time of producing one order or more than one order, and not the time of performing one operation or one product cycle production.

The proposed "*small changes*" model is formulated as follows.

Indices	
T	number of periods for "small changes"
M	number of machines
O	number of operations to be performed on machines
P	number of products
L	number of locations inside a facility or a department
N	number of characteristics to evaluate the *suitability* between machines and locations
Parameters	
Co_m	operating cost of machine m
Cm_m	production capacity of machine m
Mc_{mpo}	capability of machine m, to produce operation o of product p
Q_{pot}	quantity of product p to be produced at operation o, in period t
No_{ovp}	1, if v is the operation following operation o, of product p; 0 otherwise
a_l	area of position l
a_m	area of machine m
$r_{1,k}$	distance between position l and position k
ct_t	transport cost of a unit of material, per unit of distance, in period t
cr_m	cost of shifting machine m
Ct	total material handling cost
Cr	total reconfiguration cost
Chm_{mn}	rating of requirements of machine m for characteristic n
Chl_{nl}	rating of characteristic n of location l
Uns	total unsuitability value
cl_{mht}	closeness rating between machines m, and h in period t

$Prox_{l,k}$	proximity rating between locations *l* and *k*
Adj	total adjacency value
α, β, γ and δ	weights for the multi-objective function
Decision variables	
U_{pomt}	1, if operation *o* of product *p* is produced at machine *m*, in period *t*; 0, otherwise
B_{mht}	total flow between machine *m* and machine *h*, in period *t*
x_{ilt}	1, if machine *m* is placed at position *l* in period *t*; 0, otherwise

$$Min\ Y = OC + Z \tag{6.1}$$

$$OC = \sum_{t=1}^{T} \sum_{p=1}^{P} \sum_{o=1}^{O} \sum_{m=1}^{M} \left(Q_{pot}\ U_{pomt}\ Mc_{mpo}\ Co_{m}\right) \tag{6.2}$$

$$Z = \alpha\ Ct_{Norm} + \beta\ Cr_{Norm} + \gamma\ Uns_{Norm} - \delta\ Adj_{Norm} \tag{6.3}$$

Subject to:

$$\left(U_{pomt}\ Mc_{mpo}\right) \leq 1, \quad \forall\ p,o,m,t \tag{6.4}$$

$$B_{mht} = \sum_{p=1}^{P} \sum_{v=2,\ o=1}^{O} \left(No_{ovp}\ U_{pomt}\ U_{pvht}\ Q_{pot}\right) \quad \forall m,h,t \tag{6.5}$$

$$\left[cm_{m} - \sum_{p=1}^{P} \sum_{o=1}^{O} \left(U_{pomt} * Q_{pot}\right)\right] \geq 0 \quad \forall\ m,t \tag{6.6}$$

$$\left[\sum_{m}^{M} \left(U_{pomt} * Q_{pot}\right)\right] = Q_{pot} \quad \forall p,o,t \tag{6.7}$$

$$\sum_{m=1}^{M} x_{mlt} \leq 1 \quad \forall\ l,t \tag{6.8}$$

$$\sum_{l=1}^{L} x_{mlt} = 1 \quad \forall m,t \tag{6.9}$$

$$al_{l}\ x_{ilt} \geq am_{m}\ x_{mlt} \quad \forall m,l,t \tag{6.10}$$

$$\left[\left(Chd_{ni} - Chl_{nl}\right)\ x_{ilt}\right] \leq 0 \quad \forall t,l,i,n \tag{6.11}$$

$$\alpha + \beta + \gamma + \delta = 1 \tag{6.12}$$

$$U_{pomt} \in \{0,1\} \quad \forall p,o,m,t \tag{6.13}$$

$$x_{ilt} \in \{0,1\} \quad \forall i,l,t \tag{6.14}$$

<u>Phase I - Product allocation</u>

Initially the model assigns operations of products to machines (allocation), according to the operation sequence of each product, and machines capabilities. There are machines of several types, capacities, and operating costs. Expression (6.2), that minimizes the *total operation cost* (OC), is used to find the global minimum, production cost, by selecting the more suitable machines to produce each product and, at the same time, the less expensive solution, with the constraints usually applied to this kind of production allocation problems. Constraints (6.4) ensure that each operation of each product only takes place in compatible machines. Constraints (6.5) determine the total flow between machines, in each period. With constraints (6.6) the model guarantees that the capacity of each machine, is never be exceeded in each period. Constraints (6.6) guarantee that all operations of each product are performed at one machine in each period. Finally, constraints (6.13) guarantee that all variables are binary.

Phase II - Machine location

With the flows between machines (B_{mht}), determined at the previous phase, we perform the allocation of machines to positions inside departments. Here the inputs are: the flows between machines, the physical characteristics, of the places, and the dimensions of existing locations and machines.

To duly capture the multi-objective nature of the problem, four different objectives have been considered. They were aggregated in a single weighted function defined by equation (6.3), with the different objectives duly normalized (e.g. Ct_{Norm} is the normalized value for Ct, the total material handling costs).

The first component of the objective function are the *total material handling costs* (MHC), commonly applied in the literature of the unequal area FLP (Drira et al., 2007) and for machine layout problems ((Kia et al., 2014), (Ulutas & Islier, 2015), (Sakhaii et al., 2016), among others)). It is defined by expression (6.15).

$$Ct = \sum_{t=1}^{T} \sum_{m,h=1}^{M} \sum_{l,k=1}^{L} [B_{mht}\ r_{lk}\ ct_t\ x_{mlt}\ x_{ht}] \tag{6.15}$$

*The reconfiguration costs (*RC) are the second term of the objective function, reflecting the total costs of reconfiguring the layout, by changing the location of machines during the time window being analysed, as commonly done in dynamic layouts (see e.g. (Sakhaii et al., 2016), (Shah et al., 2015).

$$Cr = \sum_{s=2}^{T} \sum_{l,k=1}^{L} \sum_{m=1}^{M} (cr_m\ x_{mls}\ x_{mk\ s-1}) \tag{6.16}$$

The Unsuitability between machines and locations (UC) is the third term of the objective function. As explained before, this is a new objective proposed in this research, to measure the gap between the ideal characteristics of machines (Chm_{nm}) and the actual characteristics of the existing location (Chl_{nl}). It is defined by expression (6.17).

$$\boldsymbol{Uns} = \sum_{t=1}^{T} \sum_{n=1}^{N} \sum_{m=1}^{M} \sum_{l=1}^{L} \left[\frac{Chl_{nl}}{Chm_{nm}} \; x_{ml} \right] \tag{6.17}$$

At this level, this new objective can also be very important in layout reconfiguration, to take advantage of the existing locations, for example for reducing the cost to prepare the place to put a machine.

The *adjacency between machines* (ADJ) (to be maximized) is the last term of the objective function, and is commonly used for the FLP. However, as far as we know, it has not yet been used in machine layout problems. We propose the use of this objective, to allow the design of functional layouts, trying to join machines of the same type, or to organize machines according to the route of a product. But it also allows the possibility of separating machines, that should not be close (e.g., due to security constraints, process constraints, etc.). Similar to the "*large changes*" model, this is based on a closeness rating (cl_{mht}), in a scale from 0 to 5, defining the importance of proximity between machines (for this purpose we have used the classification by Jaafari et al. (2009)). To provide more flexibility and the possibility of analysing different situations, the needs for closeness can change along time (Abedzadeh et al., 2013). The fact that machines can be allocated to different buildings can limit, in different ways, the relationships between machines, e.g. imposing constraints on sharing the same specialized equipment or workers. To cope with these situations, the model considers a proximity rating (with values from 0 to 5) between the locations *l* and *k* where the machines are positioned ($Prox_{lk}$), as presented in Figure 4. 2. The adjacency of a pair of machines (m,h) is determined by expression (6.18).

$$\boldsymbol{Adj} = \sum_{t}^{T} \sum_{l,k}^{L} \left[cl_{mht} Prox_{l,k} \, x_{mlt} \; x_{hkt} \right] \tag{6.18}$$

Here, the constraints are those usually applied to unequal FLPs (Wang et al., 2005) specially for the machines layout problem ((Jaramillo & McKendall, 2010), (Ulutas & Islier, 2015), etc.). Constraints (6.8) ensure that each position inside a department has at most one machine, at each period. Constraints (6.9) guarantee that each machine is assigned only to one position, in each period. Constraints (6.10) ensure that the area of a position (al_l) is never exceeded by the machine area (am_m) assigned to it. Constraints (6.11) guarantee that a machine is only assigned to locations with characteristics values larger or equal to the values required by each machine. Finally, constraints (6.12) guarantee that the total value of the weights is 1 (Singh & Singh, 2010).

6.3 Illustrative examples

The "small change" model will be illustrated in two situations: in the design of the layout for a specific department; and in the design of a complete facility.

6.3.1 Designing the layout of a department

This example was designed for a department with 14 locations and 14 machines. The dimensions considered here are presented in Figure 6.4.

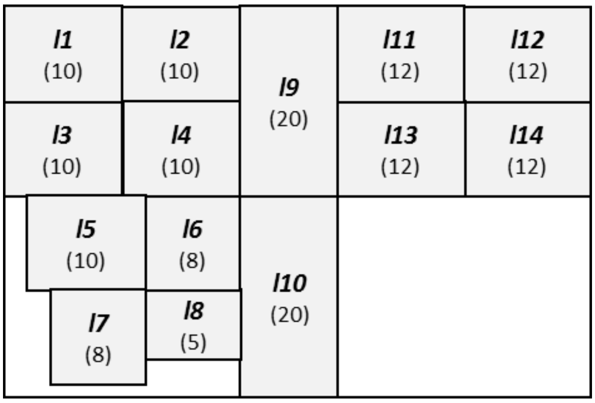

Figure 6. 4 – A department with 14 locations (e.g. location *l1* has an area of 10 units).

Two characteristics (see Table 6.1) need to be considered when allocating some machines: a) if the location has cranes, to move the tools of these machines (Chl_1); and b) if the location has a connection with the pipes to directly supply the raw materials (Chl_2).

Table 6. 1 – Characteristics of locations in a department with 14 positions.

Location	*l1*	*l2*	*l3*	*l4*	*l5*	*l6*	*l7*	*l8*	*l9*	*l10*	*l11*	*l12*	*l13*	*l14*
Characteristics														
Chl₁ *– cranes*	5	4	5	5	5	5	5	5	4	5	5	5	5	4
Chl₂ *- connection with feed pipes*	3	3	4	5	5	5	5	5	5	3	3	4	4	5

The 14 machines to be positioned in this department have the characteristics presented in Table 6.2, and the capabilities to perform the operations of each product as shown in Table 6.3.

Table 6. 2 – Information on the machines.

Machines	***m1***	***m2***	***m3***	***m4***	***m5***	***m6***	***m7***	***m8***	***m9***	***m10***	***m11***	***m12***	***m13***	***m14***
Machine type	***I***		***II***			***III***					***IV***		***V***	
Characteristics														
Chm_1 – *cranes*	3	3	5	5	5	4	4	4	4	4	5	5	2	2
Chm_2 - *connection with feed pipes*	5	5	3	3	3	4	4	2	2	2	3	3	3	3
area	20	20	12	12	12	10	10	10	10	10	8	8	5	5
Reconfiguration cost	80	80	75	75	75	70	70	60	60	60	60	60	50	50
Production cost	8	8	6	6	6	5	5	4	4	4	3	3	4	4
Capacity	600	600	500	500	500	800	800	400	400	400	200	200	50	50

Table 6. 3 – Machines capability (e.g. machine *m6* can perform *operation 2* (O2) and 4 (O4) of *product 3* (p3)).

	m1	***m2***	***m3***	***m4***	***m5***	***m6***	***m7***	***m8***	***m9***	***m10***	***m11***	***m12***	***m13***	***m14***
P1	O1	O1	-	-	-	O2	O2	O3	O3	O3	O3	O3	-	-
P2	O1	O1	-	-	-	O2	O2	-	-	-	-	-	-	-
P3	O2	O2	O2	O2	O2	O2,O4	O2,O4	O3,O4	O3,O4	O3,O4	O3	O3	O3	O3
P4	-	-	-	-	-	O3	O3	O3,O4	O3,O4	O3,O4	O3,O4	O3,O4	-	-
P5	-	-	O1,O3	O1,O3	O1,O3	O1,O3	O1,O3	O2,O4	-	-	-	O3	O3	O3
P6	O1	O1	O1,O2	O1,O2	O1,O2	O2,O4	O2,O4	O3,O4	O3,O4	O3,O4	O3,O4	O3,O4	-	-

This department will manufacture 6 products with 4 operations (for example: O1 - injection, O2 – welding, O3 - press) during 5 periods, according to a given demand (Table 6.4).

Table 6. 4 – Product information, for example of 14 Machines.

Products	**Operations sequence**	**Demand**				
		t1	***t2***	***t3***	***t4***	***t5***
P1	**O1,O2,O3,O4**	400	400	400	400	0
P2	**O1, O2**	0	600	600	600	600
P3	**O2,O2,O4**	0	150	150	0	150
P4	**O3,O4**	200	200	200	0	200
P5	**O1,O3**	500	0	500	500	0
P6	**O1,O2,O3,O4**	400	400	0	0	0

The results of phase I, are presented in Table 6.5. Figure 6.5 shows the used capacity for each machine. Naturally, machines *m13* and *m14* are never used, because they don't have enough capacity to produce these types of products. All the other machines are intensively used.

Table 6. 5 – Product allocation for 5 periods (P1O1 is operation 1 of product 1).

Machines	***m1***	***m2***	***m3***	***m4***	***m5***	***m6***	***m7***	***m8***	***m9***	***m10***	***m11***	***m12***	***m13***	***m14***
t1	-	P1 O1	P5O3 P6O1	-	P5O3	P1O2 P602	P5O1	P6O4	P1O3	P6O3	P4O4	P4O3	-	-
t2	P2 O1	P1 O1	P6O2	P6O1	-	P2O2 P3O2	P1O2 P6O4	P6O3	P3O3 P3O4	P1O3	P4O4	P4O3	-	-
t3	P1 O1	P2 O2	P5O3	P5O1	-	P2O2 P3O2	P1O2	P3O4	P3O3	P1O3	P4O4	P4O3	-	-
t4	P2 O1	P1 O1	P5O3	P5O1	-	P2O2	P1O2	P1O3	-	-	-	-	-	-
t5	-	P2 O1	-	-	-	P2O2 P3O2	-	-	P3O3 P3O4	-	P4O4	P4O3	-	-

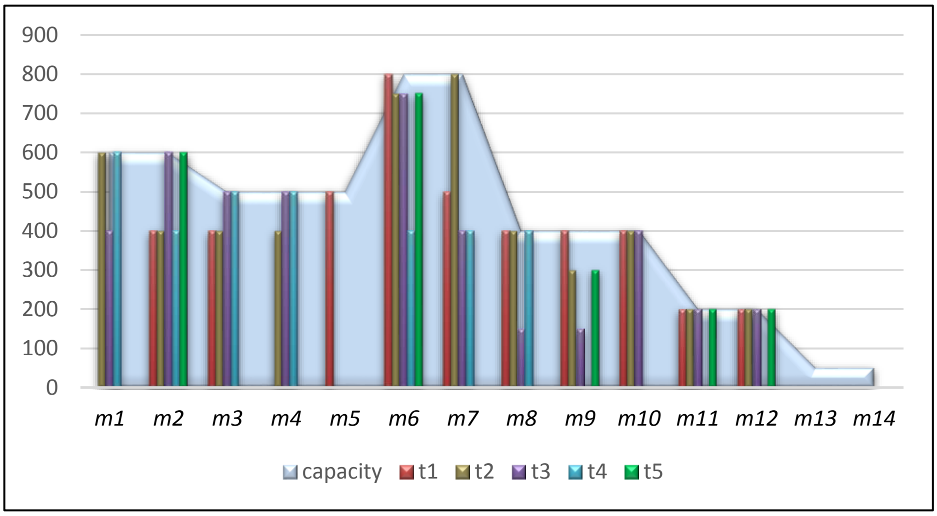

Figure 6. 5 – Capacity utilization with the optimal solution.

The resulting flows from phase I are outlined in Figure 6.6, and they are used as the input of phase II, for machine location.

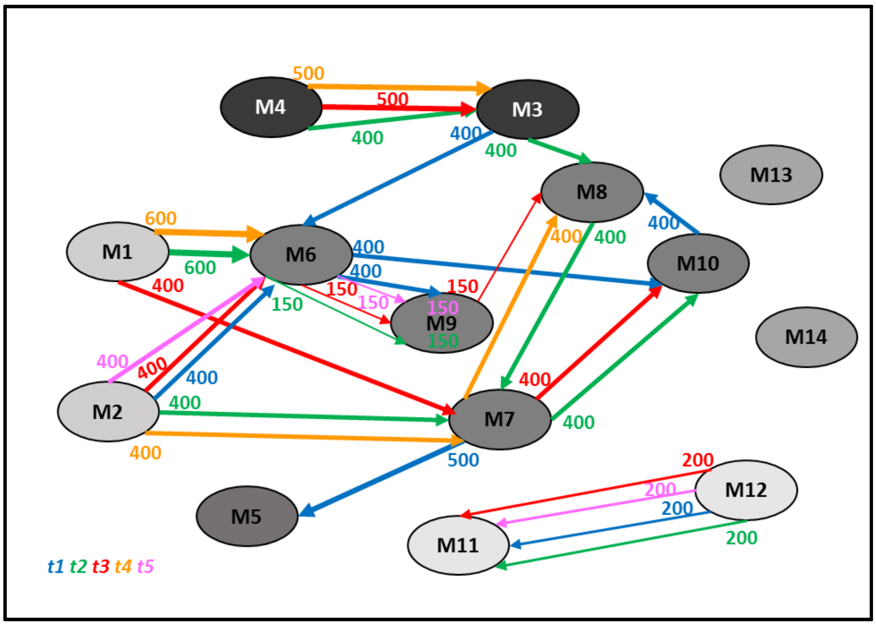

Figure 6. 6 – Flows between machines.

To have a better idea about the impact of each objective, the model was run taking into account 5 different combinations of weights for the objectives. Table 6.6 shows the results for each objective, when they are considered to have equal importance.

Table 6. 6 – Results for the illustrative example (14 machines, 5 periods).

Objective weight	Total cost	phase I	phase II				
		OC	MHC	RC	Adj	Uns	Reconfigurations
25% each	198 940	102 550	96 250	140	3325	**195,42**	2
100% MHC	**86 385**	102 550	**84 000**	**2 385**	3185	196,92	**36**
100% RC	223 550	102 550	121 000	**0**	**3125**	**197,92**	**0**
100% Adj	**231 340**	102 550	**128 000**	790	**3425**	**195,42**	12
100% Uns	223 190	102 550	120 000	640	**3425**	**195,42**	8

For example, when MHC has the highest weight (100%), the optimal solution (Figure 6.8) is the one with less MHC (84 000), but also with the minimum total cost (86 385), despite being the solution with more reconfigurations (36) (see Figure 6.7 and Figure 6.12). This shows, in some way, the benefits of the model and the advantages of performing layout reconfigurations, so often overlooked and postponed by many companies.

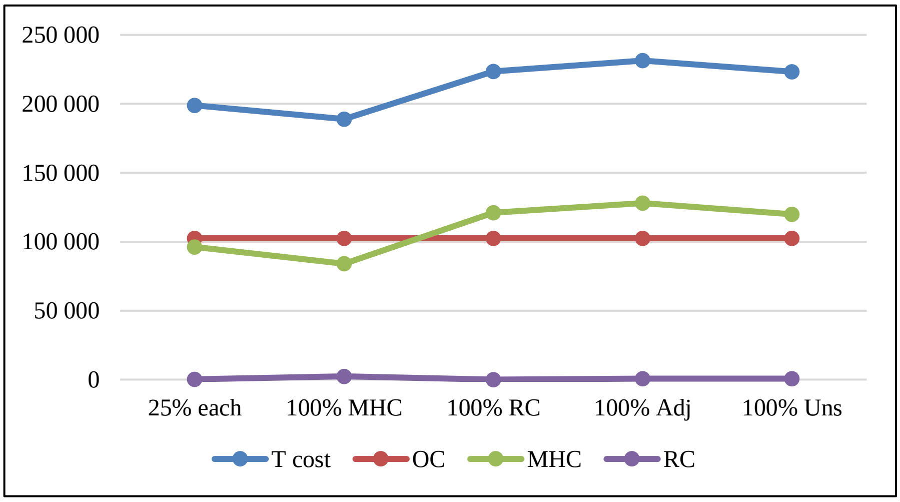

Figure 6. 7 – Cost in the optimal solutions.

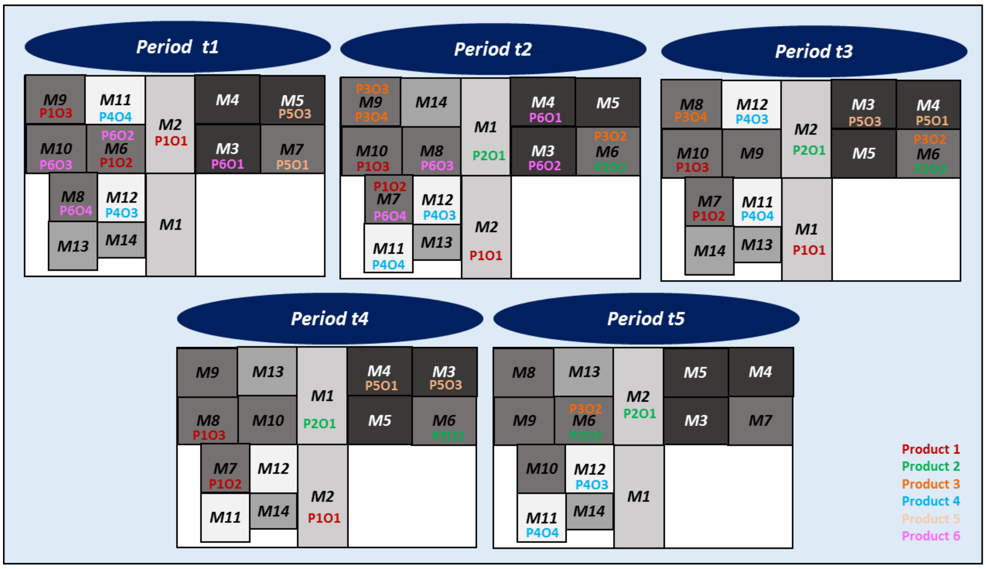

Figure 6. 8 - Optimal layout configuration and product assignment (considering the weight of 100% to MHC).

For this example, we can see how important it is to put machines of the same type close together (with a value of “5” for closeness). In fact, the optimal solutions for some of these experiments have the maximum value for adjacency (3 425), not only when we consider *adjacency* as the more important objective (Figure 6.9), but also when *unsuitability* is the most important objective (Figure 6.10). This optimal solution has also the highest MHC (128 000) and the highest total cost (231 340) of these 5 tests. However, we can observe that some machines (machines *m11* and *m12*, or *m6* and *m7*), are seldom positioned near to machines of their type, as expected. That can be due to the characteristics of the place in terms of *unsuitability* and in terms of the area constraints, but also to the quantity of flows between machines. For example, machines *m6* and *m7*, despite being of the same type, have almost no flows between them, so, they do not need to be together. Between machines *m11* and *m12*, there are flows, but of small quantities (200), when compared with other machines (*m10* and *m8* or *m7*, with flows of 400, frequently positioned between *m11* and *m12*).

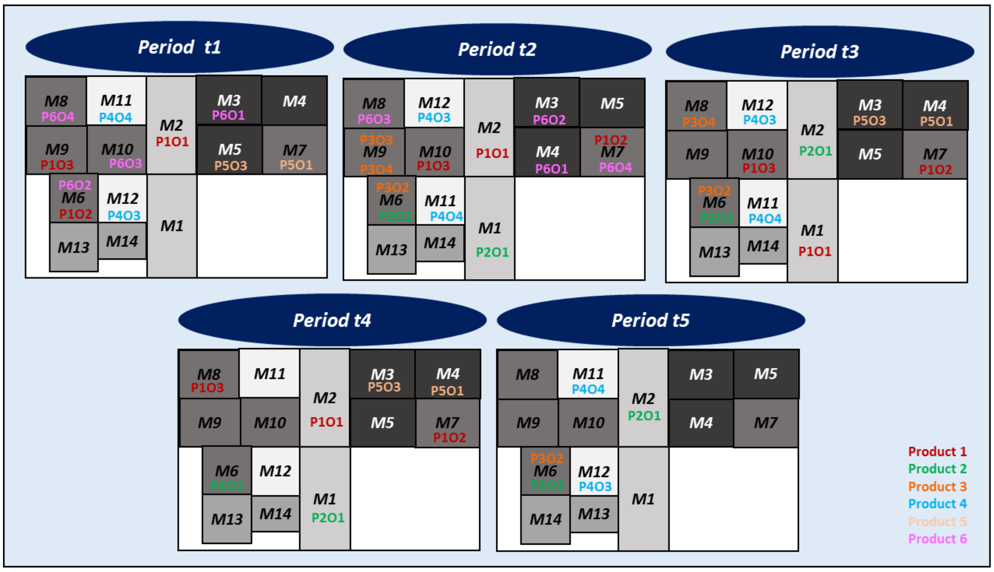

Figure 6. 9 - Optimal layout configuration and product assignment (maximizing *adjacency*).

When we consider *unsuitability* as the most important objective (Figure 6.10), the optimal solution has an *unsuitability* value 195,42. That is the same value for most of the other tests (see Table 6.6). This solution has also the maximum *adjacency* value (3 425). The costs of this solution are not the best of these 5 tests (223 190). Nonetheless this might not be a worst situation in terms of cost, because when we allocate machines to locations that fit totally, we can have several gains (e.g. quick reconfigurations, productivity, etc.). The model does not detail this type of gains, because they can be very specific, according to the characteristic under analysis. These issues are outside the scope of this research work, but they could be an interesting area for future research on the *unsuitability* objective.

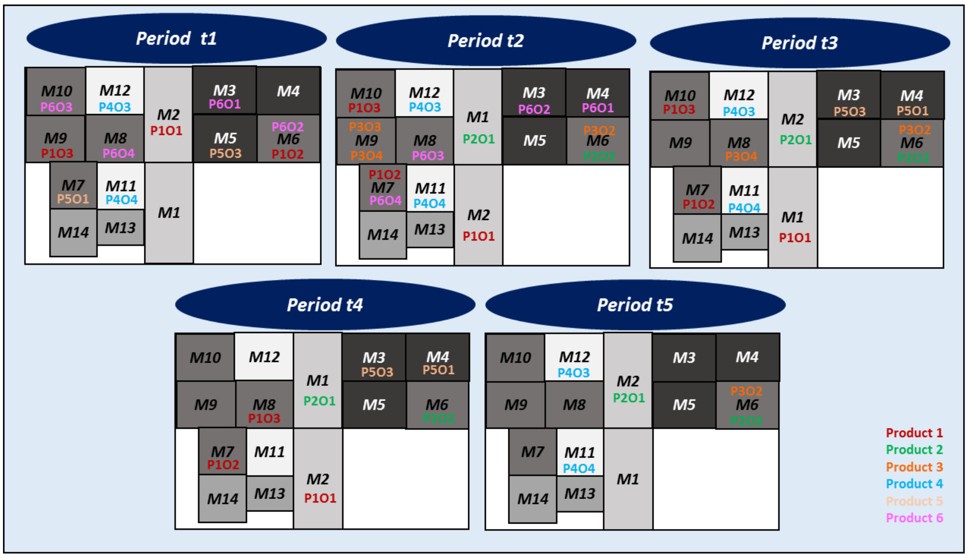

Figure 6. 10 - Optimal layout configuration and product assignment (minimizing *unsuitability*).

The optimal solution for this test is based in two configurations, (see Figure 6.11). We can observe that only *m3*, *m11 and m12* suit totally in both characteristics, and other machines suit totally in at most one characteristic - mainly on C_1 (*m4*, *m5 and m6*) and on C_2 *(m1 and m2)*. However, there are more solutions with this *unsuitability* value (see Table 6.6).

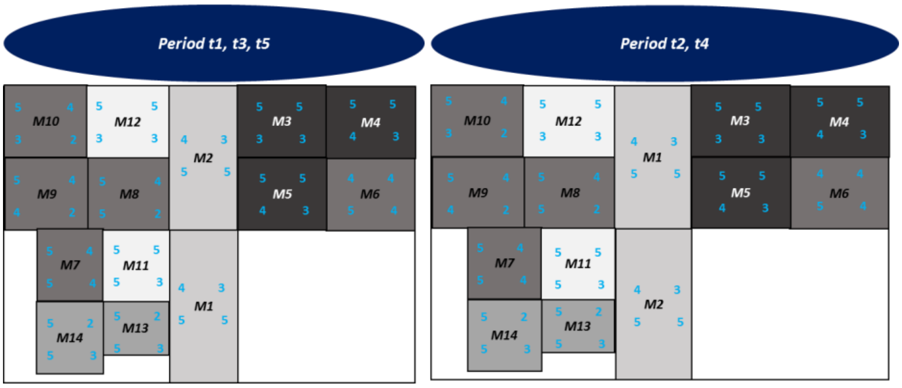

Figure 6. 11 – *Unsuitability* score (minimizing *unsuitability*).

When we consider that all the objectives have the same importance, the optimal solution has two layout configurations, with a distinct configuration only at period 2, by exchanging only the positions of machines *m6* and *m7* (Figure 6.12). In fact, this solution is interesting, with costs (198 940) near the optimal configuration, when we are only minimizing *costs*, with the optimal value of *unsuitability* (Uns = 195,42), and a near optimal value for the *adjacency* (3 325).

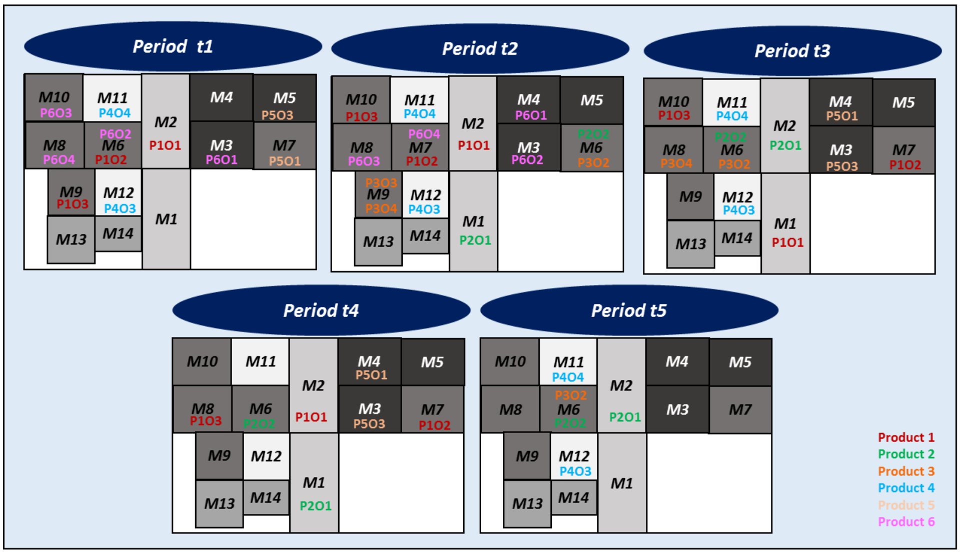

Figure 6. 12 – Optimal layout configuration and product assignment (objectives with the same weight).

We can also observe that the minimal values of *unsuitability* can occur on other tests (equal weights or 100% *adjacency*). That is due to the fact that several positions have the same value for all characteristics, allowing the location of machines on multiple positions. For example, machines *m1* or *m2* can be positioned at locations *l9* or *l10* - the *unsuitability* value will be the same, because they have the same characteristics, and also the same dimensions.

The same can be verified for the *adjacency*, since there are several positions where some machines can be allocated, they can exchange positions, but always staying close, so the *adjacency* value will be the same. But if they have more or less flows between them, or if they do not change their position, the *MHC costs* or *reconfiguration costs*, can be reduced.

6.3.2 Designing the layout of a complete facility

The "*small changes*" model can also be applied to design a complete facility. This can be the case when we want to re-organize the existing departments and machines following a strategy different from the strategy previous defined by the "*large changes*" model. With this model, we can organize the machines of all departments of this facility, independently of the remaining facilities, without changing the external flows.

Consider a facility with 32 locations (see Figure 6.13), with the characteristics presented in Table 6.7, and with 5 departments, with 30 machines in total (see Table 6.8).

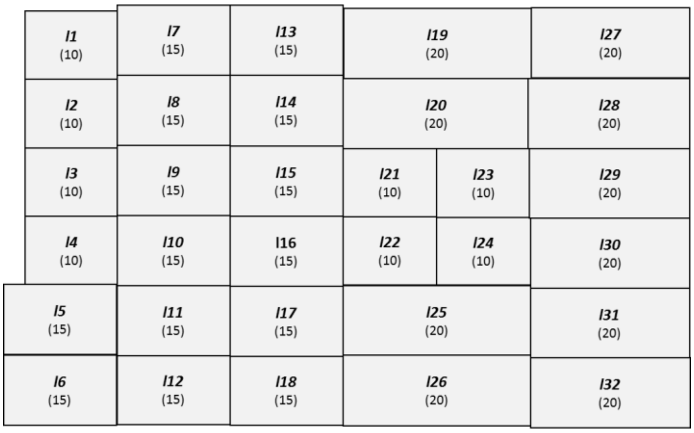

Figure 6. 13 - Location areas of a facility with 32 locations (e.g. location *l1* has an area of 10 units).

Table 6. 7 – Characteristics of locations inside a facility with 32 positions.

Location	**Location characteristics**	
	Chl_1 *- floor*	***Chl_2****-cranes*
l1	2	2
l2	2	2
l3	3	2
l4	3	2
l5	5	5
l6	5	5
l7	3	4
l8	3	3
l9	3	3
l10	3	4
l11	5	5
l12	5	5
l13	3	4
l14	3	4
l15	3	4
l16	3	4
l17	5	5
l18	5	5
l19	5	4
l20	5	4
l21	3	2
l22	3	2
l23	3	2
l24	3	2
l25	5	5
l26	5	5
l27	5	4
l28	5	4
l29	4	5
l30	4	5
l31	5	5
l32	5	5

Table 6. 8 – Information on the machines.

Department	Machine	Area	Reconfiguration cost	Production cost	Capacity	Machine characteristics	
						Chm$_1$ - floor	*Chm$_2$- cranes*
A	m1	10	200	20	600	1	2
	m2	10					
	m3	10					
	m4	10					
	m5	5		18			1
	m6	5					
	m7	5					
B	m8	15	500	50	700	4	5
	m9	15					
	m10	15					
	m11	15					
	m12	15				3	
	m13	15					
	m14	15					
C	m15	20	700	70	800	2	1
	m16	20					
	m17	20					
	m18	15		65			
D	m19	20	800	85	700	3	3
	m20	20					
	m21	20					
	m22	20					
	m23	20				5	
	m24	20					
E	m25	15	300	35	800	5	4
	m26	10		30			
	m27	10					
	m28	10				4	
	m29	10					
	m30	10					

This facility will be able to produce 8 products, with 10 operations. Table 6.9 shows the demand for the next two periods, and the operations sequence of each product. The machines capability to perform the operations of each product are shown in Table 6.10.

Table 6. 9 – Demand for 8 products.

Products	Operations sequence	Demand	
		t1	*t2*
P1	O1, O2, O3, O4, O5	100	300
P2	O1, O3, O5, O7, O9	200	100
P3	O2, O4, O6, O8, O10	0	400
P4	O1, O6, O9	300	600
P5	O2, O3, O4, O6, O8, O10	400	0
P6	O3, O4, O5, O6, O7, O8, O9, O10	500	0
P7	O3, O4, O8, O10	600	500
P8	O1, O6, O10	0	700

Table 6. 10 – Machines capability (e.g. machine *m8* can perform *operation 2 (O2)* of *product 1(P1)* and *operation 4 (O4)* of *product 5 (P5)*).

Department	Machine	Capability							
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**
A	m1	O1	O1			O2		O8	
	m2	O1		O2				O8	
	m3	O1			O6		O3		
	m4	O1		O2		O2			
	m5		O3				O3		
	m6		O3	O3	O3	O3	O3	O10	
	m7		O3		O6			O10	
B	m8	O2				O4			
	m9			O4			O9		
	m10	O2			O3		O4		
	m11		O7				O9	O4	
	m12	O2		O4		O4	O10		
	m13		O7		O3		O10		
	m14	O2					O4	O4	
C	m15	O4				O6	O10	O3	
	m16		O3	O6			O5		O5
	m17	O4		O6			O5		O6
	m18		O3			O6		O3	
D	m19	O3		O8		O8			
	m20						O8		
	m21		O9		O1, O9		O6		
	m22	O3					O8		O10
	m23			O10		O8			O1
	m24		O9		O9		O6		O1
E	m25	O5		O10		O10			
	m26								
	m27						O7		O10
	m28		O5			O10			
	m29		O7	O7	O5	O9	O7		
	m30		O5	O5	O10		O8		

With all this information, we have run the model in CPLEX, with the standard default parameters. The optimal solution for phase I was found in 68 seconds, with a total operation cost of 1 030 500. The allocation of products to the machines is presented in Table 6.11. The flows between the machines (Figure 6.14), were considered as the input for the second phase of the model, to design the layout of the facility.

Table 6. 11 – Product allocation (8 products, with 10 operations and 30 machines).

Machine	t1	t2
m1	P2O1	P1O1, P2O1
m2	P7O8	P7O8
m3	P1O1, P6O3	P4O6
m4	P5O2	P3O1
m5	-	P2O3
m6	P7O10	P7O10
m7	P2O3, P4O6	-
m8	P5O4	-
m9	P6O9	P3O2
m10	P6O4	P1O2
m11	-	P7O4
m12	P6O10	-
m13	-	-
m14	P1O2, P7O4	-
m15	P1O4, P7O3	P1O4, P7O3
m16	P5O5	P3O6
m17	-	P8P6
m18	P5O6	-
m19	P1O3, P5O8	P1O3, P3O8
m20	-	-
m21	P4O1, P4O9	P2O9, P4O1
m22	-	-
m23	-	P8O1
m24	P2O9, P6O6	P4O9
m25	P1O5, P5O10	P1O5, P3O10
m26	-	-
m27	P6O7	P8O10
m28	P2O5	P2O5
m29	P2O7	P2O7
m30	P6O8	-

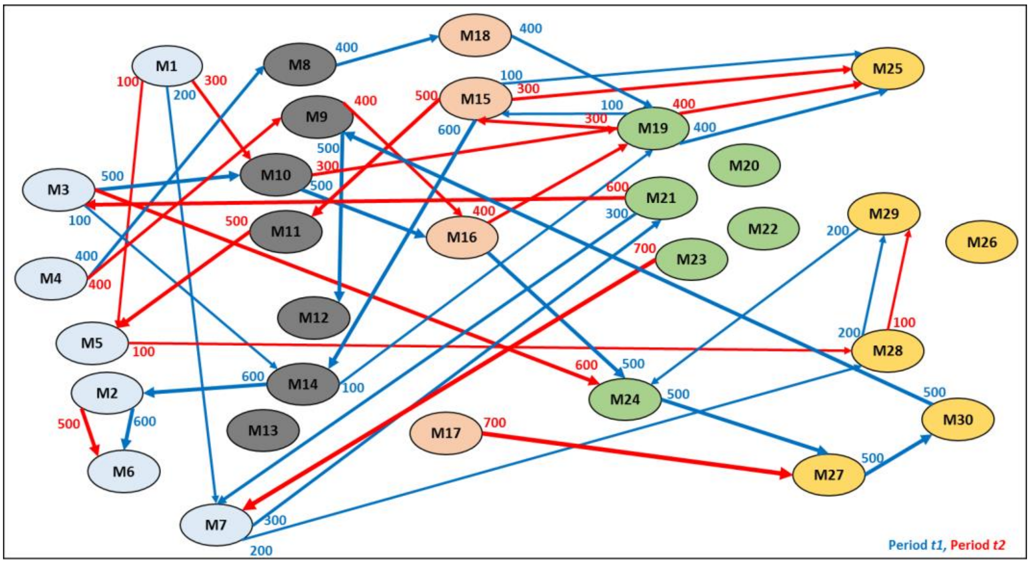

Figure 6. 14 – Flows between machines.

If we increase the number of departments, locations and periods, the complexity of the problem naturally increases exponentially, as we are dealing with a difficult combinatorial problem. So, for this example, the second part of the model can only find the optimal solution quickly when we consider the *unsuitability* as the main objective (100%). For the other combinations of objectives, we have run the model for 2 hours (7 200 seconds), generating interesting feasible solutions. In practice, "optimal" solutions are never fully implemented, as they have to be "tuned" to consider practical aspects or constraints that have not been taken into account in the model.

Table 6.12 presents the values of the objectives in some illustrative instances. Like in the example of 14 machines previously presented, when we consider MHC as the main objective, the solution has the minimum cost, with the largest number of reconfigurations (and therefore, a higher cost for reconfiguration). For the other objectives results are also more or less as expected.

Table 6. 12 – Results for different objective weights (30 machines, 2 periods).

Objective weight	Total cost	OC	MHC	RC	Adj	Uns	Reconfigurations
25% each *(join machines by departments)*	1 320 500	1 030 500	284 000	6 000	5 140	220,83	15
25% each *(join machines by product)*	1 282 700	1 030 500	244 500	7 700	5 045	212,17	17
100% MHC	**1 164 100**	1 030 500	**120 500**	13 100	4 765	215,17	**27**
100% Adj *(join machines by departments)*	1 341 000	1 030 500	**310 500**	**0**	**5 500**	232,33	0
100% Adj *(join machines by product)*	1 314 500	1 030 500	284 000	**0**	**5 690**	218,67	0
100% Uns	**1 423 000**	1 030 500	307 500	**85 000**	4 880	**209,17**	17

As previously explained, the *adjacency* objective can be used in several circumstances, to join or separate machines. To show this application, we have run the model, taking into account two different situations: organizing machines by departments or by products.

When we organize the machines by departments, we try to put together the machines of the same type - the resulting configuration, considering equal weights for the objectives, is presented in Figure 6.15. In fact, we can clearly see the emerging departments. Due to the characteristics of the locations and the constraints of *unsuitability* and area, it is not possible to put together all the machines of the same departments.

However, department C has the totality of joined machines, but the other departments are frequently divided in two sub-departments.

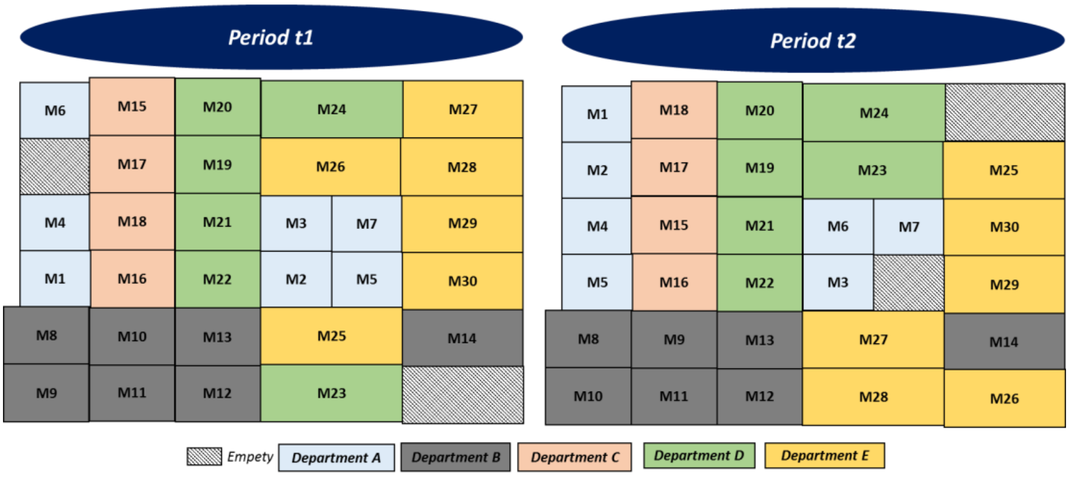

Figure 6. 15 - Layout configuration of a facility (with equal objectives), joining machines of the same department.

On the other hand, if we consider that machines must be organized by products, the resulting layouts are different (see Figure 6.16). With this configuration, the total cost is lower than in the previous configuration, even if now we have more reconfigurations (Table 6.12), and better *unsuitability* values.

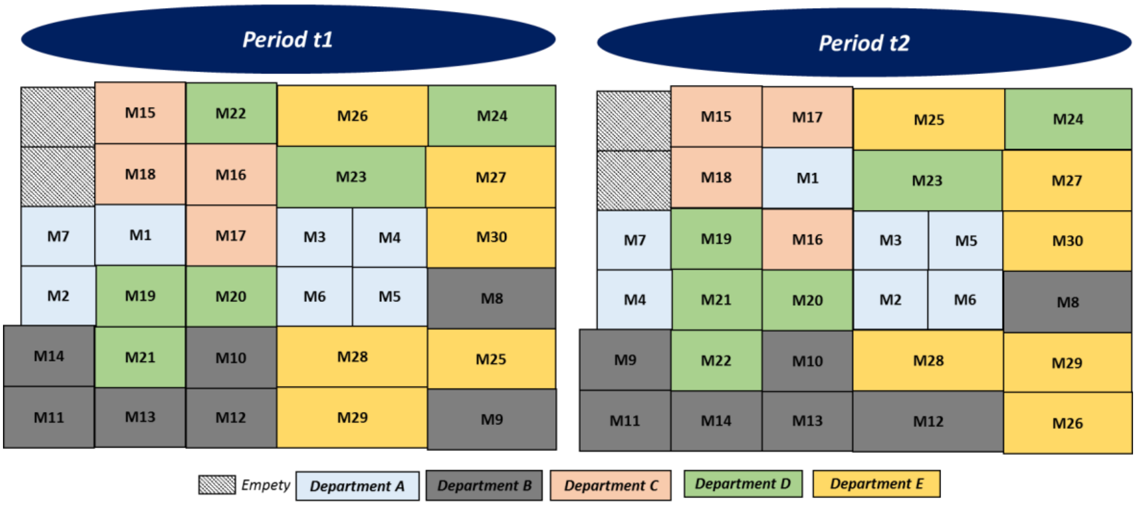

Figure 6. 16 - Layout configuration of a facility (with equal objectives), joining machines that manufacture the same product.

Figure 6.17 and Figure 6.18 allow us to better understand how the products are distributed by machines inside the facility confirming that most of the products have the machines that produce them, closer when the layout is organized by products than when it is organized by departments (see the case of products 1, 5 and 8). Obviously, that area and *unsuitability* constraints strongly limit the machines closeness of some other products.

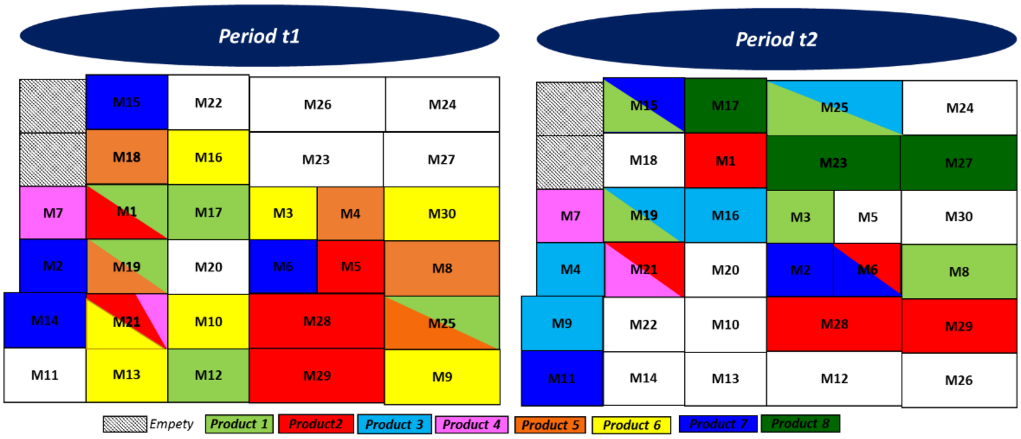

Figure 6. 17 – Product allocation to machines in a layout organized by product (equal objectives).

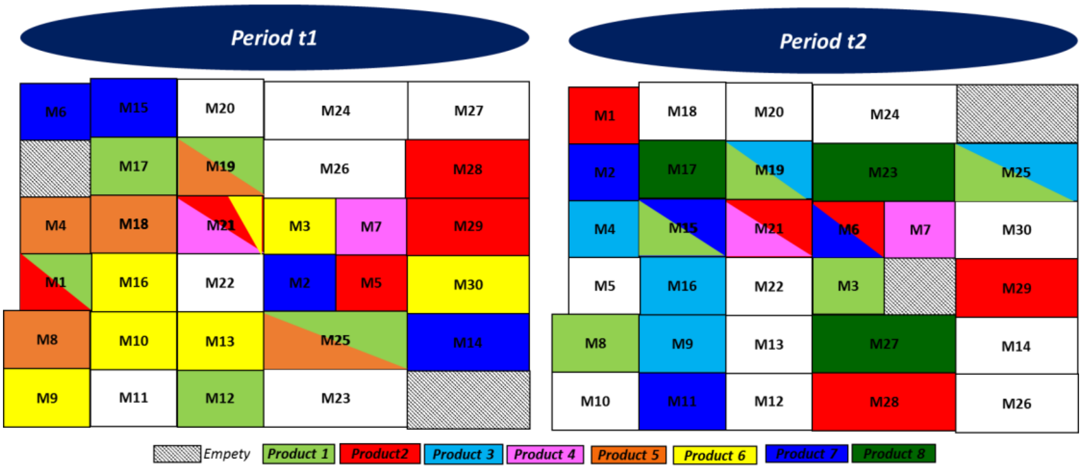

Figure 6. 18 – Product allocation to machines in a layout organized by department (equal objectives).

These are some examples of the variety of analysis that can be made with the “*small changes*” model developed in this work.

6.4 Computational assessment

This was also tested with the IBM ILOG CPLEX V12.6.1 optimization software, using the default pre-process values, at a portable computer (16Gb RAM, and 2,6 Ghz CPU Intel Core). Based on the case study, we have constructed the previously presented illustrative examples. For each of these examples, several computational tests were performed, making in this way a sensitivity analysis of some key features, such as the dimension of the problem instances, and the impact of considering multiple objectives.

6.4.1 Problem dimension

As the “*small changes*” model is a combinatorial optimization problem, the computational effort is expected to increase exponentially with the size of the problem (see Table 6.13 and Table 6.14).

Table 6. 13 – Dimension of instances and models for phase I (“*small changes*”).

Machines	Products	Operations	Periods	Constraints (linear + quadratic)	Variables (binary + continuous)	Iterations	Feasible solutions	Time (sec)
14	6	4	1	1 046 + 196	336 + 533	22	3	0,01
			2	2 092 + 392	672 + 1 065	48	3	0,02
			3	3 138 + 588	1 008 + 1 597	61	3	0,22
			5	5 230 + 980	1 680 + 2 661	71	3	0,22
30	8	10	1	7 310 + 900	2 400 + 3 301	0	1	0,02
			2	14 620 + 1 800	4 800 + 6 601	0	1	0,02
			3	21 930 + 2 700	7 200 + 9 901	0	1	0,03
			5	36 550 + 4 500	12 000 + 16 501	0	1	0,06

Table 6. 14 – Dimension of instances and models for phase II (“*small change*”).

Machines	Locations	Periods	Constraints	Variables (binary + continuous)	Iterations	Feasible solutions	Time (sec)
14	14	1	616	196 + 1	1 456	4	41,00
		2	1 232	392 + 1	300 431	5	17,380
		3	1 848	588 + 1	555 994	11	64,80
		5	3 080	980 + 1	1 026 358	12	168,69
30	32	2	5 884	1 920 + 1	2 436 419	9	7 200,00

This is particularly evident in the phase II (machine location) partially because of the multi-objective nature of the problem (see the number of iterations and the processing time).

6.4.2 Impact of multiple objectives

The proposed model considers four main objectives at the machine location phase: the minimization of *costs* (Material handling (MHC) and reconfiguration costs (RC)); the minimization of *unsuitability* between machines requirements and locations characteristics; and the maximization of the *adjacency* between machines. These objectives can have different combinations of weights, thus reflecting the specific decision-maker concerns. To perform a comprehensive sensitivity analysis, we have made 30 tests, considering the example of designing a department (see section 6.3.1), with 14 machines and 14 locations, during 5 periods. We vary the weight of each objective by 10%, 20%, 30% and 40%. We have also performed a test considering all the objectives with the same weight (25%) and another considering only the costs (50% MHC and 50% RC). The results of the first five tests have already been presented in Table 6. 6, with the respective layout configurations in Figure 6.8 to Figure 6.12. The results of all the 30 tests are ordered by total costs in Table 6.15.

Table 6. 15 - Multi-objective tests of the “*small changes*” model (14 machines, for 5 periods).

Total Costs	MHC	RC	Uns	Adj	Test	Tests (weights) (%)				# Reconf.	Time	Iterations	Feasible solutions
	(α)	(β)	(γ)	(δ)	#	α	β	γ	δ		(seg)		
86 385	**84 000**	**2385**	196,92	3185	2	**100**				**36**	0,33	340	3
190 080	87 000	530	195,67	3315	8	40	10	20	30	8	600,17	3 442 294	15
190 080	87 000	530	195,67	3315	9	40	10	30	20	8	331,23	2 210 040	11
191 950	89 000	400	**195,42**	3325	14	30	10	20	40	6	528,78	3 603 622	15
191 950	89 000	400	**195,42**	3325	15	30	10	40	20	6	571,38	3 725 424	**20**
193 830	91 000	280	**195,42**	3325	6	40	30	10	20	4	291,26	1104 157	12
193 830	91 000	280	**195,42**	3325	7	40	30	20	10	4	90,52	668 167	9
193 830	91 000	280	**195,42**	3325	10	40	20	30	10	4	268,59	1 662 773	13
193 830	91 000	280	**195,42**	3325	11	40	20	10	30	4	837,56	3 926 962	12
193 830	91 000	280	**195,42**	3325	16	30	20	40	10	4	285,66	2 137 797	8
193 830	91 000	280	**195,42**	3325	17	30	20	10	40	4	782,3	4 216 853	11
193 830	91 000	280	**195,42**	3325	20	20	10	40	30	4	713,41	4 479 140	17
198 940	96 250	140	**195,42**	3325	1	25	25	25	25	2	**997,35**	4 839 902	10
198 940	96 250	140	**195,42**	3325	12	30	40	10	20	2	273,08	1 655 345	7
198 940	96 250	140	**195,42**	3325	13	30	40	20	10	2	169,02	954 849	11
198 940	96 250	140	**195,42**	3325	19	20	30	10	40	2	258,42	1 605 864	13
198 940	96 250	140	**195,42**	3325	22	20	40	30	10	2	263,83	1 380 171	13
198 940	96 250	140	**195,42**	3325	23	20	40	30	10	2	158,58	**6 726 673**	11
198 940	96 250	140	**195,42**	3325	30	50	50	0	0	2	4,81	6 350	9
199 640	96 750	340	**195,42**	3405	21	20	10	30	40	5	673,38	3 592 636	15
208 190	105 500	140	**195,42**	**3425**	18	20	30	10	40	2	926,53	4 986 790	11
208 190	105 500	140	**195,42**	**3425**	26	10	20	30	40	2	667,39	3 932 273	11
208 190	105 500	140	**195,42**	**3425**	27	10	20	40	30	2	670,64	3 899 231	10
221 050	118 500	**0**	**195,42**	**3425**	24	**10**	**40**	**20**	**30**	**0**	480,13	2 915 308	10
221 050	118 500	**0**	**195,42**	**3425**	25	**10**	**40**	**30**	**20**	**0**	268,72	1 345 874	6
221 050	118 500	**0**	**195,42**	**3425**	28	**10**	**30**	**40**	**20**	**0**	427,44	2 583 162	11
221 050	118 500	**0**	**195,42**	**3425**	29	**10**	**30**	**20**	**40**	**0**	746,45	4 015 410	8
223 190	120 000	640	**195,42**	**3425**	5			100		8	**0,01**	**36**	**2**
223 550	121 000	**0**	**197,92**	**3125**	3		100			**0**	0,23	403	**2**
231 340	**128 000**	790	**195,42**	**3425**	4				100	10	4,00	6 015	3

Test 2, considering only the minimizations of MHC (100%), is naturally the cheapest configuration with a total cost of 188 935. This solution is also the one with the largest number of reconfigurations (36) and the most expensive in terms of reconfiguration costs (RC = 2 385). However, this is somehow balanced with the cheapest MHC of all the tests made (MHC = 84 000).

On the other hand, the more expensive solution is the one obtained in *test 4,* when we consider only the *adjacency* as the main objective (100% Adj). With a total cost of 231 340, this solution has the more expensive *MHC* (128 000) and larger *reconfiguration* *costs* (790), with 10 reconfigurations. As we are maximizing *adjacency*, machines of the same type, tend to be together, and the maximum value for this parameter is 3 425. This value was obtained not only with this configuration, but also with the tests considering 10% of MHC, and with *test5* considering 100% of *unsuitability*.

In Table 6.15 and in Figure 6.19 we can also observe that the processing time of this model can vary between 0.01 seconds (considering 100% *unsuitability*) and 997.35 seconds (equal weights for the objectives). It seems that tests considering a single objective run faster than those with more objectives. It is also possible to verify that tests needing more time to find the optimal solution, are frequently the ones with a larger weight for the *adjacency* objective.

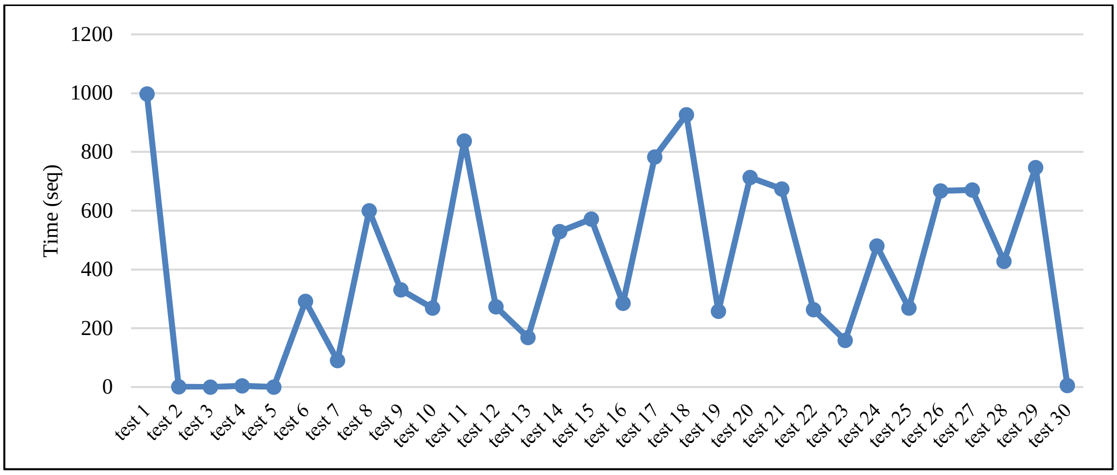

Figure 6. 19 – Processing times of the multi-objective tests of the "*small changes*" model (14 machines, for 5 periods).

For this instance, the model finds several feasible solutions (see Figure 6.20), *test 15*, is the one with more solutions funded (20). As these department has several positions with the same area and good characteristics for the unsuitability measure, it can enlarge the possible configurations, and consequently the solutions funded.

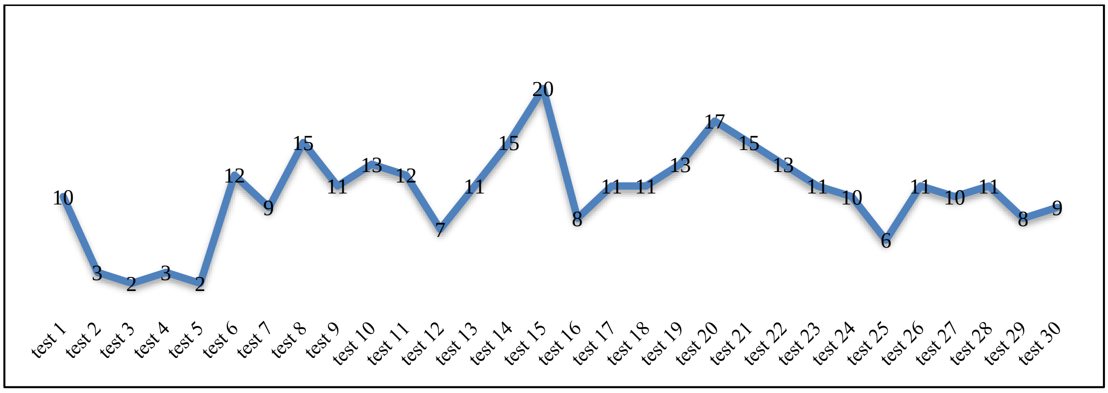

Figure 6. 20 – Solutions found with the multi-objective tests of the "*small changes*" model (14 machines, 5 periods).

We can also see Table 6.15, that there are several tests with the same values for the objectives and with the same layout configuration (solution). In total, there are 20 different configurations of the layout for the 5 periods, as presented in Table 6.16 and detailed in Table C.6.1.

From Figure 6.21, we see that, as expected, the total costs of each configuration essentially vary according to the MHC. The reconfiguration costs have a reduced impact, when compared with the other costs. However, the model in fact minimizes these costs, by selecting the configurations with reduced changes of machines.

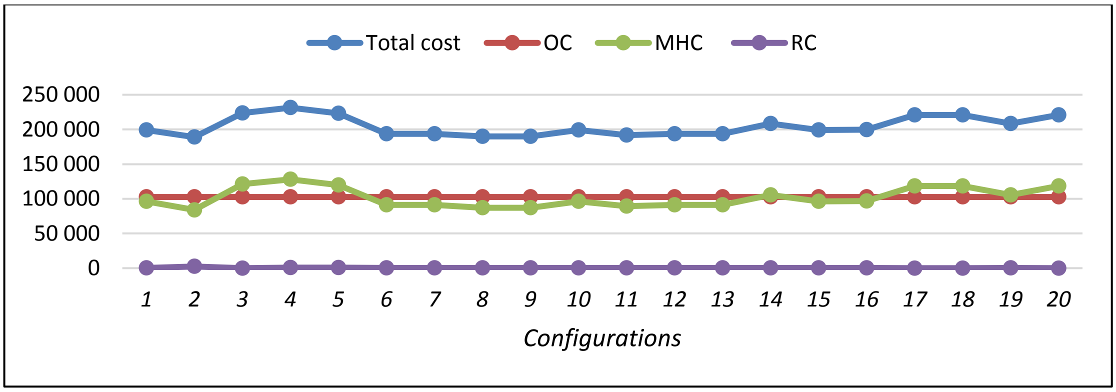

Figure 6. 21 – Costs of the different configurations found when varying the weights of the objectives.

The *adjacency* of these configurations, (see Figure 6.22) can vary between 3 125 of *configuration 3* (resulting from only minimizing the reconfiguration costs), and a maximum value of 3 425. In fact, we can observe that there are a considerable number of configurations with the maximum value of adjacency, and only two configurations with the lowest values (*configurations 3* and *2*).

Table 6. 16 – Results for the "*small changes*" model, changing the weights of the objectives.

Layout configuration	Total cost	Phase I	Phase II				Test	Test (weights) (%)			
		OC	MHC (α)	RC (β)	Adj (δ)	Uns (γ)	#	α	β	δ	γ
1	198 940	102 550	96 250	140	3325	**195,42**	1	25	25	25	25
							13	30	40	10	20
							22	20	40	10	30
							30	50	50		
2	188 935	102 550	84 000	2 385	3185	196.92	2	100			
3	223 550	102 550	121 000	0	3125	197.92	3		100		
4	231 340	102 550	128 000	790	**3425**	**195.42**	4			100	
5	223 190	102 550	120 000	640	**3425**	**195.42**	5				100
6	193 830	102 550	91 000	280	3325	195.42	6	40	30	20	10
7	193 830	102 550	91 000	280	3325	195.42	7	40	30	10	20
							10	40	20	10	30
							11	40	20	30	10
8	190 080	102 550	87 000	530	3315	195.67	8	40	10	30	20
9	190 080	102 550	87 000	530	3315	195.67	9	40	10	20	30
10	198 940	102 550	96 390	140	3325	195.42	12	30	40	20	10
11	191 950	102 550	89 400	400	3325	195.42	15	30	10	20	40
							14	30	10	40	20
12	193 830	102 550	91 000	280	3325	195.42	16	30	20	10	40
13	193 830	102 550	91 000	280	3325	195.42	17	30	20	40	10
							20	20	10	30	40
14	208 190	102 550	105 500	140	3425	195.42	18	20	30	40	10
15	198 940	102 550	96 250	140	3325	195.42	19	20	30	20	40
							23	20	40	30	10
16	199 640	102 550	96 750	340	3405	195.42	21	20	10	40	30
17	221 050	102 550	118 500	0	3425	195.42	24	10	40	30	20
							28	10	30	20	40
18	221 050	102 550	118 500	0	3425	195.42	25	10	40	20	30
19	208 190	102 550	105 500	140	3425	195.42	26	10	20	40	30
							27	10	20	30	40
20	221 050	102 550	118 500	0	3425	195.42	29	10	30	40	20

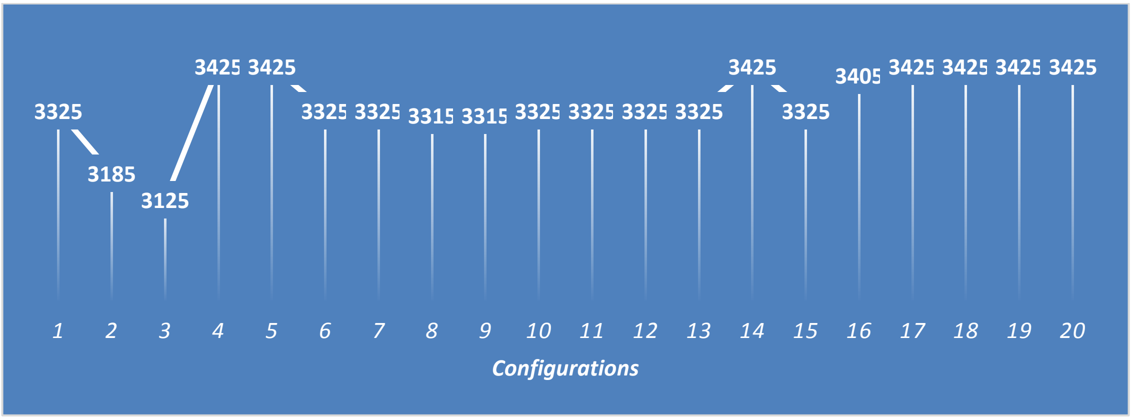

Figure 6. 22 – ***Adjacency*** **values with different weights for the objectives.**

Most of the configurations also have optimum or near optimum values for the *unsuitability* (195,42), see Figure 6.23. The exceptions are *configurations 2* and *3*.

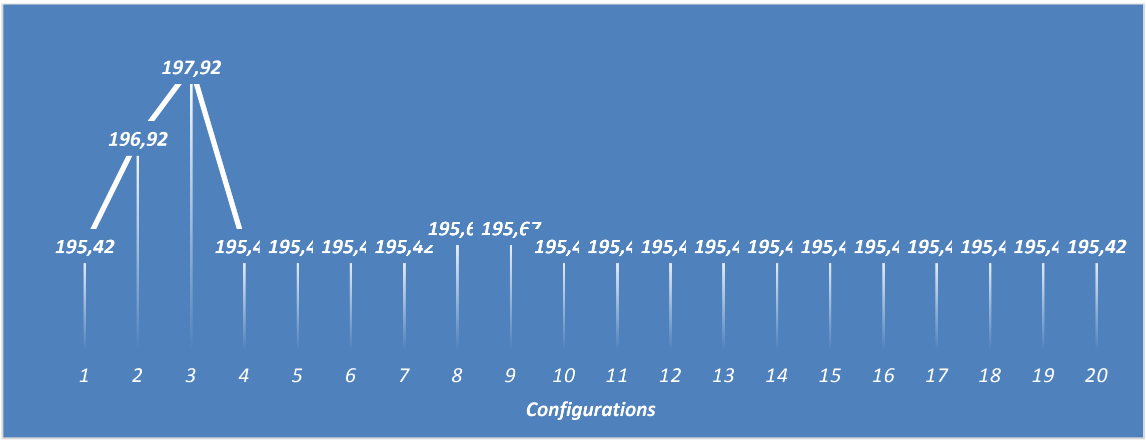

Figure 6. 23 – ***Unsuitability*** **values with different weights for the objectives.**

We can also observe (Table 6.16), that there are some configurations with the same values, for all the objectives. For example (Figure 6.24): *configuration 6* has the same layout for periods 1, 2 , 5, and exchange the locations of machine *m6* with *m7*, for periods 3 and 4; *configuration 7*, has similar layouts, but for periods 1, 5, and for periods 2, 3, 4, the locations of machines *m11* and *m12* are exchanged.

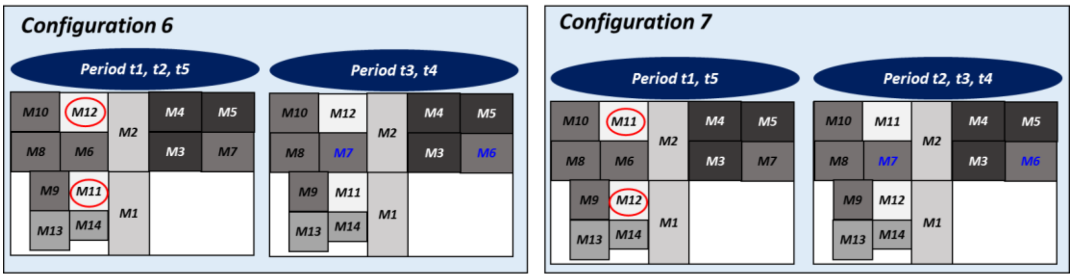

Figure 6. 24 – Layout of ***configurations 6*** **and** ***7*****.**

Configurations 8 and *9*, have also the same values for all the objectives, and, in fact, similar layouts in each period (Figure 6.25). The main difference is the location of machines *m13* and *m14*, that are exchanged. The remaining machines are positioned and change their locations in the same way, in both configurations (e.g. machines *m10*, *m7*, *m8* and *m6*, in period 2).

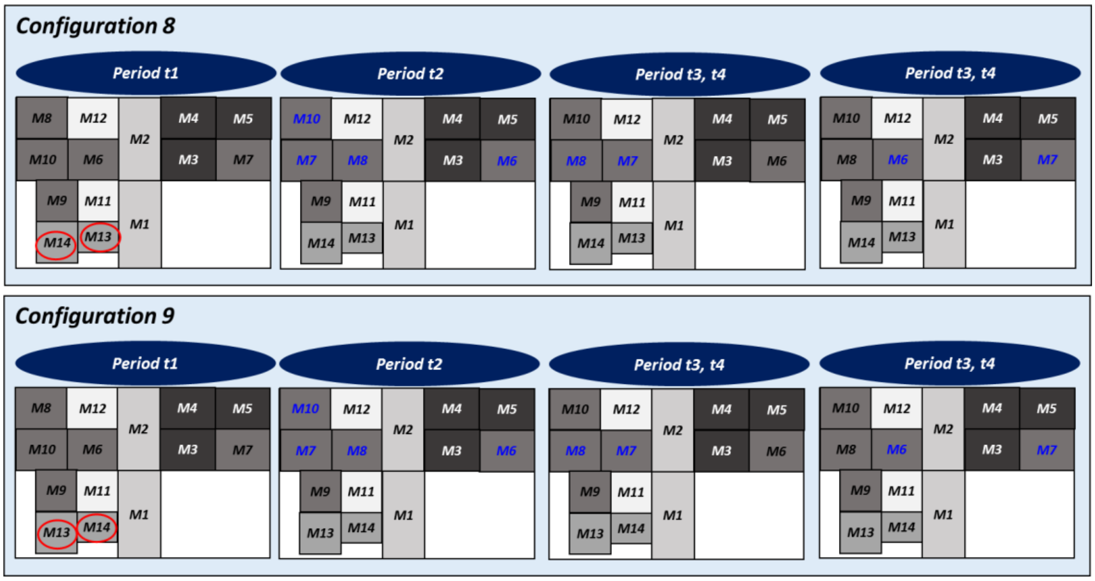

Figure 6. 25 – Layouts of *configurations 8* and *9*.

The same can be observed with *configurations 12* and *13*, but now with machines *m11* and *m12* (Figure 6.26).

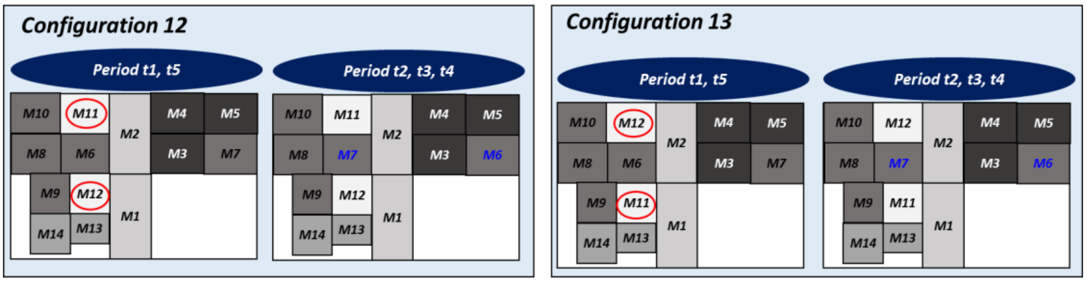

Figure 6. 26 – Layouts of *configurations 12* and *13*.

With a total cost of 221 050, and the same values for all the objectives, *configurations 17, 18 and 20* have similar layouts, with static layouts for the 5 periods see Figure 6.26. The main differences between these configurations are the locations of machines *m11*, *m12*, and *m13*, *m14*, that are exchanged.

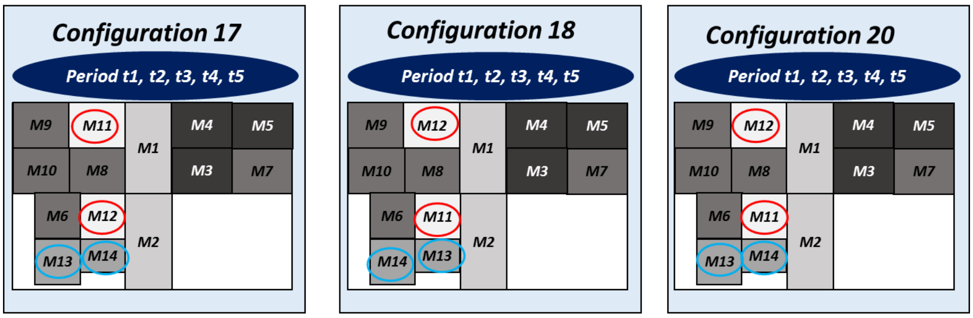

Figure 6. 27 – Layouts of *configurations 17, 18* and *20*.

Configurations 14 and *19* also have the same values for all objectives. As showed in Figure 6.28, both configurations have a first layout in period 1, and then change to another layout, by exchanging the locations of machines *m6* and *m7*. The difference between these configurations is the location of machines *m11*, *m12*, and *m13*, *m14*.

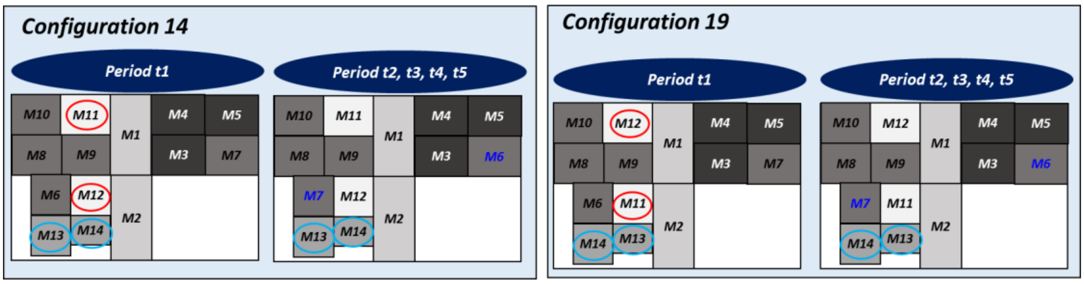

Figure 6. 28 – Layouts of *configurations 14* and *19*.

The model naturally allows more types of analyses, for example, to understand what are the best locations for the machines, in each period (see Table 6.17). For instance, machines *m1* and *m2*, frequently exchange their locations, during the 5 periods.

Table 6. 17 – Locations of each machine, in each period.

	Period				
Machine	***t1***	***t2***	***t3***	***t4***	***t5***
m1	*l10, l9*	*l9, l10*	*l9, l10*	*l9, l10*	*l9, l10*
m2	*l10, l9*	*l9, l10*	*l9, l10*	*l9, l10*	*l9, l10*
m3	*l11, l13*	*l11, l13*	*l11, l13*	*l11, l13*	*l11,l12, l13*
m4	*l11, l12*	*l11, l12, l13*	*l11, l12*	*l11, l12*	*l11, l12, l13*
m5	*l12, l13*	*l12, l13*	*l12, l13*	*l12, l13*	*l12, l13*
m6	*l4, l5, l14*	*l4, l5, l14*	*l4, l5, l14*	*l4, l5, l14*	*l4, l5, l14*
m7	*l5, l14*	*l3, l4, l5, l14*	*l4, l5, l14*	*l4, l5, l14*	*l4, l5, l14*
m8	*l1, l3, l4, l5*	*l1, l3, l4*	*l1, l3, l4*	*l1, l3, l4*	*l1, l3, l4*
m9	*l1, l3, l4, l5*	*l1, l3, l4, l5*	*l1, l3, l4, l5*	*l1, l3, l4, l5*	*l1, l3, l4, l5*
m10	*l1, l3, l4*	*l1, l3, l4*	*l1, l3, l4*	*l1, l3, l4*	*l1, l3, l4, l5*
m11	*l2, l6, l7*	*l2, l6, l7*	*l2, l6, l7*	*l2, l6, l7*	*l2, l6, l7*
m12	*l2, l6*	*l2, l6*	*l2, l6, l7*	*l2, l6*	*l2, l6*
m13	*l7, l8*	*l7, l8*	*l7, l8*	*l2, l7, l8*	*l2, l7, l8*
m14	*l2, l7, l8*	*l2, l7, l8*	*l2, l7, l8*	*l2, l7, l8*	*l2, l7, l8*

6.5 Conclusions

In this chapter, we have presented the "*small changes*" model for the design of layouts, at the machine level. This model can be applied in several situations and at different moments of a layout life cycle: to make some specific and local reconfigurations inside a department, or even to exchange and reconfigure the layout of a complete facility.

The model is organized in two phases: first, products are assigned to machines; and then, with the information of the first phase, machine locations inside a facility or department are determined. To be more realistic, the model considers four objectives (minimize total material handling costs, minimize re-layout costs, minimize unsuitability between machines and locations, and maximize the adjacency between machines) allowing the decision maker to weight the objectives, according to his own strategy, and therefore to compare several alternative solutions.

The model was implemented and tested on the CPLEX solver, with some illustrative instances, to design and reconfigure the layout of a complete facility, and to design the layout of a specific department.

We believe this work has interesting contributions for industry, since it allows the experimentation of various situations in the daily operation of companies, such as adding new machines or optimizing the flows inside a facility or a department. With the *adjacency* objective, the model can test and compare several layouts and production organization forms of machines, in a dynamic and flexible way. With the *unsuitability* objective, we can organize the layout in a more suitable way, considering the existing characteristics of each place and the specific needs of each machine, maximizing the efficiency of the layout and, at the same time, minimize the re-layout costs and time. As this is a multi-objective model, it also allows to analyse and compare the impacts on layout configurations and production systems of all the objective, that can be combined with different weights or individually.

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7. USING THE MODEL AS A DECISION SUPPORT TOOL

In this chapter, we present some possible applications of the proposed models for designing and reconfiguring multiple facilities, at different levels. Through some small examples we show how these models can be used as a decision support tool, thus demonstrating their potential.

Contents of this chapter:

7.1 Introduction

In this chapter, we intend to demonstrate how the models developed in this research project can be used as a decision support tool. We present some possible utilization scenarios, and some extensions of these models, that can support several decision making processes.

This research project was inspired by a real case study, defined on a first-tier supplier of the automotive industry, as previously presented in chapter 3. We now show, how the proposed models can be combined and used by the company as a decision support tool, by comparing the current situation with two scenarios: a) minimizing total material handling costs; and b) centralizing product warehouses, at the same facility.

Another frequent situation is the introduction of new projects, and the need of previously defining, during the project design and negotiation, what are the companies to be involved, and what are the main impacts of this network for each company.

The diversity of situations where these layout design models can be applied is quite broad. We present there some cases we consider to be well representative of practical situations that may occur in the daily life of companies. A first natural extension of the MFL model deals with the occurrence of a new project and what impacts can it bring to the other projects and to the layout configuration of the facilities of the network. Changing the size of the network, by adding or eliminating facilities, is another extension of the model, explored in this chapter.

7.2 Application to the case study

7.2.1 The data

We have 3 facilities (SP, IN and PL), with 49 departments in total, and 49 locations, currently allocated as presented in Figure 7.1. To distinguish the positions inside each facility we numerate the positions with a letter for each facility, for example *l12I* is location 12 of facility IN, and *l12S* is location 12 of facility SP. The same terminology is used for the departments currently positioned in each facility. For example, department I1S is one of the Injection departments currently positioned at facility SP, and I2S is the other (see Table 7.2).

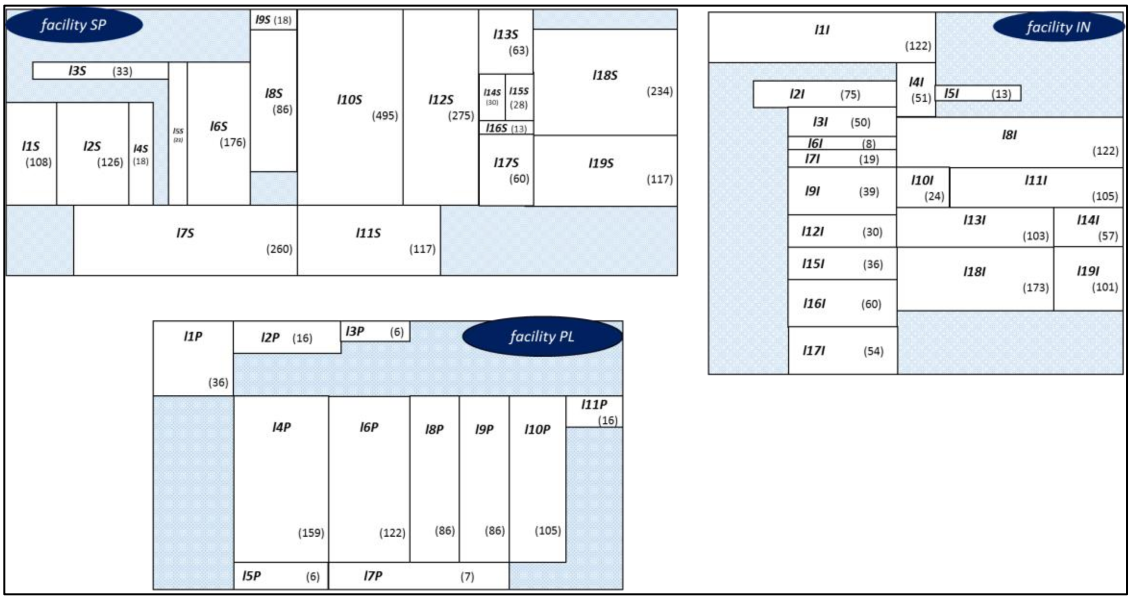

Figure 7. 1 – Location areas for the facilities of the case study network (e.g. location *l3S* has an area of 33 units).

The information about the existing locations of each facility is presented in Table 7.1. This network has, in total, eight types of departments with the characteristics presented in Table 7.2.

Inside the departments, we have machines of several types, with different capacities and capable of producing several types of products. For example, department I1S, currently allocated to facility SP (see Figure 7.1), in location *l18S*, which has 35 positions (see Figure 7.2), and has the characteristics detailed in Table 7.3. For the injection departments, it is important for some machines to be connected through pipes, to directly feed the machines with the raw material. But not all the locations have this connection, this being reflected by the characteristic *ch1*, for the *unsuitability* objective.

Another important aspect for some injection machines, specially the larger ones, is the way moulds are transported. For this, cranes need to be available, so this is the characteristic *ch2*. Other interesting characteristics can be considered, but these are the most important for injection machines.

Table 7. 1 – Information on locations for each facility of the case study (e.g. location *l3S* is location 3 of facility SP).

Facility	**Location**	**Area**	**Characteristics**	
			floor (Chl_1)	***cranes (Chl_2)***
SP	*l1S*	108	1	3
	l2S	126	2	3
	l3S	33	1	1
	l4S	18	1	1
	l5S	21	1	1
	l6S	176	4	3
	l7S	260	1	1
	l8S	56	4	2
	l9S	18	1	1
	l10S	495	5	3
	l11S	117	1	1
	l12S	275	5	3
	l13S	63	5	3
	l14S	30	5	3
	l15S	28	5	3
	l16S	14	5	3
	l17S	6	5	3
	l18S	234	5	3
	l19S	117	5	3
IN	*l1I*	122	1	1
	l2I	75	1	1
	l3I	50	5	3
	l4I	51	1	1
	l5I	13	1	1
	l6I	9	3	1
	l7I	19	3	1
	l8I	122	5	5
	l9I	39	5	3
	l10I	24	5	5
	l11I	105	5	5
	l12I	30	2	3
	l13I	103	5	3
	l14I	57	5	5
	l1I	36	5	2
	l16I	60	5	3
	l17I	54	5	3
	l18I	173	5	3
	l19I	101	5	4
PL	*l1P*	36	1	1
	l2P	16	1	1
	l3P	6	1	1
	l4P	159	5	3
	l5P	8	5	1
	l6P	123	5	3
	l7P	7	5	1
	l8P	86	5	3
	l9P	86	5	3
	l10P	105	3	3
	l11P	16	2	2

Table 7. 2 – Information on the departments (e.g. A2I is the Assembly department number 2 of facility IN).

Departments		Reconfiguration cost	Area	Characteristics	
				floor (Chd_1)	*cranes (Chd_2)*
Raw material warehouse	R1S	5 000	28	1	1
	R2S	500	20	1	1
	R3S	500	15	1	1
	R4S	500	11	1	1
	R5S	50 000	4	1	1
	R6S	1 000	65	1	1
	R1I	1 000	73	1	1
	R2I	50 000	13	1	1
	R3I	500	9	1	1
	RP	1 000	14	1	1
Injection	I1S	826 500	110	5	3
	I2S	861 000	153	5	3
	I1I	150 000	28	5	3
	I2I	331 500	63	5	3
	I3I	361 000	51	5	3
	I1P	723 500	100	5	3
	I2P	550 000	60	5	3
Assembly	A1S	28 000	56	1	1
	A1I	125 000	86	1	3
	A2I	5 000	20	1	3
	A3I	5 100	29	1	1
	A1P	36 100	70	1	1
Components warehouse	C1S	500	396	1	1
	C2S	500	159	1	1
	C3S	1 000	17	1	1
	C4S	5 000	151	1	1
	C1I	500	32	1	1
	C2I	500	36	1	1
	C1P	5 000	25	1	1
	C2P	1 000	100	2	3
Product warehouse	P1S	10 000	396	2	3
	P2S	5 000	159	2	3
	P3S	1 000	17	2	2
	P1I	10 000	151	2	3
	P2I	2 000	32	2	3
	P3I	2 000	36	2	3
	P4I	500	25	2	2
	P1P	5 000	100	2	3
Painting	P	800 000	90	5	3
Maintenance	MS	2 000	26	5	3
	MI	2 000	40	5	3
	MP	1 000	5	5	1
Support	S1S	1 000	30	1	1
	S2S	1 000	126	1	1
	S1I	1 000	30	1	1
	S2I	1 000	75	1	1
	S1P	1 000	6	1	1
	S2P	1 000	5	1	1
	S3P	1 000	5	1	1

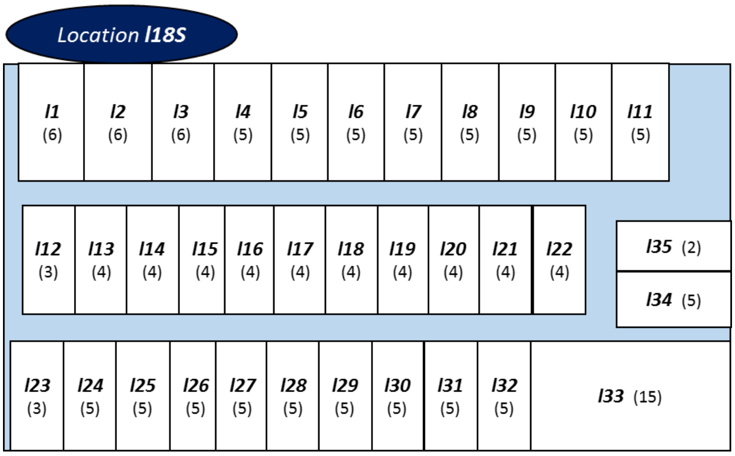

Figure 7. 2 – Positions inside location *l18*S of facility SP (e.g. position *l1* has an area of 6).

Table 7. 3 – Information about the current positions inside location *l18S* of facility SP.

Location	Area	Characteristics	
		pipes (*Chl_1*)	*cranes* (*Chl_2*)
l1	6	5	5
l2	6	5	5
l3	6	5	5
l4	5	5	5
l5	5	5	5
l6	5	5	5
l7	5	5	5
l8	5	5	5
l9	5	5	5
l10	5	5	5
l11	5	5	5
l12	3	5	5
l13	4	5	5
l14	4	5	5
l15	4	5	5
l16	4	5	5
l17	4	1	5
l18	4	1	5
l19	4	1	5
l20	4	1	5
l21	4	1	5
l22	4	1	5
l23	3	1	5
l24	5	1	5
l25	5	1	5
l26	5	1	5
l27	5	1	5
l28	5	1	5
l29	5	1	5
l30	5	1	5
l31	5	1	5
l32	5	1	5
l33	15	1	3
l34	5	1	3
l35	2	1	1

Department I1S has 31 machines of 8 types, with the characteristics presented in Table 7.4.

Table 7. 4 – Information about machines of department I1S.

Machine	Type	Capacity	Area	Reconfiguration cost	Characteristics	
					pipes (Chm_1)	*cranes (Chm_2)*
M1	I	150	1,53	20 000	1	5
M2		200	1,44	20 000	1	5
M3		200	1,44	20 000	1	5
M4		200	1,44	20 000	1	5
M5		200	1,44	20 000	1	5
M6		200	1,44	20 000	1	5
M7		200	1,53	20 000	1	5
M8		240	2,2	20 000	1	5
M9		275	2,2	20 000	1	5
M10	II	300	2,2	20 000	1	5
M11		300	2,2	20 000	1	5
M12		300	2,2	20 000	1	5
M13		350	2,16	20 000	3	5
M14		350	2,16	20 000	3	5
M15		350	2,16	20 000	3	5
M16		350	2,16	20 000	3	5
M17	III	400	2,42	30 000	5	5
M18		400	2,42	30 000	5	5
M20		400	2,42	30 000	5	5
M21		400	2,42	30 000	5	5
M22		400	2,42	30 000	5	5
M23		420	2,42	30 000	1	5
M24		420	2,42	30 000	1	5
M25	IV	550	3,08	30 000	5	5
M26		600	4,5	30 000	5	5
M27		600	4,5	30 000	5	5
M28	V	700	6,9	30 000	1	5
M29	VI	800	5,76	30 000	5	5
M30	VIII	900	5,95	50 000	5	5
M31		900	5,95	50 000	5	5

Position *l12S* has 21 locations as shown in Figure 7.3, with the characteristics presented in Table 7.5.

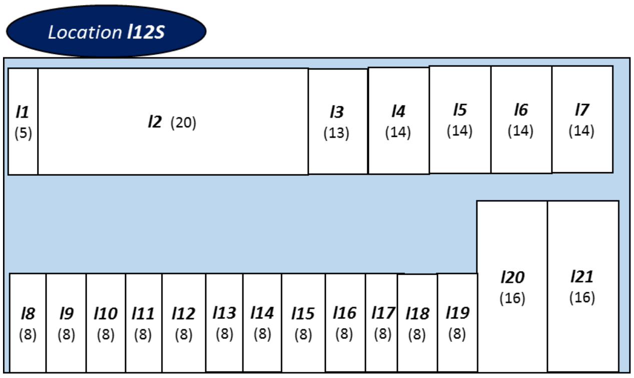

Figure 7. 3 – Positions inside location *l12S* of facility SP.

Table 7. 5 – Information about the current positions inside location *l12S* of facility SP.

Location	**Area**	**Characteristics**	
		***pipes* (Chl_1)**	***cranes* (Chl_2)**
l1	5	3	5
l2	20	3	5
l3	13	3	5
l4	14	3	5
l5	14	3	5
l6	14	3	5
l7	14	3	5
l8	8	5	5
l9	8	5	5
l10	8	5	5
l11	8	5	5
l12	8	5	5
l13	8	5	5
l14	8	5	5
l15	8	5	5
l16	8	5	5
l17	8	5	5
l18	8	5	5
l19	8	5	5
l20	16	5	5
l21	16	5	5

Department I2S, currently allocated to position *l12S*, has 20 machines with the characteristics in Table 7.6.

Table 7. 6 – Information about machines of department I2S.

Machine	**Type**	**Capacity**	**Area**	**Reconfiguration cost**	**Characteristics**	
					***pipes* (Chm_1)**	***cranes* (Chm_2)**
M1	I	240	1	20 000	3	3
M2	II	600	4	30 000	3	5
M3	III	800	5	30 000	5	3
M4		800	5	30 000	5	3
M5	IV	900	6	50 000	5	5
M6		900	6	50 000	5	5
M7		900	6	50 000	5	5
M8	V	1000	6	50 000	3	5
M9		1000	6	50 000	3	5
M10		1000	6	50 000	4	5
M11	VI	1100	6	50 000	3	5
M12		1100	7	50 000	3	5
M13	VII	1400	13	50 000	3	5
M14	VIII	1500	8	50 000	3	5
M15	IX	1600	9	50 000	3	5
M16		1600	8	50 000	3	5
M17	X	2000	10	50 000	2	5
M18	XI	2700	10	50 000	1	5
M19	XII	3200	15	50 000	2	5
M20	Aux		5	500	1	4

As previously referred, for us, a machine can be one machine only, or a group of machines (for example a cell or a single workstation). At the injection department, usually machines are alone, but in some situations, near the machines, we can have some assembly activities, with some tools (that is why we consider this group of resources as a single production centre). At the assembly department, the diversity is large, and in fact we can have small assembly workstations and larger cells or even lines. But a "machine" can be any type of production centers that transform, some inputs into an output. Some of these production centers have specific requirements to be installed, such as the need of compressed air or cranes – we therefore consider these equipments as two important characteristics to be used in terms of *unsuitability* for the assembly departments. One example can be the assembly department A1S, currently located in location *l19S.* This position has 15 locations (see Figure 7.4), and detailed in Table 7.7.

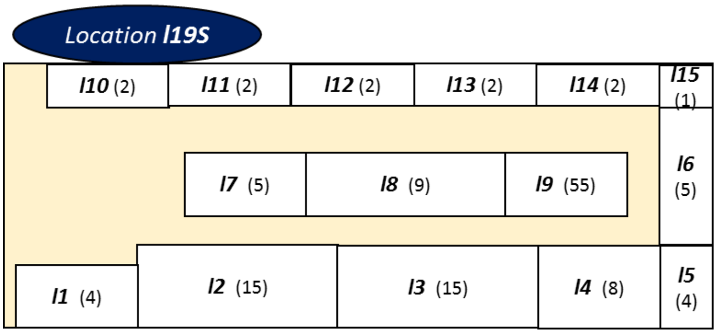

Figure 7. 4 - Positions inside location l19S of facility SP (e.g. position *l1* has an area of 4).

Table 7. 7 – Information about the current positions inside location *l19S* of facility SP.

Location	**Area**	**Characteristics**	
		***compressed air* (*Chl_1*)**	***cranes* (*Chl_2*)**
l1	4	5	
l2	15	5	5
l3	15	5	5
l4	8	5	5
l5	4	5	5
l6	5	5	4
l7	5	3	3
l8	9	3	3
l9	5	3	3
l10	2	5	1
l11	2	5	1
l12	2	5	1
l13	2	5	1
l14	2	5	1
l15	1	5	1

In Table 7.8, we have the requirements of this machines of this department.

Table 7. 8 – Information about machines of department A1S.

Machine	Area	Reconfiguration cost	Characteristics	
			compressed air (Chm_1)	*cranes (Chm_2)*
M1	15	500	1	1
M2	15	5 000	5	4
M3	5	5 000	5	3
M4	1	1 000	5	2
M5	4	5 000	5	1
M6	9	5 000	1	1
M7	5	5 000	1	1
M8	1	500	5	1
M9	1	500	5	1
M10	1	500	1	1

The injection and assembly departments are the most critical in our case, because they are the real “productive” departments. Therefore, in our analysis, we only consider the machine level for these productive departments, due to their great impact on costs and production. However, in the literature we can find some studies on the layout design of other types of departments, where we can also apply this small changes analysis, for example in the case of the warehouse design (Moshref-Javadi & Lehto 2016), (Staudt et al. 2015), (Gu et al. 2010), (Baker & Canessa 2009), etc.).

7.2.2 Possible applications of the models

There are several situations where the proposed models (viewed here as an integrated Decision Support System (DSS)) can be applied to help decision making, in particular, at SIMOLDES. To demonstrate the utility of the DSS, we start by analysing the current layout. To allow a better comparison between the current solution with the solutions proposed by the model, we consider a static example with a single period. We follow here the Multi-Facility Layout previously proposed (see Figure 4.4).

Phase 1 – System characterization

The current layout configuration for the three facilities is presented in Figure 7.5, with the characteristics previously described (in the above sections).

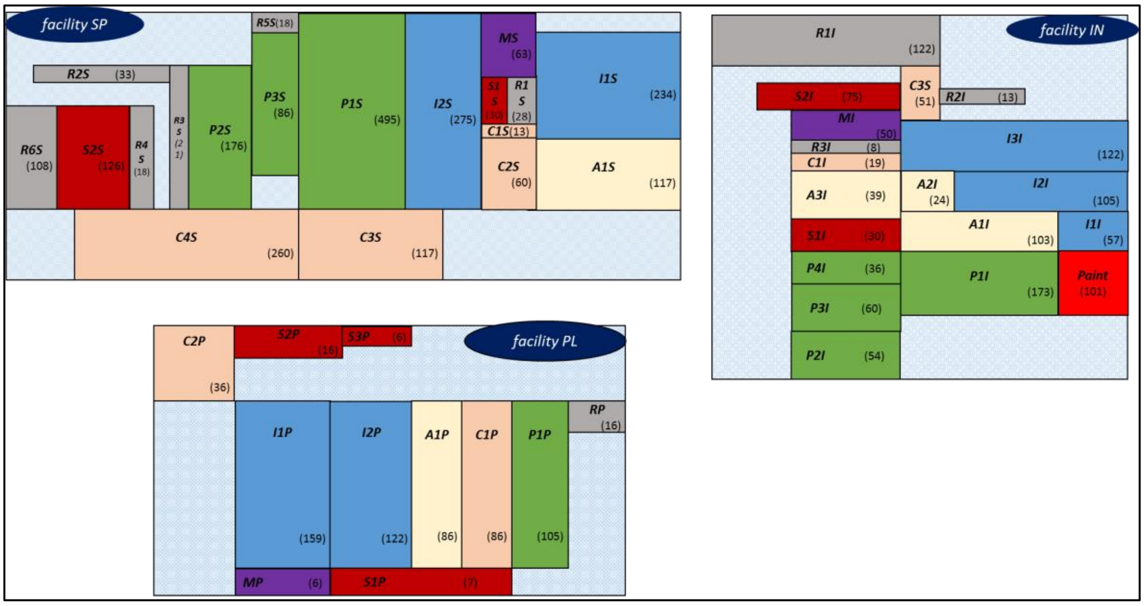

Figure 7. 5 – Current configuration of the case study facilities.

Phase 2 – System evaluation

Assuming a total demand of 19 300 units, taking into account the characteristics of each department and the product specification, the flows between departments are as presented in Figure 7.6.

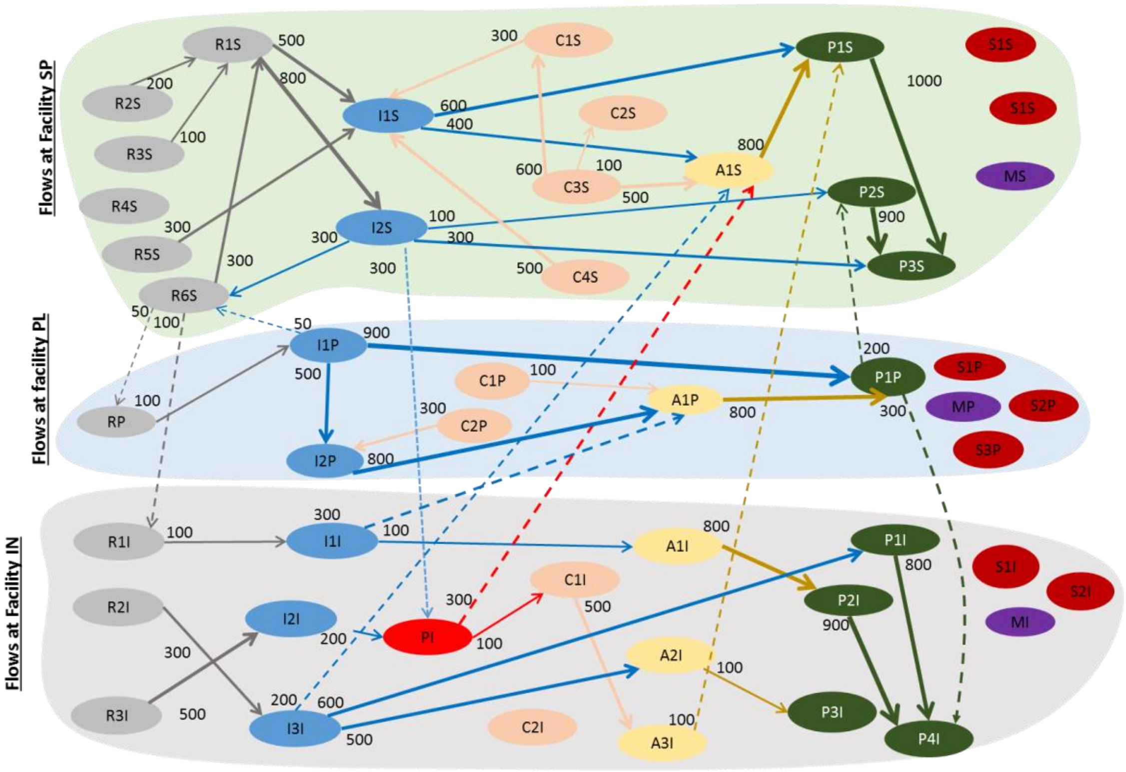

Figure 7. 6 – Flows between departments.

The total flow inside each facility and between facilities are shown in Figure 7.7.

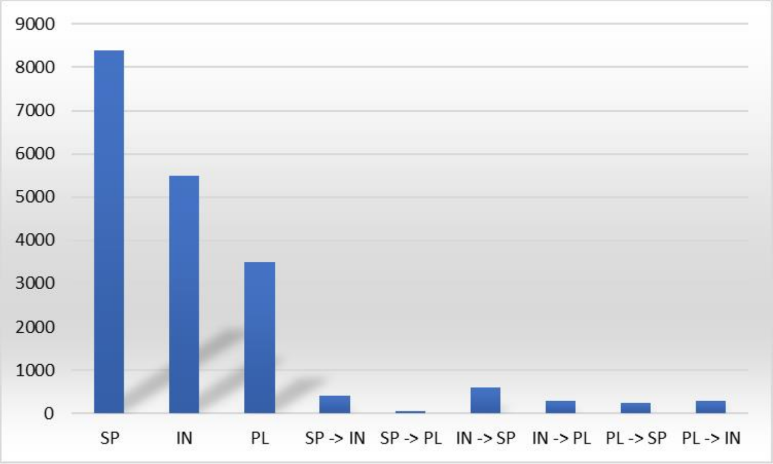

Figure 7. 7 – Flows between facilities, with the current layout configuration.

This configuration has a total internal MHC (*CtInt*) *of* 1 571 500, and a total external MHC (*CtExt) of 4* 880 000 with a total cost (*Ct*) of 6 451 500 (see Figure 7.8).

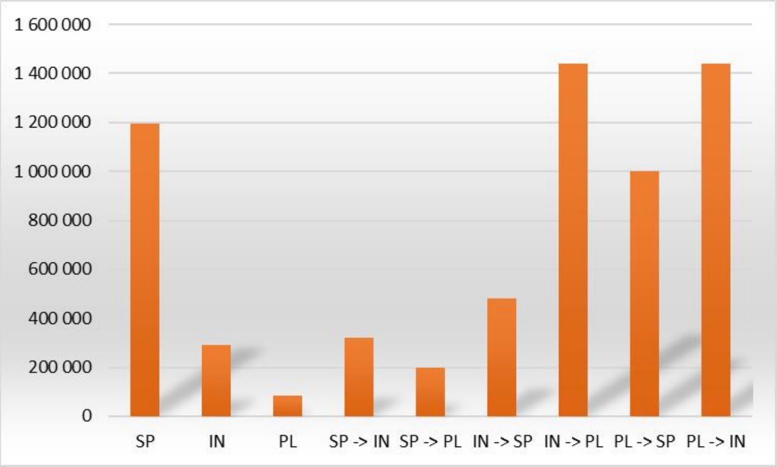

Figure 7. 8 – MHC inside and between facilities, with the current layout configuration.

The current configuration has an *unsuitability* distribution as shown in Figure 7.9. Using equation 5.10, we can compute, for the current network, a total value of *unsuitability* (*Uns)* of 192 (see Table 7.9).

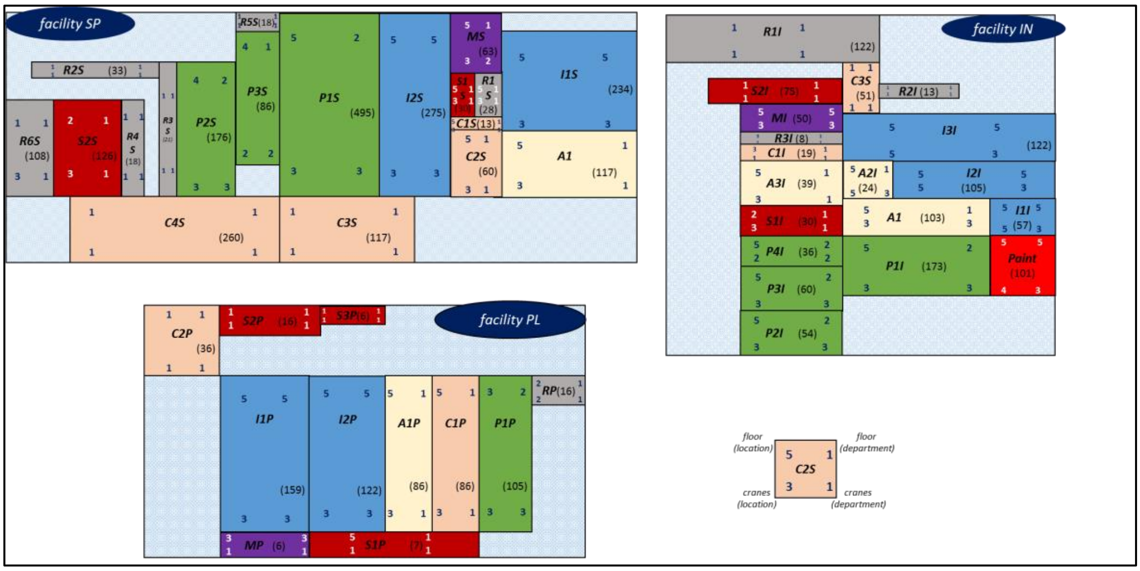

Figure 7. 9 – *Unsuitability* values, for the current network configuration.

Phase 3 – Comparing results and decide if a reconfiguration is needed:

The company is naturally interested in checking if the current configuration is the most economic. As the minimization of costs is the main objective of the model, we have run it with the data of the case study, as previously presented. The tests were made with the IBM ILOG CPLEX V12.6.1 optimization software, using the default pre-processing values, at a portable computer (16 Gb RAM, and 2,6Ghz CPU Intel Core). The optimal configuration found is the one presented in Figure 7.10. This configuration has an internal MHC cost (*CtInt)* of 1 389 000, and a total external MHC cost (*CtExt)* of 560 000), with a total MHC cost (*Ct)* of 1 949 000. This cost is much better than the estimated cost for the current layout.

Table 7. 9 – *Unsuitability* of the current configuration for the case study.

Department	**Location**	**Characteristics**		**Unsuitability**
		***floor* (*Ch*$_1$)**	***cranes* (*Ch*$_2$)**	
R1S	*l15S*	5	3	8
R2S	*l3S*	1	1	2
R3S	*l5S*	1	1	2
R4S	*l4S*	1	1	2
R5S	*l9S*	1	1	2
R6S	*l1S*	1	3	4
I1S	*l18S*	1	1	2
I2S	*l12S*	1	1	2
AIS	*l19S*	5	3	8
CIS	*l16S*	5	3	8
C2S	*l17S*	5	3	8
C3S	*l11S*	1	1	2
C4S	*l7S*	1	1	2
P1S	*l10S*	2,5	1	3,5
P2S	*l6S*	2	1	3
P3S	*l8S*	5	1	6
MS	*l13S*	5	1	6
S1S	*l14S*	5	3	8
S2S	*l2S*	2	3	5
		Total *Unsuitability* of SP		**83,5**
R1I	*l1I*	1	1	2
R2I	*l5I*	1	1	2
R3I	*l6I*	3	1	4
I1I	*l14I*	1	1,67	2,67
I2I	*l11I*	1	1,67	2,67
I3I	*l8I*	1	1,67	2,67
A1I	*l13I*	5	1	6
A2I	*l10I*	5	1,67	6,67
A3I	*l9I*	5	3	8
C1I	*l7I*	3	1	4
C2I	*l4I*	1	1	2
P1I	*l18I*	2,5	1	3,5
P2I	*l17I*	2,5	1	3,5
P3I	*l16I*	2,5	1	3,5
P4I	*l15I*	2,5	1	3,5
P	*l19I*	1	1,33	2,33
MI	*l3I*	1	1	2
S1I	*l2I*	1	1	2
S2I	*l12I*	2	3	5
		Total *Unsuitability* of IN		**68,00**
R1P	*l11P*	2	2	4
I1P	*l4P*	1	1	2
I2P	*l6P*	1	1	2
A1P	*l8P*	5	3	8
P1P	*l10P*	1,5	1	2,5
C1P	*l9P*	5	3	8
C2P	*l1P*	1	1	2
MP	*l5P*	1	1	2
S1P	*l7P*	5	1	6
S2P	*l2P*	1	1	2
S3P	*l3P*	1	1	2
		Total Unsuitability of PL		**40,5**
	Total *Unsuitability* of the Network			**192**

Phase 4 – Location of departments:

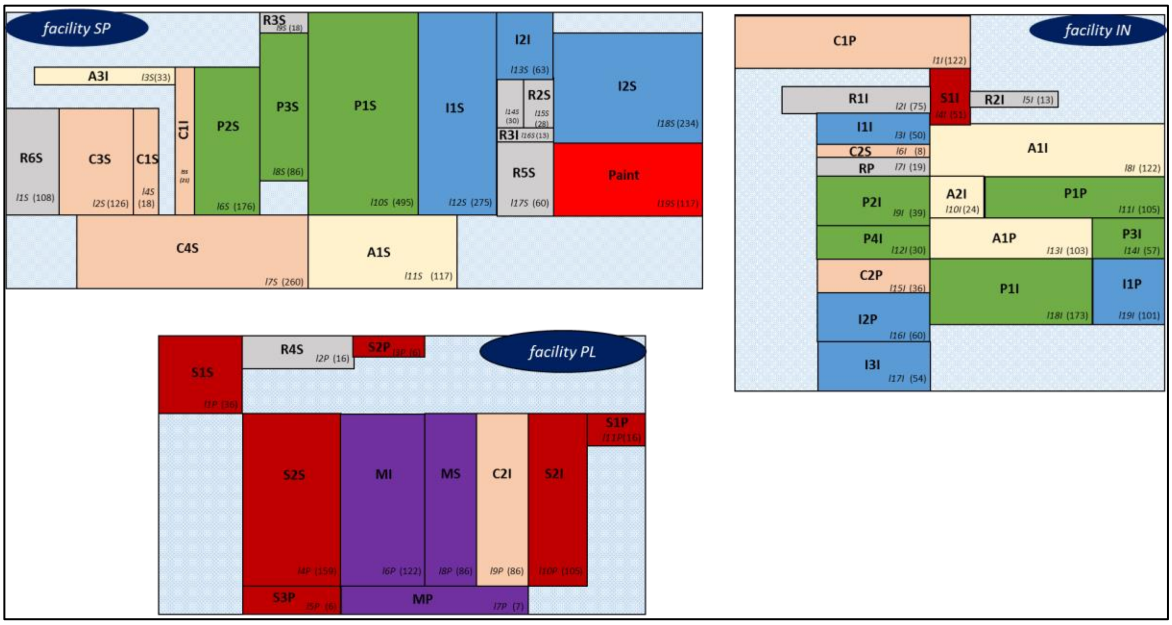

Figure 7. 10 – Optimal configuration for the facilities, considering the minimization of MHC costs.

In this configuration (Figure 7.10), we can see that facility PL concentrates almost all the departments that support production, thus minimizing the frequent need of transport for longer, inter-facilities distances. Facility SP maintains most of the departments that are currently open there. Facility IN becomes more dedicated to production, with four injection departments and three assembly departments. The product warehouses are now more concentrated on facility IN.

This optimal configuration has a total *unsuitability* value (*Uns)* of 185, which is a better value than the value of the current configuration.

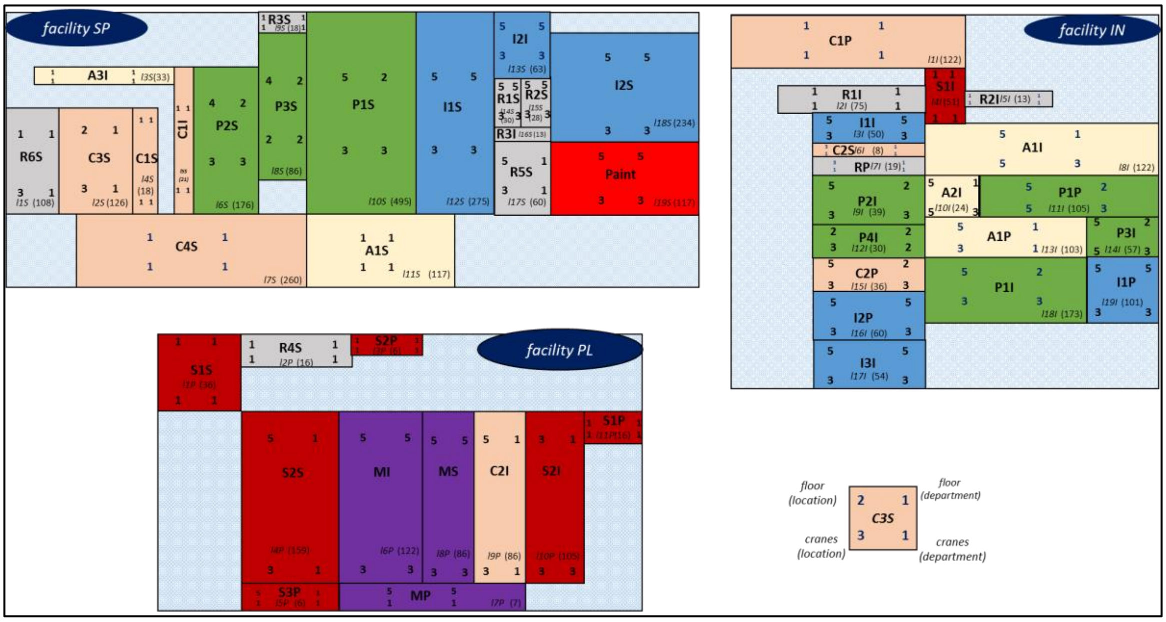

Figure 7. 11 – *Unsuitability* of the optimal configuration.

Table 7.10, shows there are some departments that remain at their current locations – in facilities SP (P1S, P2S, R3S) and IN (e.g. R2I, A2I, P1I). Other departments change their position inside the same facility, such as P2I or I3I. There are also departments that are moved to new positions inside the same facility, such as I1S and I2S.

Phase 5 – Layout design at the machine level:

For defining and analyzing the layout of the machines, we use the *small changes model*. As previously explained (chapter 3), the company works with “projects” (Figure 3.7) to produce specific complete kits (with a set of related parts for a specific car model). This may involve a great diversity of components (see e.g. Figure 3.4 and 3.6) with different dimensions and production times. Taking into account those characteristics, production is organized in such a way that each product is manufactured at a machine and then sent to the warehouse. Later it is collected at the warehouse, on the needed quantities, only when it must be assembled with other components or sent to the customer, with other components of a given *project*, these means that there is no direct transportation of materials between machines at the *injection* departments. Normally a *train* runs through the departments, delivering the raw materials at each machine and collecting its products. *Assembly* departments can work in a similar way, without transport between machines, or in some cases, with machines transferring work between them, depending on the type of product.

Table 7. 10 – Comparing the current location of departments with their optimal positions.

department	area required	Current configuration			Optimal configuration		
		position	area of position	free area	position	area of position	free area
R1S	28	*l15S*	28	0	*l14S*	30	2
R2S	20	*l3S*	33	13	*l15S*	28	8
R3S	15	*l5S*	21	6	*l9S*	18	3
R4S	11	*l4S*	18	7	*l2P*	16	5
R5S	4	*l9S*	18	14	*l17S*	60	56
R6S	**65**	***l1S***	**108**	**43**	***l1S***	**108**	**43**
R1I	73	*l1I*	122	49	*l2I*	75	2
R2I	**13**	***l5I***	**13**	**0**	***l5I***	**19**	**5**
R3I	8	*l6I*	8	0	*l16S*	13	5
RP	14	*l11P*	16	2	*l7I*	19	5
I1S	110	*l18S*	234	124	*l12S*	275	165
I2S	153	*l12S*	275	122	*l18S*	234	81
I1I	28	*l14I*	57	29	*l3I*	50	22
I2I	63	*l11I*	105	42	*l13S*	63	0
I3I	51	*l8I*	122	71	*l17I*	54	3
I1P	100	*l4P*	159	59	*l19I*	101	1
I2P	60	*l6P*	122	62	*l16I*	60	0
AIS	56	*l19S*	117	61	*l11S*	117	61
A1I	86	*l13I*	103	17	*l8I*	122	36
A2I	**20**	***l10I***	**24**	**4**	***l10I***	**24**	**4**
A3I	29	*l9I*	39	10	*l3S*	33	4
A1P	70	*l8P*	86	16	*l13I*	103	33
CIS	9	*l16S*	13	4	*l4S*	18	9
C2S	4	*l17S*	6	2	*l6I*	8	4
C3S	82	*l11S*	117	35	*l2S*	126	44
C4S	**130**	***l7S***	**260**	**130**	***l7S***	**260**	**130**
C1I	5	*l7I*	19	15	*l5S*	21	17
C2I	36	*l4I*	51	15	*l9P*	86	50
C1P	80	*l9P*	86	6	*l1I*	122	42
C2P	25	*l1P*	36	11	*l15I*	36	11
P1S	**396**	***l10S***	**495**	**99**	***l10S***	**495**	**99**
P2S	**159**	***l6S***	**176**	**17**	***l6S***	**176**	**17**
P3S	**17**	***l8S***	**86**	**69**	***l8S***	**86**	**69**
P1I	**151**	***l18I***	**173**	**23**	***l18I***	**173**	**23**
P2I	32	*l17I*	54	22	*l9I*	39	7
P3I	36	*l16I*	60	24	*l14I*	57	21
P4I	25	*l15I*	36	11	*l12I*	30	5
P1P	100	*l10P*	105	5	*l11I*	105	5
P	90	*l19I*	101	11	*l19S*	117	27
MS	26	*l13S*	63	37	*l8P*	86	60
MI	40	*l3I*	50	10	*l6P*	122	10
MP	3	*l5P*	3	0	*l7P*	7	4
S1S	30	*l14S*	30	0	*l1P*	36	6
S2S	126	*l2S*	126	0	*l4P*	159	33
S1I	30	*l12I*	30	0	*l4I*	51	21
S2I	75	*l2I*	75	0	*l10P*	105	30
S1P	6	*l7P*	7	1	*l11P*	16	10
S2P	5	*l2P*	16	11	*l3P*	6	1
S3P	5	*l3P*	6	1	*l5P*	5	0
				1309			**1382**

Thus, at the machine level of an injection department, we do not incur into MHC costs between machines, as it is normally considered in the FLP. Nevertheless, we have defined a base model for the machine layout problem (see chapter 5), that can be applied to other industrial sectors, or at companies with other production strategies. Therefore, in this model and at this level, for designing the *injection* departments layouts, we have only considered the *adjacency*, *unsuitability* and *reconfiguration* costs.

The optimal configuration, obtained with the MFLP model, proposes changing the location of several departments (Table 7.10) – almost all are productive departments (I1S, I2S, I1I, I2I, I3I, I1P, A1S, A1I, A3I and A1P).

In the next step, the layout of the machines is analyzed. For example, department I1S (Table 7.4) has 31 machines, currently positioned in location *l18S* of facility SP. If the suggested solution were adopted, these machines would be moved to location *l12S*, in the same facility. The main constraints of this location are its physical dimensions, with 35 positions (see Figure 7.12) and the fact that, at the company, the material handling system used inside the productive departments is the *train* (machines must therefore be positioned in rows, to facilitate the train movements).

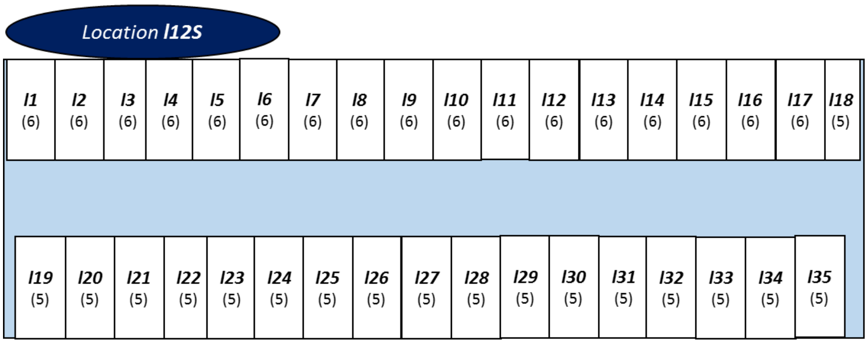

Figure 7. 12 – Positions inside location l12S, for the new configuration.

This new place distribution has the characteristics presented in Table 7.11. The distance between locations is shown in Table D.7.5, and the proximity values in Table D.7.6. Considering that machines of the same type should be close to each other, appropriate closeness values have been defined (Table D.7.7). With these data, we have run the *small changes model*, in CPLEX (the obtained layout is presented in Figure 7.13).

Table 7. 11 – Information about the existing positions inside location *l12S* of facility SP (optimal configuration).

Location	Area	Characteristics	
		pipes *(Chl_1)*	*cranes* *(Ch_2)*
l1	6	3	5
l2	6	3	5
l3	6	3	5
l4	6	3	5
l5	6	3	5
l6	6	3	5
l7	6	3	5
l8	6	3	5
l9	6	3	5
l10	6	3	5
l11	6	3	5
l12	6	3	5
l13	6	3	5
l14	6	3	5
l15	6	3	5
l16	6	3	5
l17	6	3	5
l18	5	3	5
l19	5	5	5
l20	5	5	5
l21	5	5	5
l22	5	5	5
l23	5	5	5
l24	5	5	5
l25	5	5	5
l26	5	5	5
l27	5	5	5
l28	5	5	5
l29	5	5	5
l30	5	5	5
l31	5	5	5
l32	5	5	5
l33	5	5	5
l34	5	5	5
l35	5	5	5

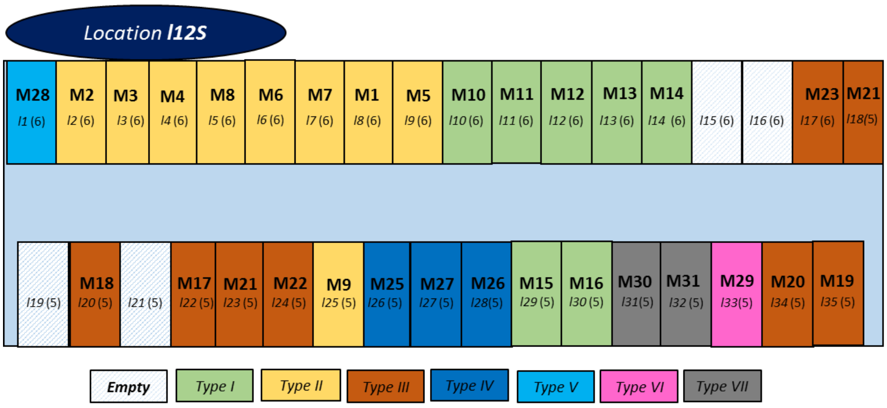

Figure 7. 13 – Machine positions of department I1S at location *l12S*.

This solution has an *adjacency* value of 2 130. In fact, most of the machines of the same type are together, taking into account their dimensions and the area constraints of the existing positions. Moreover, the solution has a total *unsuitability* value of 95.33, as a result of the machines suitability, in terms of the pipes used to receive the raw material and of the need of cranes to transport the molds (see Figure 7.14). All the machines need cranes, and as all positions have cranes, *unsuitability* is minimum ($Chl_2 = Chm_2 = 5$). In terms of pipes, with the exception of position *l19* from *l35*, it is necessary to implement them ($Chl_1 = 3$). In the solution, the machines that are supplied by pipes were located in the positions that already had them, and the others in the remaining positions (Figure 7.14). Since the whole area is larger than what is needed, 4 spaces are empty (*l15, l16, l19 and l21).*

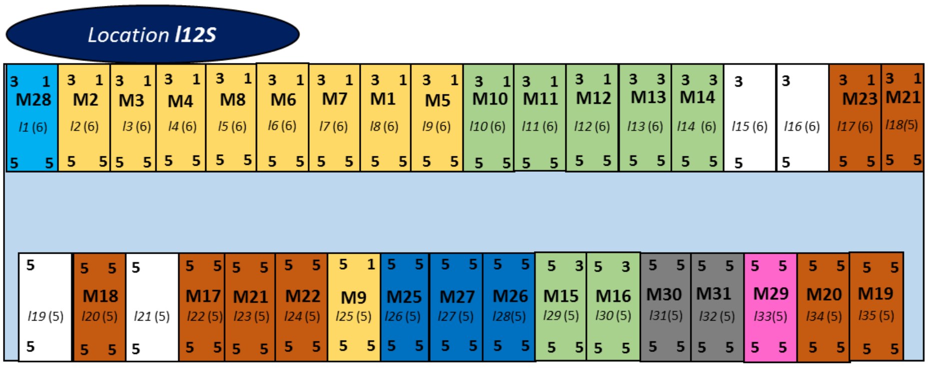

Figure 7. 14 – Unsuitability of department I1S machines, at location l12S.

Another example of a department that changes its location is department A3I. Its current location is *l9I*, at facility IN, and the model suggests to move it to location *l3S* in facility SP. Department A3I has 12 machines (with the characteristics described in Table 7.12) and produces 10 products, through 8 operations (as described in Table 7.13 and in Table 7.14.)

Table 7. 12 – Information about department A3I.

Machine	Area	Reconfiguration cost	*Operation cost*	*Capacity*	*Characteristics*	
					compressed air (Chm_1)	*cranes (Chm_2)*
M1	2	200	50	1100	5	1
M2	2	200	80	900	5	1
M3	2	200	80	1200	5	1
M4	2	200	50	1200	5	1
M5	4	200	100	1200	1	1
M6	4	200	80	1100	5	1
M7	4	200	80	900	5	1
M8	4	200	90	1200	5	1
M9	1	1000	30	900	5	1
M10	1	1000	30	1300	5	1
M11	1	1000	40	1400	5	1
M12	2	500	20	15000	1	1

Table 7. 13 – Demand of department A3I.

Products	Sequence	Operations							
		O1	O2	O3	O4	O5	O6	O7	O8
P1	O1, O2, O3	100	200	100	0	0	0	0	0
P2	O1, O3, O4	300	0	500	500	0	0	0	0
P3	O5, O6, O7	0	0	0	0	100	100	100	0
P4	O1, O2	800	700	0	0	0	0	0	0
P5	O8	0	0	0	0	0	0	0	1000
P6	O6, O8	0	0	0	0	0	600	0	600
P7	O6	0	0	0	0	0	900	0	0
P8	O8, O7	0	0	0	0	0	0	300	500
P9	O3, O5	0	0	400	0	400	0	0	0
P10	O4, O8	0	0	0	800	0	0	0	800

Table 7. 14 – Capability of machines of department A3I.

Products	Machines											
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
P1	O1	O1	-	O1	-	O2	-	O2	O3	-	O3	-
P2	O1	-	-	O1	-	O3	O3	-	-	O4	O4	-
P3	-	O7	-	-	O5, O7	-	O5, O6	-	O5	-	O6	-
P4	O1	O1	O2	O2	-	-	-	-	-	-	-	-
P5	-	-	-	-	O8	O8	-	-	-	-	-	-
P6	-	-	O6, O8	-	-	-	-	O6, O8	-	-	-	-
P7	-	-	-	-	-	-	O6	-	-	O6	-	-
P8	O7	-	-	-	-	-	-	O8	O7, O8	-	-	-
P9	-	-	-	O5	O3	-	O3	O5	-	O3	-	-
P10	-	O8	-	-	-	-	-	O8	-	O4	O4	-

Locations *l3S* has 14 positions (Figure 7.15 and Table 7.15), with the distances and proximity values between locations shown in Table 7.16 and in Table 7.17.

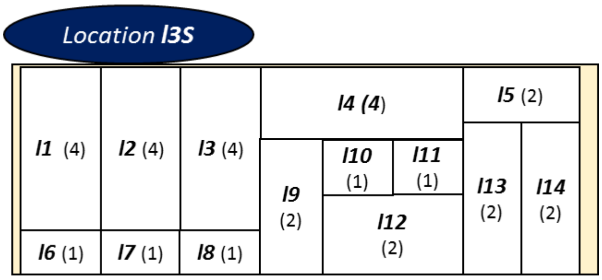

Figure 7. 15 – Positions of location *l3S*.

Table 7. 15 - Information about positions of location *l3S*.

Location	**Area**	**Characteristics**	
		compressed air **(*Chm_1*)**	***cranes*** **(*Chm_2*)**
l1	4	5	1
l2	4	5	1
l3	4	5	1
l4	4	5	1
l5	2	5	1
l6	1	5	1
l7	1	5	1
l8	1	5	1
l9	2	5	1
l10	1	5	1
l11	1	5	1
l12	2	5	1
l13	2	5	1
l14	2	5	1

Table 7. 16 - Distance between positions of location *l3S*.

Machines	***l1***	***l2***	***l3***	***l4***	***l5***	***l6***	***l7***	***l8***	***l9***	***l10***	***l11***	***l12***	***l13***	***l14***
l1	0	2	3	6	8	2	4	5	7	7	8	8	8	9
l2	2	0	2	5	6	3	2	3	4	3	4	5	6	6
l3	3	2	0	2	20	5	3	2	3	3	4	5	5	6
l4	6	5	2	0	3	6	5	3	4	1	1	2	2	3
l5	8	6	20	3	0	10	8	7	4	3	2	3	1	1
l6	2	3	5	6	10	0	2	3	5	6	7	8	9	10
l7	4	2	3	5	8	2	0	2	3	4	5	4	6	7
l8	5	3	2	3	7	3	2	0	2	4	5	3	6	7
l9	7	4	3	4	4	5	3	2	0	1	2	1	3	4
l10	7	3	3	1	3	6	4	4	1	0	1	1	2	3
l11	8	4	4	1	2	7	5	5	2	1	0	1	1	2
l12	8	5	5	2	3	8	4	3	1	1	1	0	2	3
l13	8	6	5	2	1	9	6	6	3	2	1	2	0	1
l14	9	6	6	3	1	10	7	7	4	3	2	3	1	0

Table 7. 17 - Proximity between positions inside location *l3S***.**

Machines	***l1***	***l2***	***l3***	***l4***	***l5***	***l6***	***l7***	***l8***	***l9***	***l10***	***l11***	***l12***	***l13***	***l14***
l1	0	2	3	6	8	2	4	5	7	7	8	8	8	9
l2	2	0	2	5	6	3	2	3	4	3	4	5	6	6
l3	3	2	0	2	20	5	3	2	3	3	4	5	5	6
l4	6	5	2	0	3	6	5	3	4	1	1	2	2	3
l5	8	6	20	3	0	10	8	7	4	3	2	3	1	1
l6	2	3	5	6	10	0	2	3	5	6	7	8	9	10
l7	4	2	3	5	8	2	0	2	3	4	5	4	6	7
l8	5	3	2	3	7	3	2	0	2	4	5	3	6	7
l9	7	4	3	4	4	5	3	2	0	1	2	1	3	4
l10	7	3	3	1	3	6	4	4	1	0	1	1	2	3
l11	8	4	4	1	2	7	5	5	2	1	0	1	1	2
l12	8	5	5	2	3	8	4	3	1	1	1	0	2	3
l13	8	6	5	2	1	9	6	6	3	2	1	2	0	1
l14	9	6	6	3	1	10	7	7	4	3	2	3	1	0

Running the *Small change model*, products are allocated to machines (phase 1 of the model) as shown in Table 7.18, with a total operation cost of 598 000. The machine allocation (phase 2 of the model) results in the flows between machines as presented in Figure 7.16.

Table 7. 18 - Product allocation for department A3I at location *l3S*.

Products	**Machines**											
	M1	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	**M11**	**M12**
P1	-	-	-	O1	-	-	-	O2	O3	-	-	-
P2	-	-	-	O1	-	-	O3	-	-	-	O4	-
P3	-	O7	-	-	-	-	-	-	O5	-	O6	-
P4	O1	-	-	O2	-	-	-	-	-	-	-	-
P5	-	-	-	-	-	O8	-	-	-	-	-	-
P6	-	-	O6,O8	-	-	-	-	-	-	-	-	-
P7	-	-	-	-	-	-	-	-	-	O6	-	-
P8	O7	-	-	-	-	-	-	O8	-	-	-	-
P9	-	-	-	-	-	-	-	O5	-	O3	-	-
P10	-	O8	-	-	-	-	-	-	-	-	O4	-

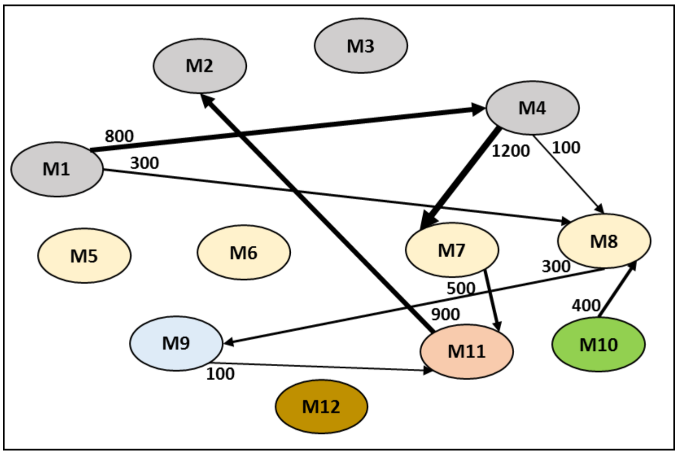

Figure 7. 16 – Flows between machines in department A3I, resulting from *small changes* model.

Given that machines that manufacture the same product should, as much as possible, be together, the resulting location of machines (Figure 7.17) has a total value of 570 for *adjacency*, and of 71 220 for the *MHC costs*.

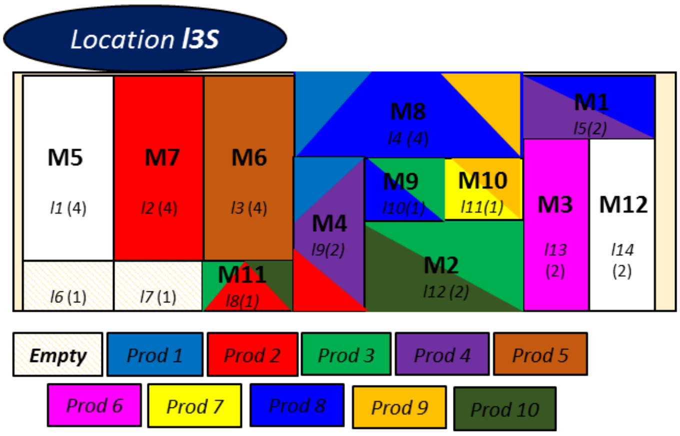

Figure 7. 17 – Allocation of machines in department A3I for location *I3S*, based on the *adjacency* of machines that manufacture the same product.

The model locates machines that manufacture the same product, close to each other, taking into account the dimension constraints. For example, machines M8, M9 and M1 (that make product 8) are put physically together. The *unsuitability* factor of this location is not critical, because all the positions have the same conditions in terms of *cranes accessibility* and *compressed air* – this means that all configurations have the same *unsuitability* value of 54.

Phase 6 – Layout evaluation:

The new solution has better values in all the objectives, in comparison with the current configuration (Table 7.19).

Table 7. 19 – Comparison of the current configuration with the optimal configuration.

Configuration	Total MHC	internal MHC	external MHC	Unsuitability	Adjacency
Current	6 451 500	1 571 500	4 880 000	192	635
Optimal MHC	1 949 000	1 389 000	560 000	185	785
Improvement	**4 502 500**	**182 500**	**4 320 00**	**7**	**150**

This configuration can lead to a decrease of the total MHC costs of 70% (4 502 500). This reduction is essentially due to the reduction of external flows, that are (in our case) the more expensive component. In the solution, there are only flows between facility IN and facility SP, that are the nearest facilities (Figure 7.18).

In terms of internal flows, there is an increase. However, since transport inside facilities is less expensive in terms of MHC costs, that increase in the flows does not have a great impact in the total costs.

The new configuration seems to be a better configuration, that uses all the resources in an optimal way. However, if we consider the investment required to change the current configuration, the quality of the decision is not so clear. As shown in Table 7.10, most of the departments must change their locations. Considering the *reconfiguration cost* (Table 7.2), adapting the facilities for the new configuration will cost 4 887 200. With the MHC costs (1 949 000) the total cost will be of 6 836 200. So, the decision maker must probably consider other (non-quantitative) aspects to make the right choice. Despite the total cost of the new configuration being larger than the current configuration, it is clearly that this new configuration is better in terms of operational efficiency.

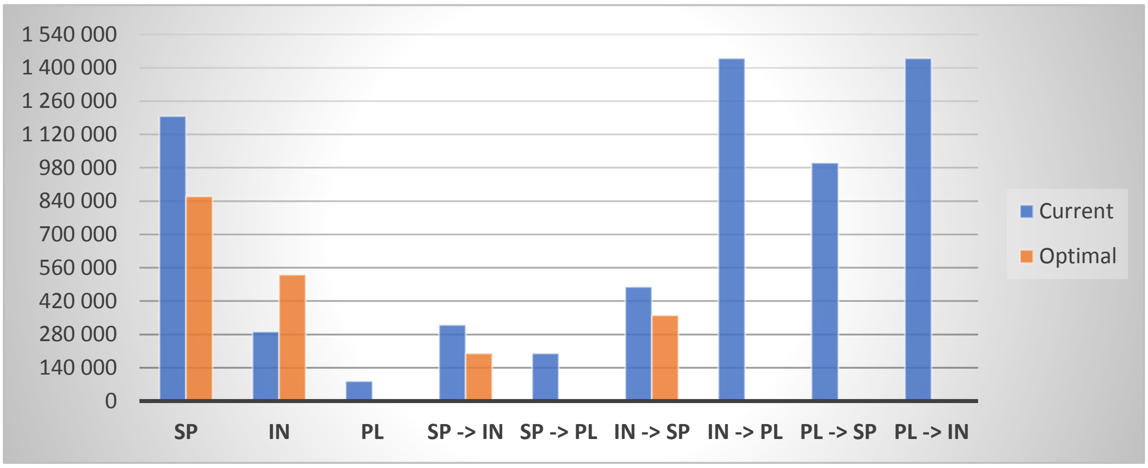

Figure 7. 18 – Material handling cost inside and between facilities, at the current and optimal configurations.

Frome Figure 7.19, we can verify that the flows inside facilities SP and IN increase, and that facility PL will not have flows. This is due to moving all the support departments to facility IN.

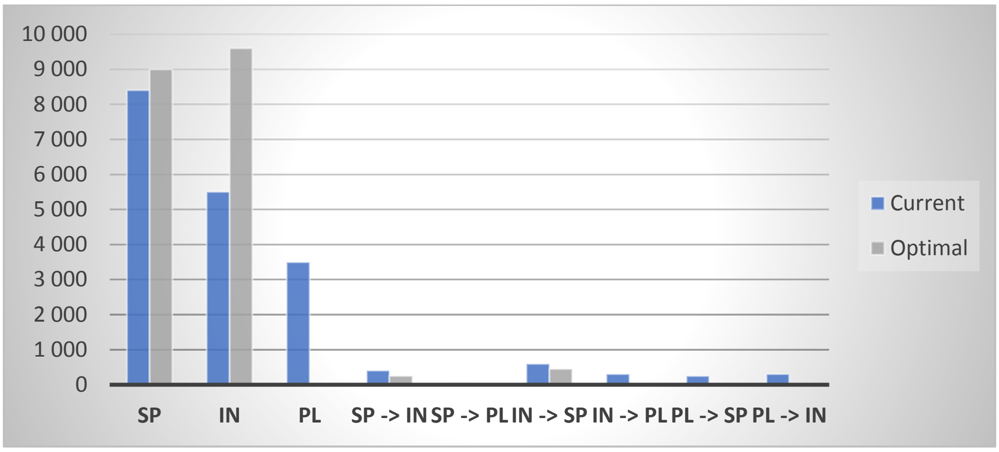

Figure 7. 19 – Flows inside and between facilities, in the current and optimal layout configurations.

If we analyse (Figure 7.20 and Figure 7.21), we can confirm that the total *distance travelled* in the new configuration decreases around 63% (from 4 053 to 1 495).

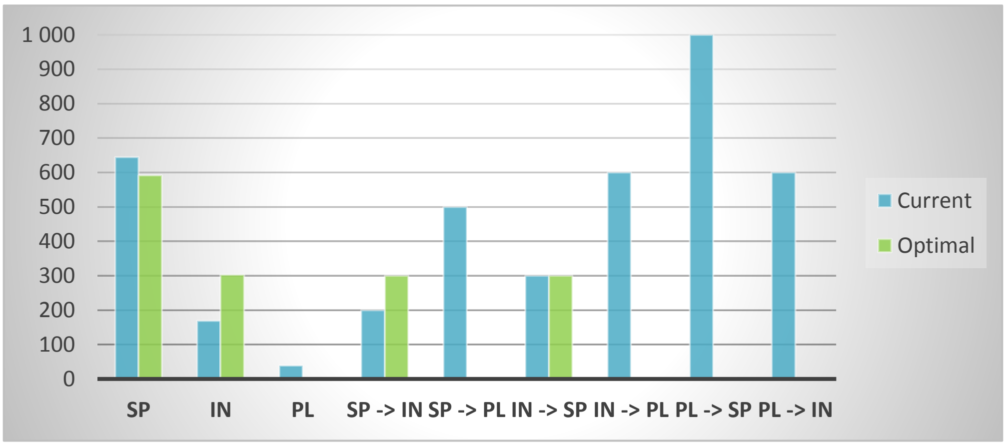

Figure 7. 20 – Distances traveled to collect and distribute the materials, inside and between facilities, at the current and in the optimal configurations.

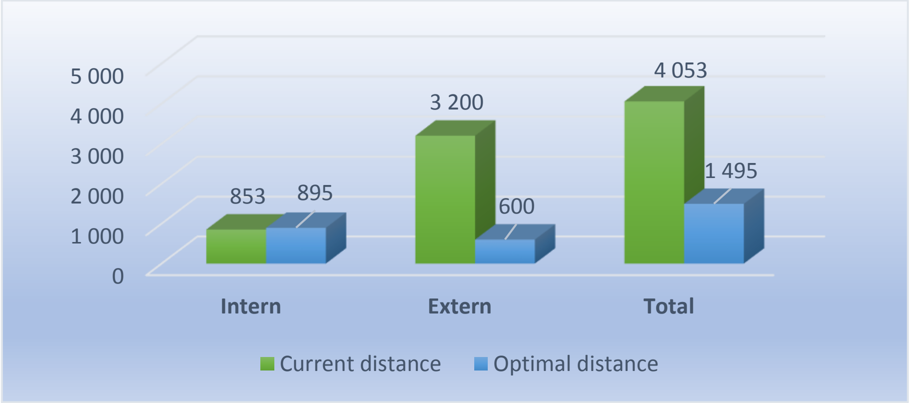

Figure 7. 21 – Total distance traveled inside and between facilities, at the current and optimal configurations.

In terms of *adjacency*, this new solution is also better, as it concentrates at the same facility more departments of the same type than the current configuration. For example, facility IN, in the new configuration, has 4 injection departments, 4 assembly departments, and 5 product warehouses.

The new configuration also allows a better use of the existing areas at each facility (Table 7.10). The current free area is 1 309, and the new configuration has a total free area of 1 382.

7.3 Centralize Product Warehouse

It became soon clear that one of the scenarios the company wanted to test was to centralize the various final product warehouses into a single facility warehouse. Based on this idea, there are several questions that need to be answered, such as:

- which facility will be transformed in a warehouse?
- where should the other departments be positioned?
- what will be the needed transport capacity between facilities?
- what will be the cost of this change?

Applying the proposed *Multi-Facility Layout Model*, we can find the answer for these questions or, at least, we can support the associated decision-making processes.

The current configuration combines at the same facility several types of departments (in general, all types of departments exist in each facility). Facility IN has 4 product warehouse departments, facility SP has 3, and facility PL only 1. Departments of the same type, existing in each facility, are located close to each other, to minimize flows (see Figure 7.5). By applying expression (5.11) and considering the *closeness* between the *product warehouses* (P1S, P2S, P3S, P1I, P2I, P3I, P4I and P1P) as “*absolutely necessary*” (with a rating of 5 – Table 4.2), and the *closeness* between the remaining departments as “*unimportant*” (with a rating of 1) we ran our model to consider the proposed scenario. The *proximity* values are shown in Table D.7.1, Table D.7.2, Table D.7.3 and Table D.7.4. The current configuration has a total adjacency value *(Adj)* of 1 270. To analyse this scenario, we have considered the demand for the next 2 periods as presented in Figure 7.22.

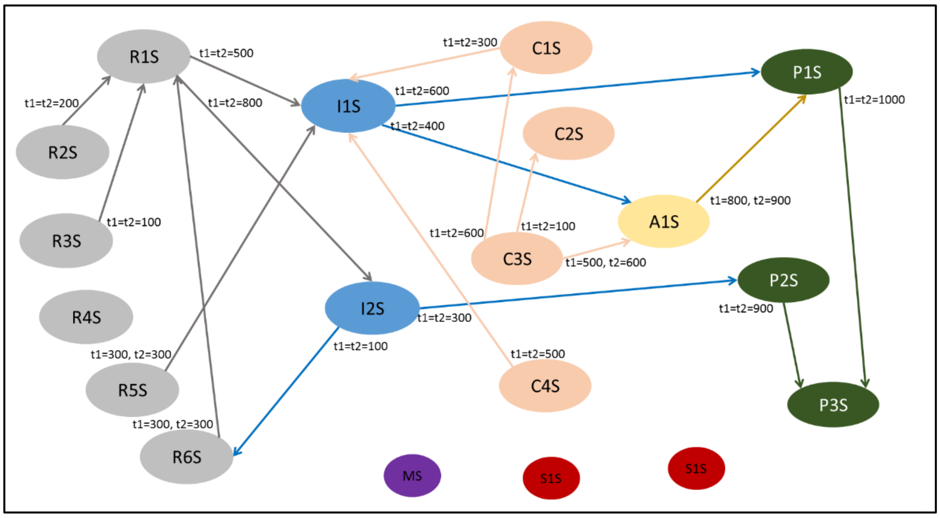

Figure 7. 22 – Demand for the next two periods.

Running the *large changes model*, considering all the objectives with the same weight, we got the configurations shown in Figure 7.23 and in Figure 7.24 (for each period).

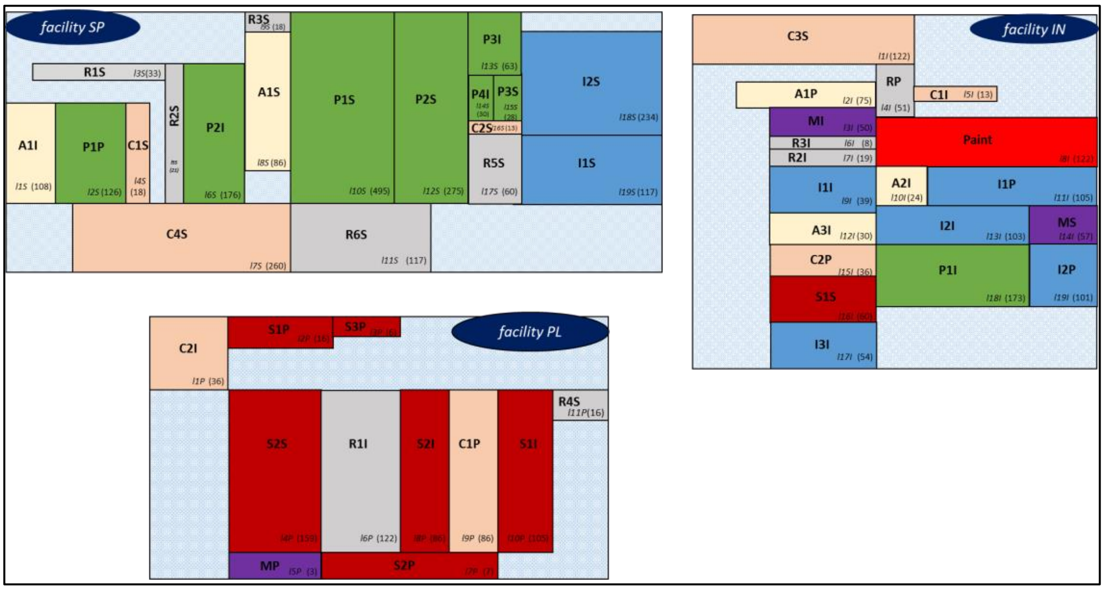

Figure 7. 23 – Facilities configuration, at period 1 (objectives with equal weight), centralizing product warehouses.

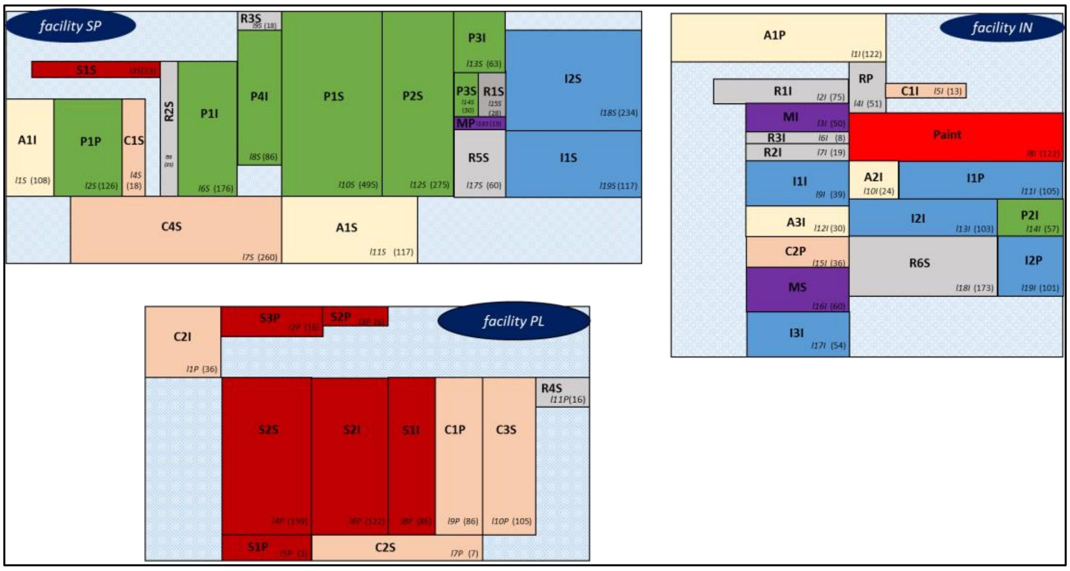

Figure 7. 24 – Facilities configuration, at period 2 (objectives with equal weight), centralizing product warehouses.

With this solution, facility SP will be the product warehouse of the company with 7 departments (P1S, P2S, P3S, P1I, P3I, P1P). The space not occupied by the warehouse can still be used by other departments. Facility IN has productive departments, and facility PL has the support departments. As, in fact, almost all the product warehouses are at the same facility, the *adjacency (Adj)* value (1 765) is a better value, when compared with the current configuration.

The solution involves a layout transformation, with the reconfiguration of 19 departments at period 2, and a reconfiguration cost (*RC)* of 95 100. These changes include product warehouse departments, two of them exchange their locations inside facility SP (P1I and P2I), and other two departments exchange their locations between facilities SP and IN (P3S and P4I).

The total *unsuitability (Uns)* is 369, a worst value in comparison with the value of the current solution (192) – Table 7.19.

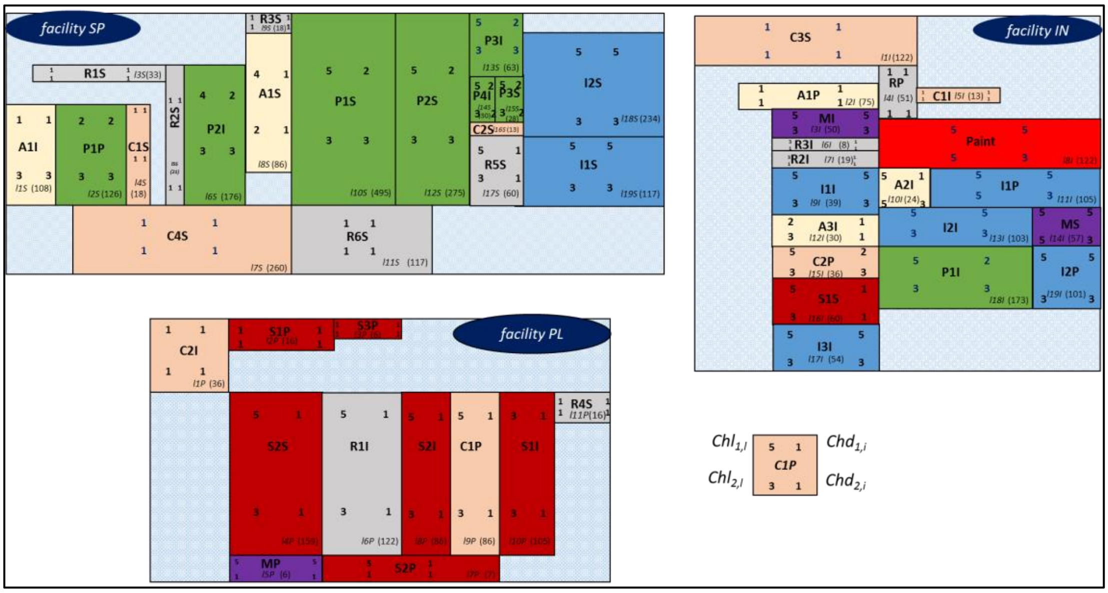

Figure 7. 25 – Unsuitability values of the configuration, at period 1 (objectives with equal weight), centralizing product warehouses.

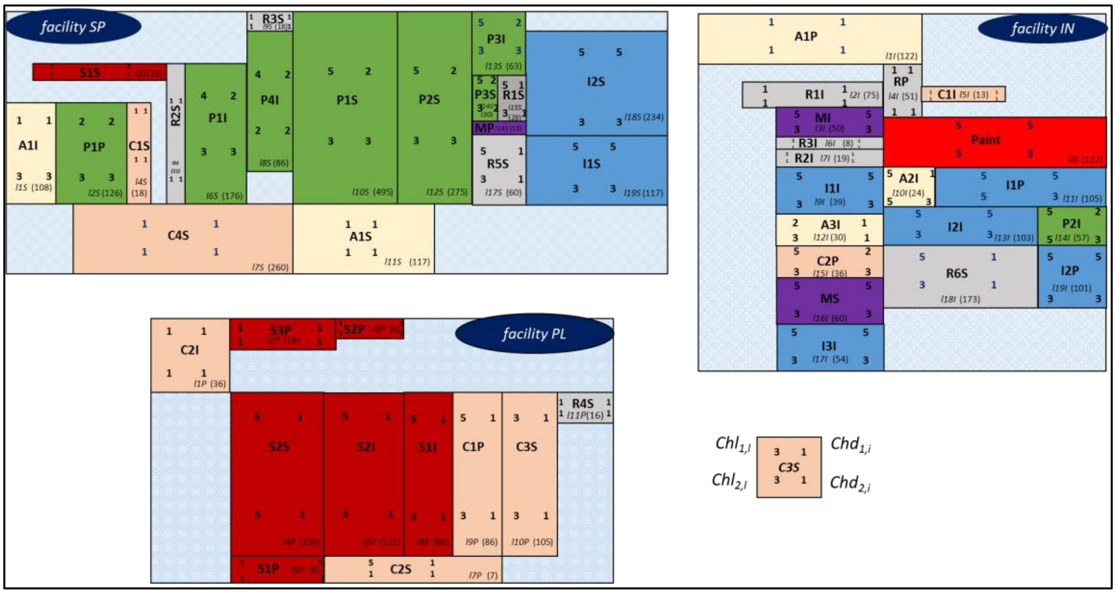

Figure 7. 26 - Unsuitability values of the configuration, at period 2 (objectives with equal weight), centralizing product warehouses.

The resulting configuration will have total internal MHC costs (*CtInt)* of 3 835 500), total external MHC costs (*CtExt)* of 15 161 600, with a total MHC *(Ct)* of 18 997 100 (see Figure 7.27).

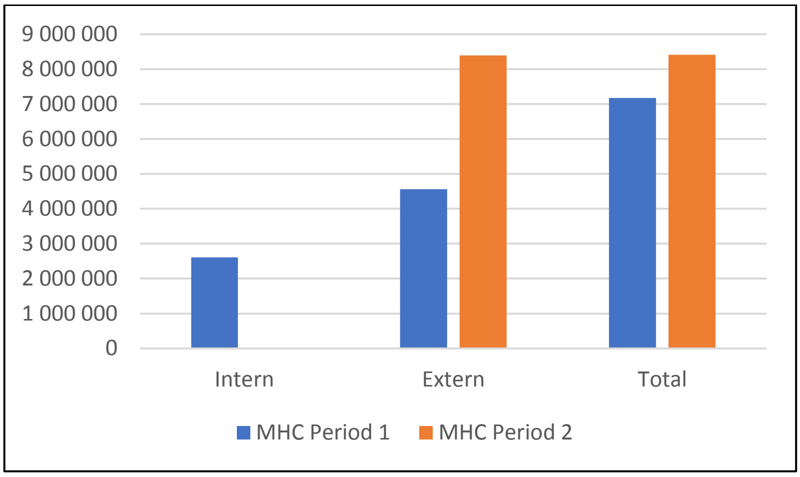

Figure 7. 27 – Comparing internal and external MHC costs.

With this configuration, the highest cost will be between facilities PL and SP, in period 2 (see Figure 7.28). Facility PL does not have inside flows and does not receive any flows from facility IN.

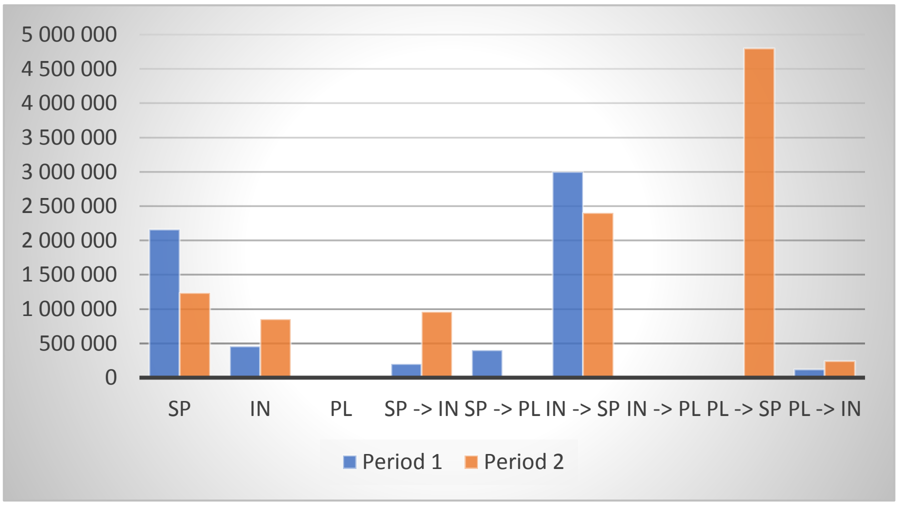

Figure 7. 28 – MHC costs inside and between facilities, in scenario I.

Figure 7.29 shows the distances travelled inside and between the facilities, for the found layout configuration.

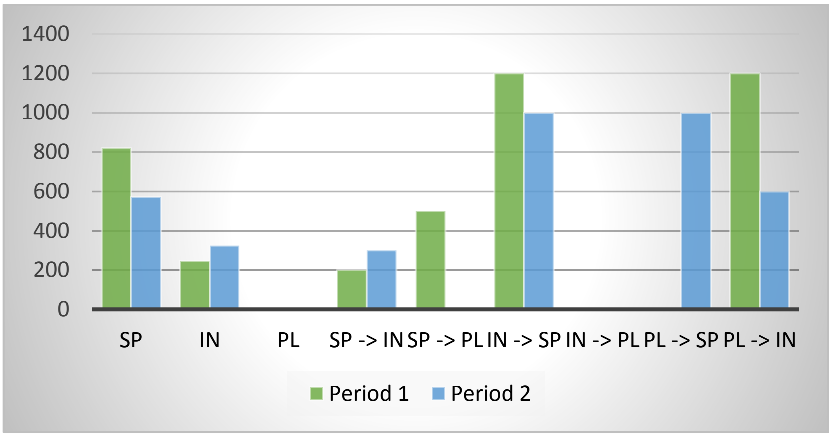

Figure 7. 29 – Distances travelled inside and between facilities, in scenario I.

This analysis will now help us in answering the questions posed above.

Which facility will be transformed in a warehouse?

Facility SP will concentrate almost all product warehouses (but in period 1, P1I is in facility IN, and in the next period, it changes with department P2I). The choice of this facility may be due to its size and because it is one of the two closest facilities. After the concentration of the product warehouses (Figure 7.25 and 7.26), facility SP has some space available. In this sense, this solution might allow locating other departments in this available area.

Where should the other departments be positioned?

Assembly departments A1S and A1I were located in facility SP, and the remaining assembly departments in facility IN. *Components warehouses* were located in the 3 facilities. *Injection* departments were concentrated in facility IN, with the exceptions of I1S and I2S, located in facility SP. Maintenance departments were mainly located in facility IN. *Painting* departments, in facility IN. *Raw material warehouses* were concentrated in facility SP (R1S, R2S, R3S, R5S and R6S), with the exceptions of RP, R2I and R3I, in facility IN, and R1I and R4S in facility PL. In period t2, R6S moved from facility SP to facility IN, and R1I moved from facility PL to facility IN. *Support* departments are mainly concentrated in facility PL.

What will be the needed transport capacity between facilities?

This configuration needs a total transport capacity, between facilities, of 4 300 (23% of the total demand) in period 1, and 5 750 (26% of the total demand) in period 2 (see Table 7.20). This 3% increase is relatively small, when compared to the 17% increase in demand.

Table 7. 20 – Flows inside and between facilities, centralizing product warehouses.

Flows	Internal	External	Total
Period 1	14 350	4 300	**18 650**
Period 2	**16 800**	**5 750**	**22 550**

What will be the cost of this change?

This solution has a reconfiguration cost *(RC)* of 95 100. However, this cost only considers changing departments from locations in period t1, to locations of period t2. In practice, to implement this optimal solution, it will be needed to transform the facilities from the current configurations, with a cost of 4 934 700 (see Table 7.22).

With these analyses, the decision-maker will have a better idea of the changes needed and their costs, when implementing this scenario (see Table 7.21).

Table 7. 21 – Comparing the current configuration with the new configuration, centralizing product warehouses (equal objectives).

Configuration	Total cost	Total MHC	internal MHC	external MHC	Unsuitability	Adjacency
Current	22 514 850	22 514 850	2 850 850	19 664 000	384	1270
New MHC	19 092 200	18 997 100	3 835 500	15 161 600	369	1765
Improvement	**3 422 650**	**3 517 750**	**-984 650**	**4 502 400**	**-15**	**495**
	15,2%	**15,6%**	**-34,5%**	**22,9%**	**-3,9%**	**39%**

As referred, the new configuration puts almost all product warehouse departments at facility SP, this leading to a better *adjacency* value, with an increase of 39%. The *unsuitability* of this configuration decreases slightly (3,9%). The new configuration will decrease the total costs in around 15%, by increasing the flows inside facilities SP and IN (see Figure 7.30).

Table 7. 22 – Changing costs from the current to the optimal configuration (centralizing product warehouses).

Department	Reconfiguration costs	Current location	New location	Total changing costs
R1S	5 000	*l15S*	*l3S*	5 000
R2S	500	*l3S*	*l5S*	500
R3S	500	*l5S*	*l9S*	500
R4S	500	*l4S*	*l11P*	500
R5S	50 000	*l9S*	*l17S*	50 000
R6S	1 000	*l1S*	*l11S*	1 000
R1I	1 000	*l1I*	*l6P*	1 000
R2I	50 000	*l5I*	*l7I*	50 000
R3I	**500**	***l6I***	***l6I***	**0**
RP	1 000	*l11P*	*l4I*	1 000
I1S	826 500	*l18S*	*l19S*	826 500
I2S	861 000	*l12S*	*l18S*	861 000
I1I	150 000	*l14I*	*l9I*	150 000
I2I	331 500	*l11I*	*l13I*	331 500
I3I	361 000	*l8I*	*l17I*	361 000
I1P	723 500	*l4P*	*l11I*	723 500
I2P	550 000	*l6P*	*l19I*	550 000
AIS	28 000	*l19S*	*l8S*	28 000
A1I	125 000	*l13I*	*l1S*	125 000
A2I	**5 000**	***l10I***	***l10I***	**0**
A3I	5 100	*l9I*	*l12I*	5 100
A1P	36 100	*l8P*	*l2I*	36 100
CIS	500	*l16S*	*l4S*	500
C2S	500	*l17S*	*l16S*	500
C3S	1 000	*l11S*	*l1I*	1 000
C4S	**5 000**	***l7S***	***l7S***	**0**
C1I	500	*l7I*	*l5I*	500
C2I	500	*l4I*	*l1P*	500
C1P	**5 000**	***l9P***	***l9P***	**0**
C2P	1 000	*l1P*	*l15I*	1 000
P1S	**10 000**	***l10S***	***l10S***	**0**
P2S	5 000	*l6S*	*l12S*	5 000
P3S	1 000	*l8S*	*l15S*	1 000
P1I	**10 000**	***l18I***	***l18I***	**0**
P2I	2 000	*l17I*	*l6S*	2 000
P3I	2 000	*l16I*	*l13S*	2 000
P4I	500	*l15I*	*l14S*	500
P1P	5 000	*l10P*	*l2S*	5 000
P	800 000	*l19I*	*l8I*	800 000
MS	2 000	*l13S*	*l14I*	2 000
MI	**2 000**	***l3I***	***l3I***	**0**
MP	1 000	*l5P*	*l5P*	0
S1S	1 000	*l14S*	*l16I*	1 000
S2S	1 000	*l2S*	*l4P*	1 000
S1I	1 000	*l12I*	*l10P*	1 000
S2I	1 000	*l2I*	*l9P*	1 000
S1P	1 000	*l7P*	*l2P*	1 000
S2P	1 000	*l2P*	*l7P*	1 000
S3P	**1 000**	***l3P***	***l3P***	**0**
				4 934 700

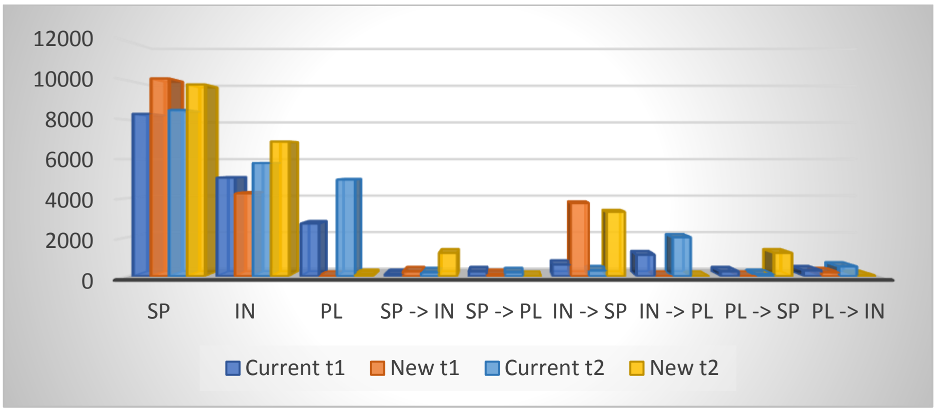

Figure 7. 30 – Flows distribution with current and new configurations, centralizing product warehouses.

Allocating almost all the support departments at facility PL, will allow a reduction of flows and distance travelled, inside the facility and with the others, once this is the facility further away of the group (see Figure 7.31).

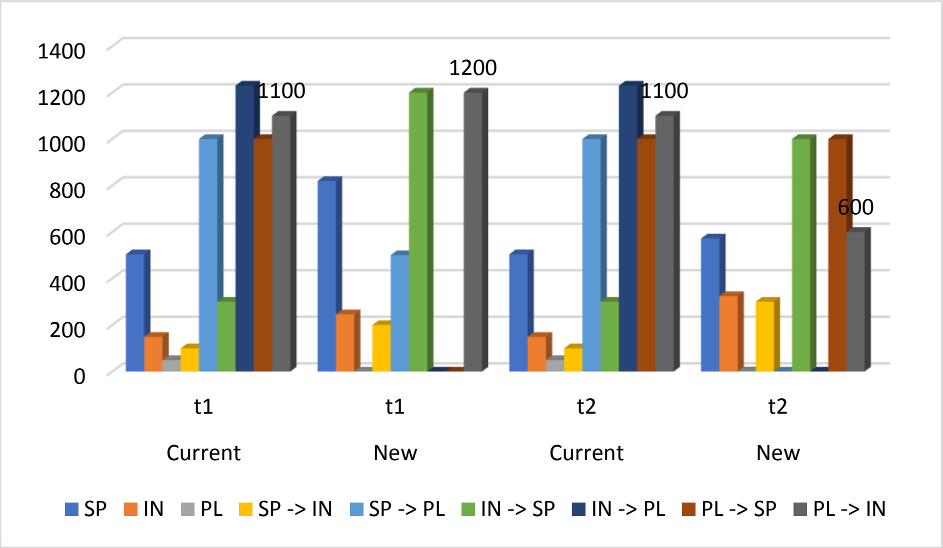

Figure 7. 31 – Distance traveled at each period (current configuration), centralizing product warehouses.

Naturally, the highest gain of costs will be with the external MHC costs (Figure 7.32), but if we go deeper in this analysis, and look with more detail for the MHC costs of each facility (Figure 7.33) we can observe that the flows between facilities IN and PL are those facilities with more significant reduction.

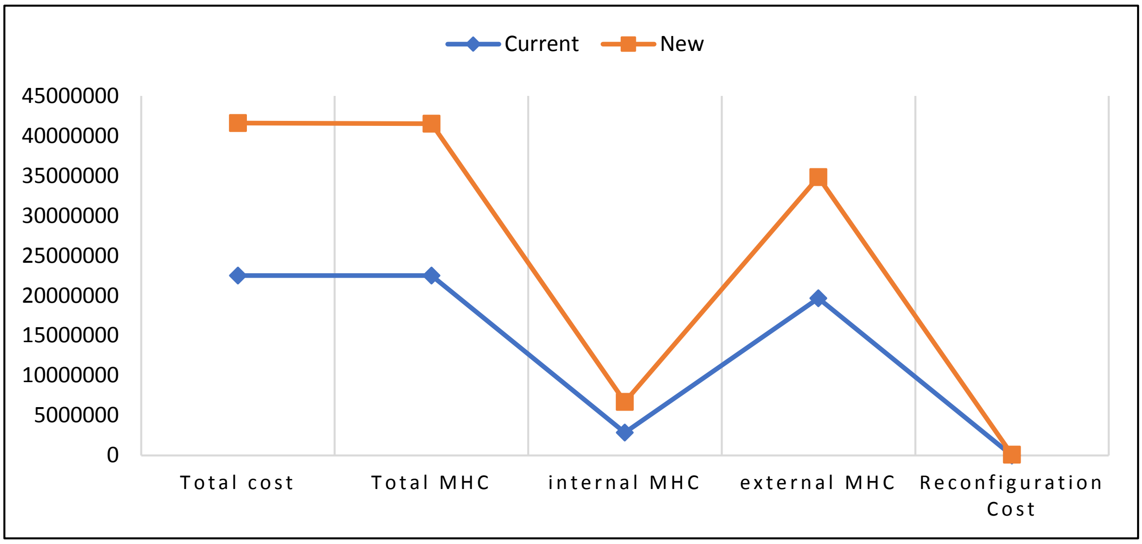

Figure 7. 32 – Costs of current and new configuration, centralizing product warehouses.

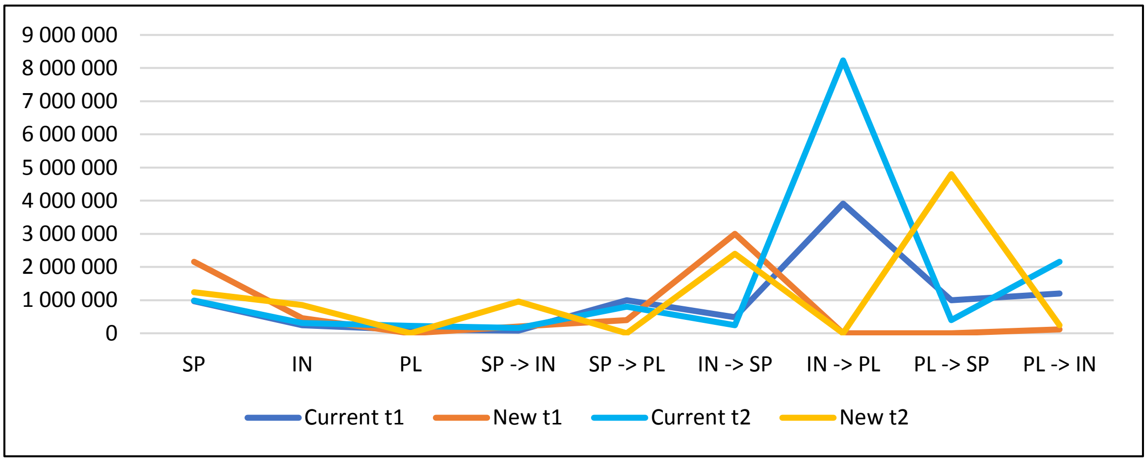

Figure 7. 33 – MHC of facilities, at each period, on current configuration (centralizing product warehouses).

Clearly, the optimal solution found by our model presents better indicators for almost all objectives, when compared with the current solution. Again, if the decision maker intends to go deeper on the analyse of this scenario it can be extended at the machine level, with the analyse of *small changes* inside each department. Obviously, other scenarios can be analysed in a similar way.

7.4 Introducing a new *project*

In the automotive industry, the process of designing new components of a car (a "*project*") is a collaborative process, involving the suppliers (such as SIMOLDES) and the OEM. As previously explained (section 3.3), new projects mean a negotiation process and a decision about which facility will supply the products, through the whole *project* lifetime. It is therefore important for a company such as SIMOLDES to have a tool to analyze the impacts of allocating a *project* to a specific facility.

For that purpose, we have extended the MFL basic model (as proposed in chapter 5) – instead of using the total flows that occur between departments in each period, we consider the detailed flows for each project. We further detail parameters q_{ijt} for each *project* (q_{hijt}), as a way to define the quantity of flow of *projec*t *h*, to move between department *i* and *j*, in each period *t*. We also consider a new parameter (C_{hift}) that will represent a "penalty" if the project is not produced at the facility that is agreed with the customer (the OEM).

Indices	
H	number of projects
Parameters	
q_{hijt}	flow (product quantity) of *projec*t *h* to move between department *i* and *j*, in period *t*
$CtInt_h$	total material handling cost of *project h*, inside facilities
$CtExt_h$	total material handling cost of *project h*, between facilities
C_{hift}	cost penalization for supply *project h* from department *i*, positioned at location *l* of facility *f*, in period *t*

To detail the *internal* and *external* MHC costs for each *project*, equations (5.1.1) and (5.1.2) are replaced by equations (7.1), (7.1.1), (7.2) and (7.2.1).

$$CtInt_t = \sum_{h=1}^{H} CtInt_h \tag{7.1}$$

$$CtInt_h = \sum_{t=1}^{T} \sum_{f=1,(f1=f2)}^{F} \sum_{l,k=1}^{L} \sum_{i,j=1}^{I} \left[q_{hijt}\, r_{(f1,l),(f2,k)}\, ctInt_t\, x_{i(f1,l)t}\, x_{j(f2,k)t}\;\; C_{hift} \right] \tag{7.1.1}$$

$$CtExt_t = \sum_{h=1}^{H} CtExt_h \tag{7.2}$$

$$CtExt_h = \sum_{t=1}^{T} \sum_{f=1,(f1 \neq f2)}^{F} \sum_{l,k=1}^{L} \sum_{i,j=1}^{I} \left[q_{ijt} \, r_{(f1,l),(f2,k)} \, ctInt_t \, x_{i(f1,l)t} \, x_{j(f2,k)t} \, C_{hift} \right]$$
(7.2.1)

To illustrate the application of this extension of the MFL model, we have designed the following example (as published in Azevedo et al. (2016)). There are three facilities (*f1, f2, f3*), with, in total, 13 locations to position the departments (Figure 7.34). The distance between *f1* and *f2* is 30 (units of distance), as well as between *f2* and *f3*; the distance between *f1* and *f3* is 50.

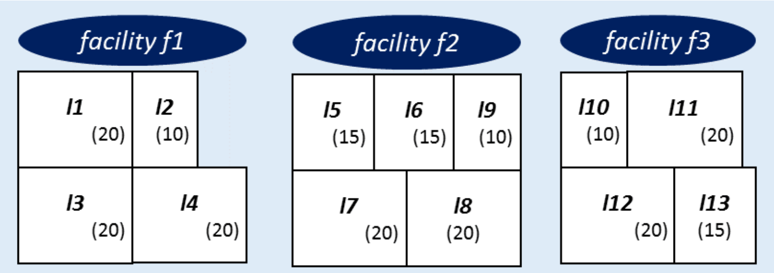

Figure 7. 34 – Available area in the facilities (e.g. location l1 has an area of 20 units).

For executing the movements between departments, we consider a distribution (transport) system based on the following assumptions: *internal transport costs* are constant along time and do not depend on the distances (5 cost units / unit of flow); *external transport costs* vary with time (t1=20, t2=22, t3=25). The capacity of transport between facilities also varies (t1=800, t2=1000 and t3=800).

There are 5 different types of departments: raw material warehousing; injection; assembly; painting; and product warehousing (Table 7.23). Due to the specific characteristics and organization of the production, the areas assigned to each department can change along time. We also consider that there are some advantages in having departments of the same type (e.g. injection – A, B, C) together in the same facility (*closeness* level equal to 5).

Table 7. 23 - Departments in the case study.

Departments		Raw material warehouse			Injection			Assembly			Painting	Product warehouse		
		A	B	C	D	E	F	G	H	I	J	K	L	M
re-layout cost		5000			20 000			10 000			80 000	5000		
active departments	t1	0	1	1	0	1	1	0	1	1	1	0	1	1
	t2	1	1	1	1	1	1	1	1	1	1	1	1	1
	t3	1	1	1	1	1	1	1	1	1	1	1	1	1
area	t1	0	10	20	0	20	20	0	15	10	20	0	15	15
	t2	10	20	20	15	20	20	10	15	10	20	15	15	15
	t3	10	20	15	15	20	15	5	15	5	20	15	15	15

We consider there are 4 *projects*, in different life cycle phases: *projects 1* and *2* have a continuous production, along the planning horizon; *project 3* finishes in period *t2*; and *project 4* starts in period *t2* (Table 7.24).

Table 7. 24 – Project flows in each period.

Periods			Project	Flows between departments			
t1	t2	t3					
✓	✓	✓	P1	C -> F (500)	F -> J (350)	J -> H (200)	H -> M (200)
✓	✓	✓	P2	B -> E (100)	E -> J (150)	J -> H (150)	H -> L (50)
✓	✓		P3	C -> F (100)	F -> I (100)	I -> M (50)	
	✓	✓	P4	A -> D (50)	D -> G (150)	G -> K (100)	

Concerning the relative importance of the different objectives, we have considered the following weights: 35% for MHC; 35% for reconfiguration costs; and 30% for adjacency.

7.4.1 No customer constraints

We have considered the case when the OEM (the customer) is not concerned in which facility is the *project* produced, and have run the extended MFL model, without penalties. The resulting configuration is shown in Figure 7.35. The solution found is the same for the three periods. In this solution, the departments of the same type are put together in the same facility – departments A, B and C; or L, K and M.

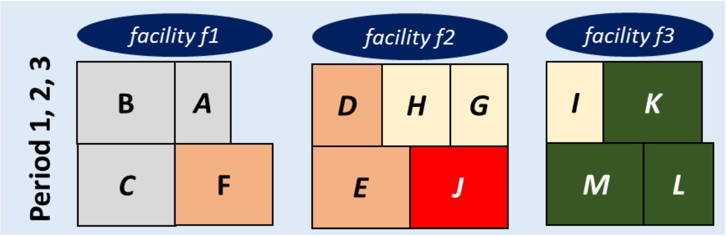

Figure 7. 35 – Configuration of facilities without customer constraints.

Table 7.25 shows how the flows of each project are distributed by facilities. There are projects involving all facilities (as *project 1*) but for example, *project P3* only goes through facilities *f1* and *f3*. *Project P4* is the most expensive in terms of internal and external MHC costs, despite being the project with smaller flows.

Table 7. 25 – Results of *large change model* extension (without customer constraints).

Project	**Network structure**	**Flows inside facilities**			**Flows between facilities**					**MHC costs**		
		f1	***f2***	***f3***	***f1-f2***	***f1-f3***	***f2-f1***	***f2-f3***	***f3-f2***	**internal**	**external**	**total**
P1	***f1,f2f3***									**3 000**	**223 250**	**226 250**
t1	*f1,f2,f3*	500	200		350			200				
t2	*f1,f2,f3*	500	200		350			200				
t3	*f1,f2,f3*	500	200		350			200				
P2	***f1,f2,f3***									**1 500**	**218 400**	**219 900**
t1	*f1,f2,f3*		300		100			50				
t2	*f1,f2,f3*		300		100			50				
t3	*f3,f2,f3*		300		100			50				
P3	***f1,f3***									**4 500**	**335 000**	**339 500**
t1	*f1,f3*	100		50		100						
t2	*f1,f3*	100		50		100						
P4	***f1,f2,f3***									**10 500**	**1 192 600**	**1 203 100**
t2	*f1,f2,f3*		150		50			100				
t3	*f1,f2,f3*		150		50			100				
		1700	**1800**	**100**	**1450**	**200**	**0**	**950**	**0**	**19 500**	**1 192 600**	**1 988 750**
Re-layout costs		**0**				**Adjacency**	**1380**					

To compare here the operation of facilities can be an interesting analysis. For example, Figure 7.36 shows the flows inside each facility and between facilities, in each period. We can observe that facilities *f1* and *f2* are the more “intensive” in terms of flows, because they have the productive departments. Facility *f3* has the warehouse departments, and therefore it has few movements with other departments. Normally, these warehouses are the last departments where products pass, before being shipped to the customers. So there are no flows between facility *f3* and the other facilities.

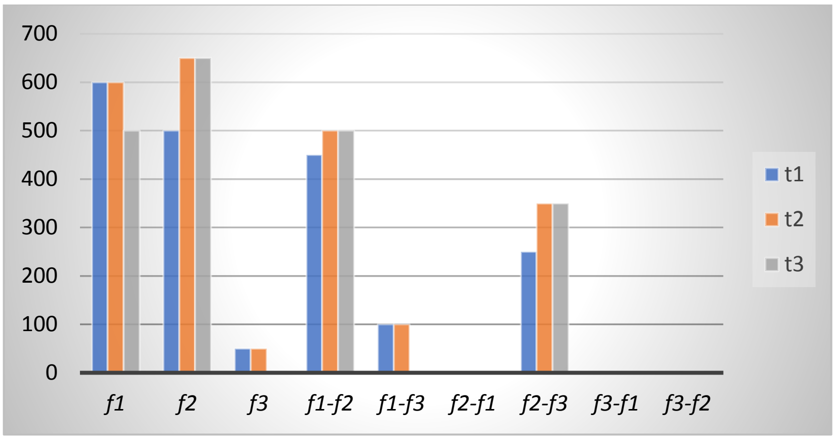

Figure 7. 36 – Flows inside and between facilities, for the configuration without customer constraints.

With this configuration, the internal flows are larger than the external flows (see Figure 7.37). We can also see that the transport capacity at each period is never exceed. In *period t1*, all the transport capacity is used, then it is increased to 1 000 and kept at this value in *period t3*.

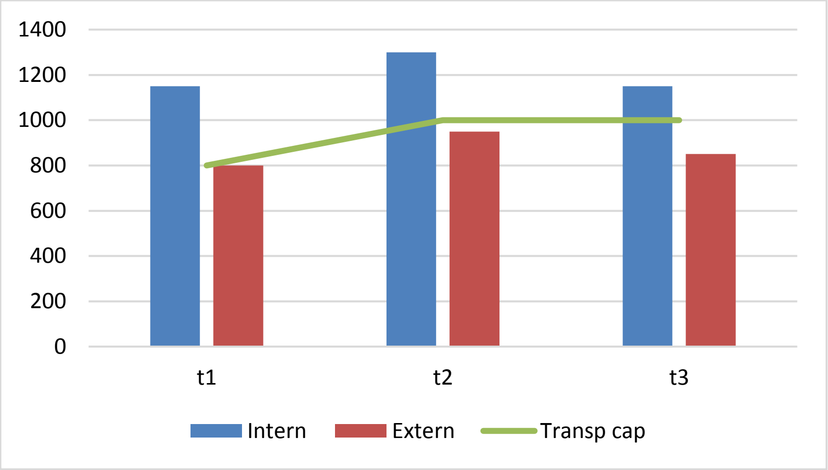

Figure 7. 37 – Internal and external flows in each period, for the configuration without customer constraints.

7.4.2 With customer constraints

Once has been agreed with the customer which facility will produce the project, all orders of this *project* must be sent to the customer from that facility, throughout the entire life of the *project*. Since normally the duration of a *project* is quite long (Figure 3. 9), whenever a new *project* is started, it may be interesting to transfer the production of older *projects* to other facilities of the group. This decision may lead to significant changes in operations and costs, possibly implying more costs, (at least with the transport from the facility that makes the product to the facility that ships it to the customer). This may require: anticipating the production, to cover the traveling time between facilities; having more storage space at both facilities; needing to increase transport capacity; repeating movements, tasks or the use of resources.

Therefore, this kind of situation can be considered in the model by the use of a penalization parameter (C_{hift}). To illustrate this case, we consider, in our example, that the customer of *project P3* requires products must always come from facility *f2*. Once products of *project P3* are shipped from warehouse M (Table 7.24), during its lifetime (*t1* and *t2*), M must be positioned in any place of facility *f2*, otherwise the MHC costs of this *project* will increase 10 times. Then in period *t3*, it is indifferent what facility it will located.

The configuration found by CPLEX is shown in Figure 7.38. This solution is the same for the three periods (department M is located in facility *f2*). It combines, in facility *f1*, all the raw material warehouses (A, B and C), and two of the product warehouses (L and K) are located in facility *f3*. The injection departments are distributed along the three facilities.

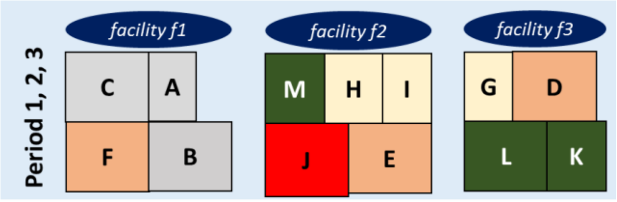

Figure 7. 38 – Configuration with customer constraints.

This configuration has a total *adjacency* value of 1 080, and total MHC costs of 1 369 100 (Table 7.26).

Table 7. 26 – Results for *large changes* model extension (with customer constraints).

Project	**Network structure**	**Flows inside facilities**			**Flows between facilities**					**MHC costs**		
		f1	***f2***	***f3***	***f1-f2***	***f1-f3***	***f2-f1***	***f2-f3***	***f3-f2***	**internal**	**external**	**total**
P1	***f1,f2***									**3 500**	**122 200**	**125 700**
t1	*f1,f2*	500	400		350							
t2	*f1,f2*	500	400		350							
t3	*f1,f2*	500	400		350							
P2	***f1,f2,f3***									**2 000**	**142 800**	**144 800**
t1	*f1,f2,f3*		300		100			50				
t2	*f1,f2,f3*		300		100			50				
t3	*f3,f2,f3*		300		100			50				
P3	***f1,f2***									**6 750**	**324 950**	**331 700**
t1	*f1,f2*	100		50	100							
t2	*f1,f2*	100		50	100							
P4	***f1,f3***									**16 500**	**750 400**	**766 900**
t2	*f1,f3*			250		50						
t3	*f1,f3*			250		50						
		1700	**2100**	**600**	**1550**	**100**	**0**	**150**	**0**	**28 750**	**1 340 350**	**1 369 100**
Re-layout costs		**0**				**Adjacency**	**1080**					

As Figure 7.39 and Figure 7.40 show, the major flows are, naturally, inside facilities. Facility *f2* is the more intensive in terms of flows, in all the three periods. In contrast, facility *f3* is the one with smaller flows, inside and between other facilities, due to the fact that it concentrates most of all the "final" departments, the product warehouses (L and K).

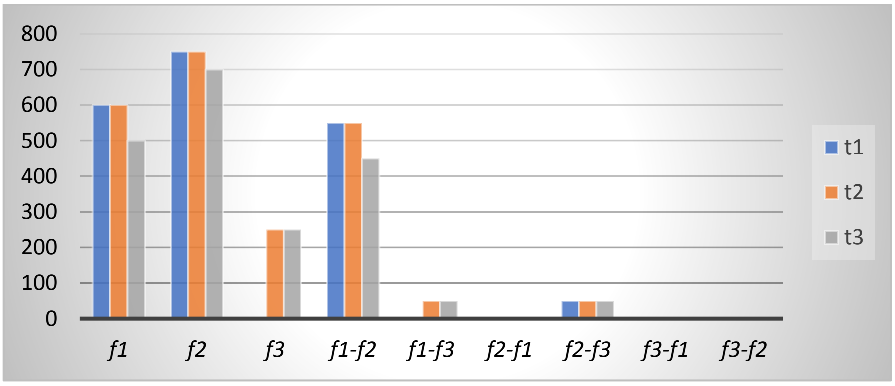

Figure 7. 39 – Flows inside and between facilities, considering customer constraints.

The more intensive external flows, are from facility *f1* to facility *f2*. As the layout of facilities is the same for the three periods, the flows at each period are similar in each facility and between facilities.

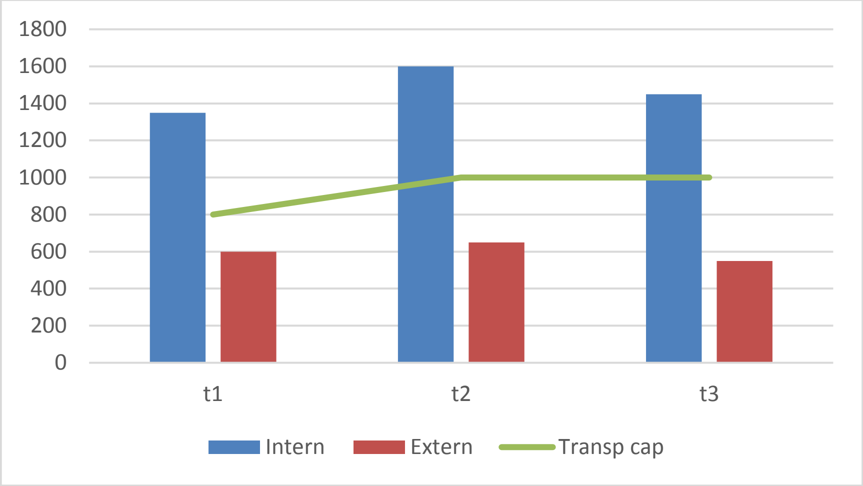

Figure 7. 40 - Internal and external flows in each period, with customer constraints.

The transport capacity between facilities (800 in period t1, and 1 000 in periods t2 and t3), is more than enough (see Figure 7.40), with a considerable remaining capacity, especially in period t3 (with 550 external flows value).

If we compare this configuration with the previous one (no customer constraints), apparently, the results are better than expected, in terms of costs (Table 7.27), but worse in terms of the other objectives. Without customer constraints, in the example we have a better *adjacency* value (1 380), with more departments of the same type at the same facility (e.g. raw material warehouses (A, B, C) at *f1;* product warehouses (L, K, M) at *f3*; injection (E, D) in f2; and assembly (H,G) in f2).

Table 7. 27 – Comparing solutions with and without customer constraints.

	Without customer constraints	**With customer constraints**
MHC	1 988 750	1 369 100
Adjacency	1380	1080
Raw material warehouse	(A, B, C) at f1	(A, B, C) at f1
Injection	(E, D) at f2	one at each facility
Assembly	(H, G) at f2	(H, I) at f2
Product warehouse	(L, K, M) at f3	(L, K) at f3

Nevertheless, when we consider MHC costs, we are only taking into account the costs related with *handling*, and somehow they may not contain all relevant real costs, such as, for example, the benefit of having departments of the same type together, allowing the use of the same resources.

With this example it is clear the importance of the proposed extension to the MFLP.

7.5 Changing the structure of the network

To face market changes, companies may have to modify their facilities in terms of size, by adding or closing departments, or in the case of a corporate group, even to add or close facilities. To enable this type of analysis, the MFLP basic model can be complemented with the following parameters and equations.

New parameters	
$lact_{lt}$	1, if position *l* is active in period *t*; 0 otherwise
$dact_{it}$	1, if department *i* is active in period *t*; 0 otherwise

The MHC expression (5.1.1) will be replaced by expression 7.3.1, and expression (5.1.2) by expression (7.3.2).

$$CtInt_t = \sum_{t=1}^{T} \sum_{f=1,(f1=f2)}^{F} \sum_{l,k=1}^{L} \sum_{i,j=1}^{I} \left[q_{ijt}\, r_{(f1,l),(f2,k)}\, ctInt_t\, x_{i(f1,l)t}\, x_{j(f2,k)t}\, lact_{lt}\;\; dact_{it} \right] \tag{7.3.1}$$

$$CtExt_t = \sum_{t=1}^{T} \sum_{f=1,(f1\neq f2)}^{F} \sum_{l,k=1}^{L} \sum_{i,j=1}^{I} \left[q_{ijt}\, r_{(f1,l),(f2,k)}\, ctInt_t\, x_{i(f1,l)t}\, x_{j(f2,k)t}\;\; lact_{lt}\;\; dact_{it} \right] \tag{7.3.2}$$

It is also necessary to add three new sets of constraints to the model. Constraints (7.4), guarantee that only active departments can be allocated to active locations in each period. Constraints (7.5) allow inactive departments to be allocated to inactive locations, in each period. And constraints (7.6), impose that the total number of active locations in each period, is greater than or equal to the number of active departments.

$$\left[\, \boldsymbol{x}_{\,i(f,l)t}\ \ \boldsymbol{lact}_{lt}\ \ \boldsymbol{dact}_{it} \right] \ \le \mathbf{1} \quad \forall\, \boldsymbol{i,l,t,f} \qquad (7.4)$$

$$\left[(\boldsymbol{dact}_{it} - \ \boldsymbol{lact}_{lt})\ \boldsymbol{x}_{\,i(f,l)t} \right] \ \le \mathbf{0} \quad \forall\, \boldsymbol{i,l,t,f}$$

(7.5)

$$\textstyle\sum_{f=1}^{F} \sum_{l=1}^{L} \sum_{i=1}^{I} [\, \boldsymbol{dact}_{it} - \ \boldsymbol{lact}_{lt}] \ \le \mathbf{0} \quad \forall\, \boldsymbol{t}$$

(7.6)

This type of model variant can be applied to the *large changes model*, by adding or removing locations and departments, but it can also be applied to the *small changes model*, by adding or removing machines and locations inside a department or a facility.

To illustrate the application of this extension of the MFL model, we have used an instance from (Azevedo et al. 2016), considering the facilities available in each period as shown in Figure 7.41.

Initially, at t1, there are 2 facilities (f1 and f2), and since t2 on, we consider a new facility (f3).

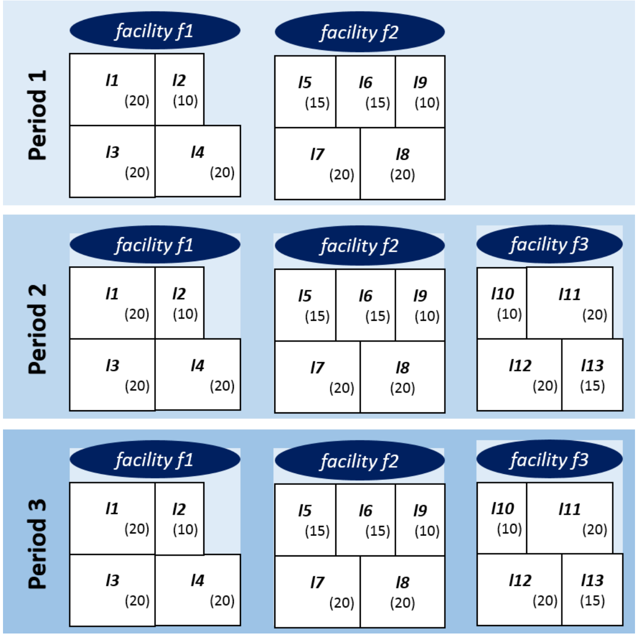

Figure 7. 41 - Available areas for the different facilities, in each period of the horizon.

7.5.1 Adding a facility

The emergence of a new *project (P4)* in t2 allows us to explore the recourse to a new facility. With the information on the departments in Table 7.23, the obtained configurations are those shown in Figure 7.42 and in Table 7.28 .

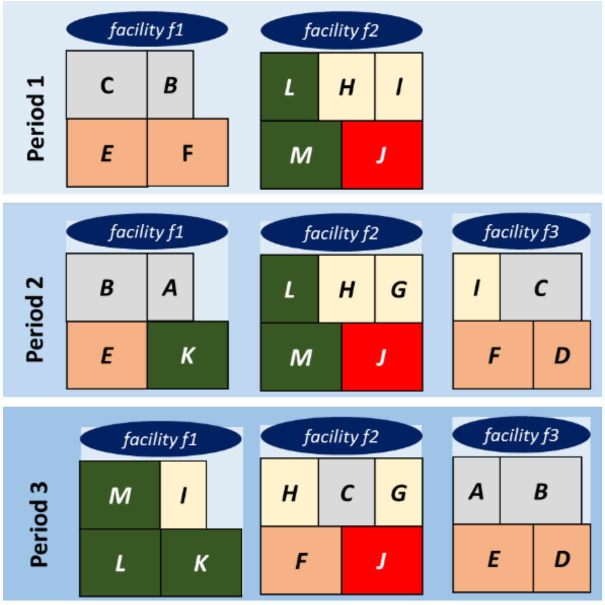

Figure 7. 42 - Configuration of facilities when adding a new facility.

Analysing these results, it is possible to conclude that:

- department J (painting) does never change its position;
- facilities tend to become specialized in some phase of the production process (e.g. *facility f2* focus on assembly, painting and product warehouse; *f1* and *f3* focus on the first production phases, with raw material warehouse, and injection; and *f1* at *t3* deals with all the product warehouses);
- *project 4* rotates among the 3 facilities, apparently due to the smaller quantities to be produced;
- flows inside facilities are naturally higher, because the distances are lower, and transport capacities are not constrained, as in the case of transport between facilities;
- external MHC costs (1 542 400) are considerably larger than internal MHC costs (34 500);

- there are 3 reconfigurations occurring inside facilities, and 10 between facilities, with a total reconfiguration cost of 165 000, and an adjacency value of 1 015.

Table 7. 28 - Results of adding facility *f3* in *t2*.

Project	**Network structure**	**Flows inside facilities**			**Flows between facilities**					**total MHC costs**
		f1	***f2***	***f3***	***f1-f2***	***f1-f3***	***f2-f1***	***f2-f3***	***f3-f2***	
P1	***f1,f2f3***									**650 150**
t1	*f1,f2*	500	400		350					
t2	*f3,f2*		400	500					350	
t3	*f2,f1*		1050		200					
P2	***f1,f2,f3***									**373 900**
t1	*f1,f2*	100	200		150					
t2	*f1,f2*	100	200		150					
t3	*f3,f2*		150	100				50	150	
P3	***f1,f2,f3***									**108 650**
t1	*f1,f2*	100	50		100					
t2	*f3,f2*			200					50	
P4	***f1,f2,f3***									**444 200**
t2	*f1,f2,f3*					50	100		150	
t3	*f1,f2,f3*			50			100		150	
		800	**2450**	**850**	**950**	**50**	**200**	**50**	**850**	**1 576 900**
Re-layout costs		**165 000**			**Adjacency**		**1015**			

7.5.2 Eliminating a facility

In a way similar to the previous scenario, we now consider the possibility of reducing the number of departments and facilities. Again, we consider here the data previously presented, and based in the case study.

In order to understand the impact of eliminating a facility, we will consider that *project 3* finishes in period *t2* (thus making departments B, E, I and L unnecessary) – see Figure 7.43 and Table 7.29.

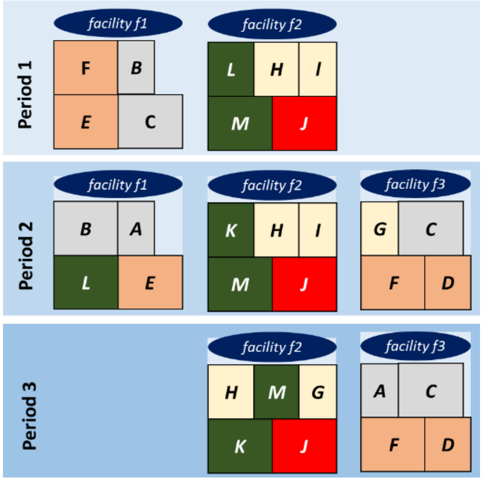

Figure 7. 43 - Configuration of facilities when closing a facility.

Table 7. 29 - Results in closing facility *f1* at *t3*.

Project	Network structure	Flows inside facilities			Flows between facilities					total MHC costs
		f1	***f2***	***f3***	***f1-f2***	***f1-f3***	***f2-f1***	***f2-f3***	***f3-f2***	
P1	***f1,f2,f3***									**766 800**
t1	*f1,f2*	500	400		350					
t2	*f3,f2*		400	500					350	
t3	*f2,f3*		900						350	
P2	***f1,f2,f3***									**247 450**
t1	*f1,f2*	100	200		150					
t2	*f1,f2*	100	150		150		50			
P3	***f1,f2,f3***									**143 900**
t1	*f1,f2*	100	50		100					
t2	*f3,f2*		50	100					100	
P4	***f1,f2,f3***									**253 400**
t2	*f1,f2,f3*			150		50			100	
t3	*f2,f3*		100	50					150	
		800	**2250**	**800**	**750**	**50**	**50**	**0**	**1050**	**1 411 550**
	Re-layout cost	**115 000**				**Adjacency**	**895**			

Analysing these results, it is possible to conclude that:

- *facility f2* has always three types of departments for the last phases of production (assembly, painting, and product warehousing);
- departments J and D do never change their positions, along the planning horizon; and departments B, E, M, H and K only move inside the same facility;
- flows (see Table 7. 29) are similar to the previous situation (adding facilities), for each facility and between facilities;
- external MHC costs (1 399 900) decrease and internal MHC costs (11 650) decrease too, when compared with the previous situation (adding a facility);

- this solution has less reconfigurations (5 inside facilities and 5 between facilities), with smaller reconfiguration costs than test1 (115 000), and a lower value of adjacency (895).

Despite their preliminary nature, the results show the potential of inter facilities collaboration in manufacturing systems, and its role in dynamically adjusting the network structure to take into account the flows requirements in different periods of the planning horizon. These experiments also show the developed model can be used to adjust the firm's strategy to respond to internal or external changes, through facility layout collaboration.

7.6 Conclusions

We have here presented how the model described in previous chapters can be applied in real situations, and how it can be extended and adapted to support complex decision-making processes.

We have first shown how the global model could be applied in the case study, by combining the *large changes model* with the *small changes model,* at SIMOLDES. Then some extensions of the MFLP model have been designed, to support practical application in the case study, namely:

- transferring projects from one facility to another – designing the layout not considering the aggregate flows between departments or machines, but rather their detailed flows by project, clearly broadens the possibilities of analysis and helps in the allocation of resources by projects;
- fixing a department at a facility can help the negotiation process with customers, at the project design phase;
- changing the dimension and structure of the network, by adding or removing facilities and departments, may help in checking the resources needed and where they should be located;
- assessing and promoting collaboration within the network, by analysing the creation of new partnerships for specific projects, with detailed resources – with our models, collaborative networks can also be extended to other companies, forming a kind of Virtual Enterprise (VE).

In addition to the examples described in this dissertation, other scenarios can obviously be explored. Here the model was applied to the automotive industry, but it can be easily adapted to other industrial sectors, in cases where there are a set of geographically separated facilities.

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8. CONCLUSIONS

This chapter briefly presents the main conclusions and contributions of this research project.

Contents of this chapter:

- *Overall conclusions*
- *Research contributions*
- *Future developments*
- *List of publications and conference participations*

8.1 Overall conclusions

In dissertation, we have presented our research on the design of layouts in complex multi-facility manufacturing systems.

The research was structured to deliver contributions in two directions (as outlined on Figure 8.1): for industry, with new approaches that can be practically applied; and for the scientific community, by developing a new methodology that integrates resolution procedures and models in one more general framework.

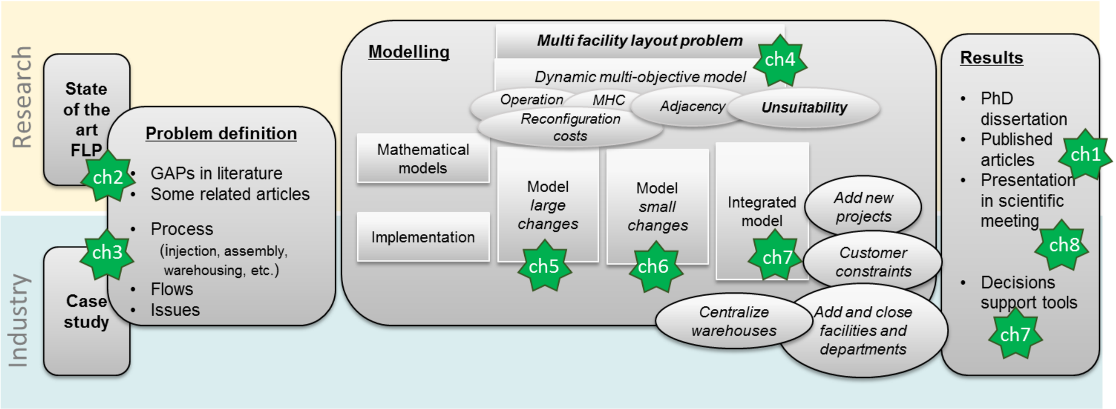

Figure 8. 1 – Thesis overview.

From the research, scientific side, we have extended the traditional *Facility Layout Problem* (FLP) with a new perspective, modelling the possibility of dynamically and simultaneously designing several facilities. Our model also combines the traditional objectives related to costs, with new objectives: the *unsuitability* and the *adjacency*.

For the industry, we have developed a decision support *framework*, based on two models (for *large changes* and *small changes*) that can be applied independently or in an integrated way. This tool allows the decision-maker to analyse and evaluate the need to rethink the layout of the facilities, and to understand the depth of possible reconfigurations. These reconfigurations can be rather simple changes, or large rearrangements, involving one or more facilities of a manufacturing network. These procedures will hopefully be a way to bring more flexibility to the company, by better assessing the impacts and costs of the layout changes.

The main ideas of each chapter of the dissertation can be synthesized as follows:

- In *chapter 2*, we have reviewed the main literature on the FLP, identifying some issues to be solved and procedures to be enhanced, in order to minimize the gap between research and practice (mainly in the manufacturing industry). One of the most stimulating findings in this comprehensive survey was the need of a new extension for the FLP, due to the fact that published works have only focused on a single facility. We believe therefore that extensions proposed in our work do open several interesting paths for future research.
- In *chapter 3*, we presented the case study that has inspired this research project. This exercise involved explaining products complexity and the whole distributed manufacturing system, as well as the need for tools to help optimize layout configurations more frequently, and to allow the analysis of new and more scenarios.
- In *chapter 4*, the proposed *multi-facility layout problem* was introduced, as well as the approach proposed to tackle it. One interesting feature of this approach is the possibility of integrating the "*small*" and "*large" changes* models, or even to apply them separately. As we are dealing with a multi-objective model (designed to minimize total *material handling costs*, to minimize *re-layout costs*, to minimize *unsuitability* between departments and locations, and to maximize the *adjacency* between departments), the decision maker has the possibility to weight the objectives, according to his own strategy and preferences.
- The "*large changes*" model (presented in *chapter 5*) allocates departments to different facilities simultaneously, considering transportation costs and operational constraints between facilities. This multi-objective model is based on the four objectives proposed for the MFLP, and was implemented and tested with the CPLEX optimizer. The model compares very positively with some well-known approaches from the literature, when tested with an illustrative example, inspired on the case study.
- In *chapter 6*, we presented the "*small changes*" model, to be applied in the design of layouts, at the machine level. This model can be used in various situations and moments of a layout life cycle, e.g. to make layout

reconfigurations inside a department, or even to make changes for a complete facility. This may be viewed as a distributed layout model, composed by two phases: first, perform product allocation to the existing machines; then, allocate the machines to the existing positions inside the departments. The model was implemented and evaluated with the CPLEX solver, with instances created to illustrate its applicability in two situations: design of the layout for a specific department, and design of a complete facility, at the machine level. We could, in this way, show the potential of the model.

- Finally, in *chapter 7*, we have shown with the case study, how the models developed in this work can be used, and combined as a decision support tool. Some scenarios have been tested, and some extensions of the model proposed, such as: changing the network structure and size, by adding or eliminating facilities; considering specific constraints imposed by customers; testing several logistic strategies (e.g. putting all the warehouses together in a single facility).

We believe the three main objectives of this doctoral project (section 1.2) were achieved, as described throughout the chapters of this dissertation.

The first purpose of this research was to understand how the classical FLP could be applied in situations where several facilities are “partners” in manufacturing a given product. Therefore, we had to: i) understand the characteristics of the problem that are new and different from the classic problem of layout reconfiguration, and how they affect the search for optimal solutions; ii) understand what kind of decision(s) (strategic, tactical or operational) are made in this process; iii) understand how often these decisions are made (as we are dealing with a network of facilities manufacturing a set of products); and iv) understand if all these aspects can be encompassed with the same model. In *chapter 2*, with the literature review on the FLP, we tried to answer these questions, showing that the classic model does not allow us to respond to the requirements posed by a network of facilities. A new extension of the classic problem is, in fact, needed to solve problems with multiple facilities. In *chapter 4*, we have proposed a multi facility layout approach, based on the concepts of "small" and "large” layout changes, to be used at different levels of reconfiguration (more strategic or tactical vs operational decisions) can be applied individually or in combination.

The second objective of this research has also been achieved: we have developed an easy to apply generic model, capable of incorporating interesting features identified in the case study (such as guaranteeing that some departments, with specific requirements, are only positioned at locations that fulfil those requirements). The illustrative examples used in this work demonstrate the potential of the model and show its applicability.

Our third objective was also accomplished: we have developed a decision support tool to analyse the impacts of some specific scenarios (for example, introducing new projects, changing the network structure and size by adding or withdrawing facilities, or considering customer requirements during the negotiation phase of the contract). This tool allows the decision maker to anticipate and analyse the consequences of a decision at the different levels: operational and strategic (with *small* and *large changes* – machine, department and network of facilities), as presented in *chapter 7*, with the proposed extensions to the MFLP.

8.2 Research contributions

The main contributions of this doctoral project, as previously refereed (Figure 8.1), can be seen from two perspectives.

From an industrial point of view, the models proposed were applied and tested in the case study that inspired this research, the Simoldes Plásticos Group (as described in chapter 7), showing their potential as a decision support tool. This tool can help in testing several scenarios, at different management levels, and in developing a set of alternative solutions in a multi-objective approach and taking into account a set of practical constraints. The development of this work also allowed the company to discuss and analyze the design and reconfiguration of the layouts of the facilities and the forms of collaboration between those facilities. With these discussions, some unknown issues emerged, such as the global cost of the facilities, or the fact that half of the space of the facilities is dedicated to warehouses. This tool allows the decision maker to "experiment" alternative actions and anticipate their impacts, for example checking if it is more convenient to share resources between plants or to maintain each facility independent of the others. This work may be practically very useful when the company is growing, with new facilities in several countries. A good example is the new facility in the Czech Republic, near one of the main customers (OEM), with joint production with Portuguese factories. Even if the case study has some specific characteristics and complexities, our tool can easily be adapted to other industrial sectors.

For the FLP literature, we have contributed to setting up a new problem, by modelling the complexity of dynamically and simultaneously redesigning several facilities, considering multiple objectives. With this research project, we have other contributions that can be applied not only with the MFLP, but also with the classical FLP and it extensions, such as:

i) The development of a new objective, the *unsuitability*, to help finding a good matching between the characteristics of each department and those of each location. This is especially important for layout reconfigurations and for facility conversion.

ii) The possibility of changing the strategy of the layout and of the production organization, with *adjacency* parameters, that can change with time. This is seldom used in the literature, specially at the machine level, but can in fact have a great utility for flexible and dynamic industrial companies.

iii) Considering other specific features of the problem, such as the handling system when designing the layouts (a topic not so much explored). We contributed by considering distinct transport ways (inside and between the facilities), reflected in the model by costs that can be adjusted with time. We have also considered the possibility of bounding the transport capacity between facilities, in given periods, thus allowing, in some way, to anticipate and reflect in terms of layout reconfigurations, possible changes in transportation (e.g. with increases in the fuel prices).

iv) Considering two levels of decision, with the concept of *large* and *small changes*, associated with differences in time and impact on production systems. Moreover, the integration of the machine layout model, used for *small changes*, with the multi-facility layout model, applied for *large changes*, creates a powerful decision support environment to increase agility and flexibility of companies.

8.3 Future developments

In this study, the model was applied to the automotive industry, but it can be easily adapted to many other industrial sectors (textile, shoes, food, furniture, etc.) in cases where there are a set of geographically separated facilities.

During the development of this research project, numerous interesting ideas have emerged, but due to natural time constraints and the nature of this work, it was not possible to further explore them. As future developments, we therefore intend to:

- extend the application of the *unsuitability* objective, by exploring more problem characteristics and constraints;
- deepen the development of facility layout design with a simultaneous selection of handling systems, namely exploring the different characteristics of transport systems;
- deal with *uncertainty* aspects, in particular, for the "*large changes*" model, due to the external transportation needs;
- consider new constraints associated to the facilities and machines (e.g. safety rules or ergonomic constraints);
- develop other optimization techniques, such as (meta)heuristics, to efficiently solve larger real size instances, or explore the integration of simulation models with optimization;
- extend the "*small changes*" model with the possibility of exchanging machines between facilities;
- apply the "*small changes*" model to Reconfigurable Manufacturing Systems (RMS), as these systems are characterized by their rapid and cost-effective response to market changes, and are therefore becoming more popular in global enterprises – the possibility of dynamically changing the area of departments can be of great applicability on RMS, due to their frequent changes in the features and dimensions of machines, and to the frequent addition and removal of tools or other equipment;
- the integration of these problems with supply chain design and management (by exploring, for example, the possibility of changing some advanced warehouses).

8.4 Publications and Conferences participation

Publications

- Azevedo, M.M., Crispim, J.A. & Pinho de Sousa, J., 2017. A dynamic multi-objective approach for the reconfigurable multi-facility layout problem. *Journal of Manufacturing Systems*, 42, pp.140–152.

- Azevedo, M.M., Crispim, J.A. & de Sousa, J.P., 2016. Layout Design and Reconfiguration in a Collaborative Manufacturing Network. In H. Afsarmanesh, L. M. Camarinha-Matos, & A. Lucas Soares, eds. *Collaboration in a Hyperconnected World: 17th IFIP WG 5.5 Working Conference on Virtual Enterprises, PRO-VE 2016, Porto, Portugal, October 3-5, 2016, Proceedings*. Cham: Springer International Publishing, pp. 545–556.

- Azevedo, M., Crispim, J. & Sousa, J. de, 2013. Flexible and Reconfigurable Layouts in Complex Manufacturing Systems. In D. Emmanouilidis, C., Taisch, M., and Kiritsis, ed. *Competitive Manufacturing for Innovative Products and Services: Proceedings of the APMS 2012 Conference, Advances in Production Management Systems*. Springer, pp. 484–493.

Participation in conferences

Reviewed communications

- 17th IFIP WG 5.5 Working Conference on Virtual Enterprises, PRO_VE 2016
- 6th Industrial Engineering and Management Symposium, IEMS'15
- International Conference Advances in Production Management Systems, APMS 2012

Abstract and posters

- 6th MIT Portugal Conference – *10 Years engineering a better future*, 2016
- 5th MIT Portugal Conference – *Light: Designed by Nature, Transformed by Science*, 2015
- 4th MIT Portugal Conference – *New frontiers for a sustainable Prosperity*, 2014
- 3rd MIT Portugal Conference – *Excellence in Engineering for Innovation in Global Markets*, 2012
- Education, Employment, Entrepreneurship forum (E3), 2012
- 2nd MIT Portugal Conference – *Creating Value Through Systems Thinking*, 2010.

APPENDIX A – Literature review data

Table A.2. 1 - Review of layout evaluation criteria in the literature of FLP.

References	Costs		Physical characteristics								Others	
	C1 - Inventory cost / Material Handling Cost	**C2 - Non-Inevntory cost**	**C3 - Distance**	**C4 - Material Flow**	**C5 - Volume density**	**C6 - Closeness**	**C7 - Space utilization**	**C8 - Building expansion**	**C9 - Non-material flow**	**C10 - Time spend**	**C11 - Layout flexibility**	**C12 - Transportation sytem characteristics**
Sakhaii et al. 2016	x	x			x	x	x					
Borzorgi, Abedzadeh and Zeinali 2015	x					x						
Abedzadeh et al. 2014	x	x				x	x	x				
Arnolds and Nickel 2013		x						x			x	
Emami and Nookabadi 2013	x	x				x		x				
Jiang and Nee 2013	x		x		x		x		x		x	
Nageshwaraniyer et al. 2013	x			x								
Tuzkaya et al. 2013	x					x						
Aiello et al. 2012	x		x			x	x					
Han, Bae and Jeong 2012			x	x	x			x				
Hasan et al. 2012	x	x		x			x		x		x	
Kia et al. 2012	x	x	x	x				x				x
Kilic et al. 2012		x		x						x		x
Koducuoglu and Bilge 2012			x									
Krishnnan et al 2012			x								x	x
Rao and Singh 2012	x					x					x	
Sahin et al. 2010	x	x		x			x		x		x	
Neumann 2009	x	x		x		x	x		x		x	x
Raman et al. 2009			x	x								
Raman et al. 2009	x	x		x								x
Raman, Nagalingam and Lin 2009						x	x				x	
Shen et al. 2009	x	x							x			
Zhang et al. 2009		x	x									
Xambre and Vilarinho 2007			x	x	x							
Zhao and Tseng 2007	x	x		x			x					
McKendall and Shang 2006	x	x	x	x								
Meng, Heragu and Zijm 2004	x	x	x	x						x		
Wu et al. 2002	x	x	x		x		x					
Lin and Sharp 1999	x	x	x		x	x	x	x			x	x
Lin and Sharp 1999	x	x	x		x	x	x	x				x
Benjaafar 1995				x	x					x		
27	18	15	14	14	7	8	10	5	5	3	8	7

Table A.2. 2 - Material handling principles (College Industry Council on Material Handling Education).

Material handling principles:

- ***Orientation:*** look at the entire system and study it first to learn how it operated. Identify the system components and their relationships, and look at relationships to other systems to find physical limitations.
- **Planning**: prepare a plan to meet the basic requirements (*What* materials to moves, *when* and *where* and the method *how* and *who*)
- **Systems:** integrate the handling, packaging and storage activities that make up a coordinated system
- **Unit-load:** pick up products as a unit
- **Space utilization:** optimize the utilization of all space
- **Standardization:** standardize the methods and equipment employed, reduce customization
- **Ergonomic:** adapt working conditions to workers' needs and abilities
- **Energy:** reduce energy consumption by the Material handing activities
- **Ecology:** minimize adverse effects on the environment when selecting Material handling systems components
- **Mechanization:** use machines, where they can be justified, to replace human effort
- **Flexibility:** use methods and components that can work with reasonable tolerance and can perform a variety of tasks
- **Simplification:** change handling procedures by eliminating, decreasing, or combining unnecessary movements or equipment
- **Gravity:** rely on gravity to move materials easily wherever possible
- **Safety:** provide safe material handling system components to handle the entire system
- **Computerization:** use computers to operate both individual pieces of equipment and massive supply chains spread across several continents
- **Systems flow:** integrate data flow with the physical material handling to make a coordinated system
- **Layout:** organize an operation sequence and equipment layout for all variable system solutions
- **Cost:** recognize that all material handling alternatives have associated costs and that these costs must be carefully considered as the system is devised.
- **Maintenance:** schedule a plan for maintenance on Material handling equipment
- **Obsolescence:** establish a long-term and economical program to replace obsolete equipment and methods
- **Automation:** apply electronics and computer-based systems to operate and control the entire system activities
- **The team-solution:** collaborate with material handling team members to devise the best system
- **The just-in-time:** hold products that are not moved until needed
- **Minimum travel:** system should be set up so that loads move the shortest distances
- **Using the right equipment:** use equipment that is needed for material handling
- **Designing capacity for present and future:** consider the development of material handling systems in future system design
- **Developing technological assessments:** prepare assessments that make operations simple with using technological facilities
- **Using the systematically approach:** consider the components and their relationships as an integrated system to unify them and increase efficiency.

APPENDIX B – Test instance for the “*large changes*” model

Additional data for instance 2 (30 departments)

This data complements the data presented in Chapter 5.

Table B. 5. 1 - Location characteristics (30 locations).

Location		**Characteristics**	
		floor	cranes
Facility 1	**l1**	5	3
	l2	5	5
	l3	5	4
	l4	1	1
	l5	1	3
	l6	2	1
	l7	2	5
	l8	1	4
	l9	5	5
Facility 2	**l10**	5	4
	l11	5	5
	l12	5	5
	l13	1	1
	l14	5	5
	l15	2	3
	l16	2	1
	l17	2	3
	l18	1	1
Facility 3	**l19**	5	3
	l20	1	5
	l21	5	4
	l22	5	5
	l23	2	5
	l24	1	1
	l25	5	5
	l26	5	4
	l27	1	1
	l28	1	1
	l29	1	1
	l30	2	2

Table B. 5. 2 - Departments characteristics.

Departments		**Area**		**Department characteristics**		**Re-layout cost**
		period 1	period 2	floor	cranes	
Raw Material Warehouse	**Wr1**	10	10	1	4	5 000
	Wr2	20	20			
	Wr3	20	20			
	Wr4	10	10			
Injection	**I1**	20	20	5	3	20 000
	I2	15	15			
	I3	10	10			
	I4	20	20			
Assembly	**A1**	15	15	1	1	10 000
	A2	20	20			
	A3	20	20			
	A4	15	15			
Painting	**Paint**	10	10	4	2	80 000
Product Warehouse	**Wp1**	10	10	1	5	5 000
	Wp2	20	20			
	Wp3	15	15			
	Wp4	20	20			
Component warehouse	**C1**	15	15	1	1	3 000
	C2	10	10			
	C3	15	15			
	C4	15	15			
Maintenance	**M1**	15	15	3	5	1 000
	M2	20	20	3	5	1 000
	M3	15	15	2	1	500
Quality	**Q1**	5	5	1	1	200
	Q2	5	5	4	4	
	Q3	5	5	1	1	
Empty warehouse	**E1**	10	10	2	2	150
	E2	10	10	1	1	
	E3	10	10	1	1	

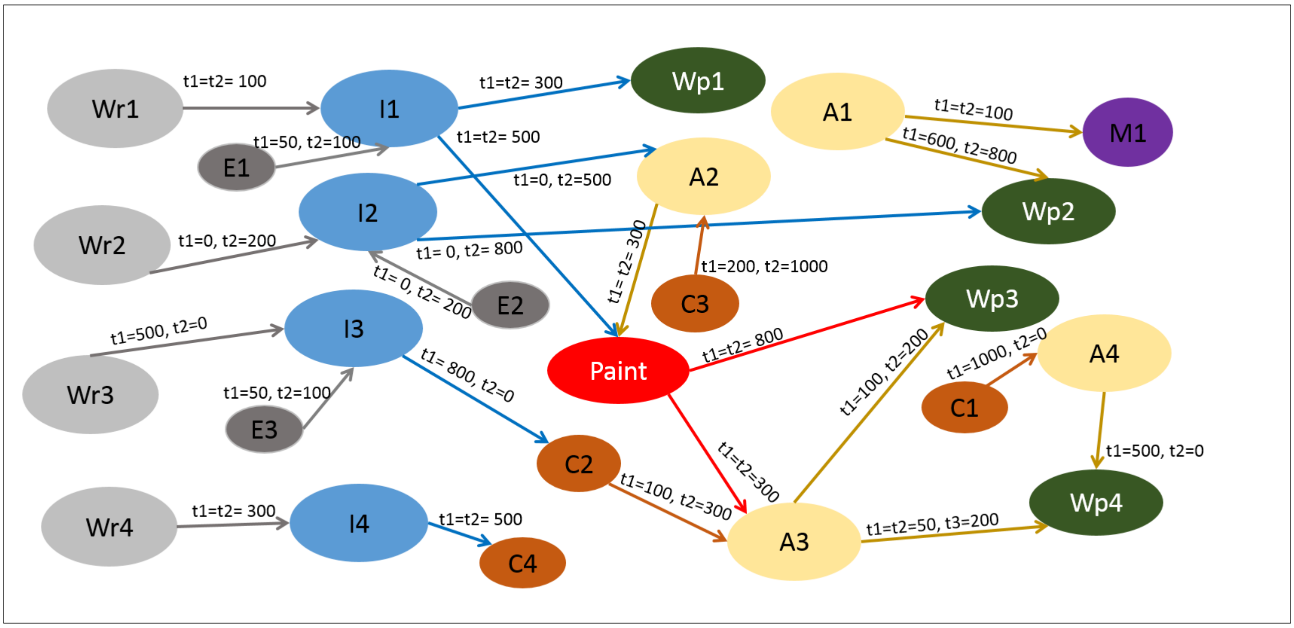

Figure B.5. 1 - Flows between departments (instance 2, 30 departments).

APPENDIX C – Multi-objective tests of the “*small changes*” model

Table C.6. 1 – Multi-objective tests of the “*small changes*” model (14 machines, 5 periods).

Conf	Test		Layout													
conf 1			**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	**M11**	**M12**	**M13**	**M14**
	test 1	t1	l10	l9	l13	l11	l12	l4	l14	l3	l5	l1	l2	l6	l7	l8
	test 13	t2	l10	l9	l13	l11	l12	**l14**	**l4**	l3	l5	l1	l2	l6	l7	l8
	test 22	t3	l10	l9	l13	l11	l12	l14	l4	l3	l5	l1	l2	l6	l7	l8
	test 30	t4	l10	l9	l13	l11	l12	l14	l4	l3	l5	l1	l2	l6	l7	l8
		t5	l10	l9	l13	l11	l12	l14	l4	l3	l5	l1	l2	l6	l7	l8
conf 2			**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	**M11**	**M12**	**M13**	**M14**
	test 2	t1	l10	l9	l13	l11	l12	l4	l14	l5	l1	l3	l2	l6	l7	l8
		t2	**l9**	**l10**	l13	l11	l12	**l14**	**l5**	**l4**	l1	l3	**l7**	l6	**l8**	**l2**
		t3	**l10**	**l9**	**l11**	**l12**	**l13**	l14	l5	**l1**	**l4**	l3	**l6**	**l2**	l8	**l7**
		t4	**l9**	**l10**	l11	l12	l13	l14	l5	**l3**	**l1**	**l4**	l7	**l6**	**l2**	**l8**
		t5	**l10**	**l9**	**l12**	**l11**	l13	**l4**	**l14**	**l1**	**l3**	**l5**	l7	l6	l2	l8
conf 3			**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	**M11**	**M12**	**M13**	**M14**
	test 3	t1	l10	l9	l13	l12	l11	l4	l14	l1	l5	l3	l7	l6	l8	l2
		t2	l10	l9	l13	l12	l11	l4	l14	l1	l5	l3	l7	l6	l8	l2
		t3	l10	l9	l13	l12	l11	l4	l14	l1	l5	l3	l7	l6	l8	l2
		t4	l10	l9	l13	l12	l11	l4	l14	l1	l5	l3	l7	l6	l8	l2
		t5	l10	l9	l13	l12	l11	l4	l14	l1	l5	l3	l7	l6	l8	l2
conf 4			**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	**M11**	**M12**	**M13**	**M14**
	test 4	**t1**	l10	l9	l11	l12	l13	l5	l14	l1	l3	l4	l2	l6	l7	l8
		t2	l10	l9	l11	**l13**	**l12**	l5	l14	l1	l3	l4	**l6**	**l2**	l7	l8
		t3	l10	l9	l11	**l12**	**l13**	l5	l14	l1	l3	l4	l6	l2	l7	l8
		t4	l10	l9	l11	l12	l13	l5	l14	l1	l3	l4	**l2**	**l6**	l7	l8
		t5	l10	l9	l11	**l13**	**l12**	l5	l14	l1	l3	l4	l2	l6	**l8**	**l7**
conf 5			**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	**M11**	**M12**	**M13**	**M14**
	test 5	**t1**	l10	l9	l11	l12	l13	l14	l5	l4	l3	l1	l6	l2	l8	l7
		t2	**l9**	**l10**	l11	l12	l13	l14	l5	l4	l3	l1	l6	l2	l8	l7
		t3	**l10**	**l9**	l11	l12	l13	l14	l5	l4	l3	l1	l6	l2	l8	l7
		t4	**l9**	**l10**	l11	l12	l13	l14	l5	l4	l3	l1	l6	l2	l8	l7
		t5	**l10**	**l9**	l11	l12	l13	l14	l5	l4	l3	l1	l6	l2	l8	l7
conf 6			**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	**M11**	**M12**	**M13**	**M14**
	test 6	**t1**	l10	l9	l13	l11	l12	l4	l14	l3	l5	l1	l6	l2	l7	l8
		t2	l10	l9	l13	l11	l12	l4	l14	l3	l5	l1	l6	l2	l7	l8
		t3	l10	l9	l13	l11	l12	**l14**	**l4**	l3	l5	l1	l6	l2	l7	l8
		t4	l10	l9	l13	l11	l12	l14	l4	l3	l5	l1	l6	l2	l7	l8
		t5	l10	l9	l13	l11	l12	**l4**	**l14**	l3	l5	l1	l6	l2	l7	l8
conf 7			**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	**M11**	**M12**	**M13**	**M14**
	test 7	**t1**	l10	l9	l13	l11	l12	l4	l14	l3	l5	l1	l2	l6	l7	l8
	test 10	**t2**	l10	l9	l13	l11	l12	**l14**	**l4**	l3	l5	l1	l2	l6	l7	l8
	test 11	**t3**	l10	l9	l13	l11	l12	l14	l4	l3	l5	l1	l2	l6	l7	l8
		t4	l10	l9	l13	l11	l12	l14	l4	l3	l5	l1	l2	l6	l7	l8

		t5	*l10*	*l9*	*l13*	*l11*	*l12*	***l4***	***l14***	*l3*	*l5*	*l1*	*l2*	*l6*	*l7*	*l8*
conf 8			***M1***	***M2***	***M3***	***M4***	***M5***	***M6***	***M7***	***M8***	***M9***	***M10***	***M11***	***M12***	***M13***	***M14***
	test 8	**t1**	*l10*	*l9*	*l13*	*l11*	*l12*	*l4*	*l14*	*l1*	*l5*	*l3*	*l6*	*l2*	*l8*	*l7*
		t2	*l10*	*l9*	*l13*	*l11*	*l12*	***l14***	***l3***	***l4***	*l5*	***l1***	*l6*	*l2*	*l8*	*l7*
		t3	*l10*	*l9*	*l13*	*l11*	*l12*	*l14*	***l4***	***l3***	*l5*	*l1*	*l6*	*l2*	*l8*	*l7*
		t4	*l10*	*l9*	*l13*	*l11*	*l12*	*l14*	***l4***	*l3*	*l5*	*l1*	*l6*	*l2*	*l8*	*l7*
		t5	*l10*	*l9*	*l13*	*l11*	*l12*	***l4***	*l14*	*l3*	*l5*	*l1*	*l2*	*l6*	*l8*	*l7*
conf 9			***M1***	***M2***	***M3***	***M4***	***M5***	***M6***	***M7***	***M8***	***M9***	***M10***	***M11***	***M12***	***M13***	***M14***
	test 9	**t1**	*l10*	*l9*	*l13*	*l11*	*l12*	*l4*	*l14*	*l1*	*l5*	*l3*	*l6*	*l2*	*l7*	*l8*
		t2	*l10*	*l9*	*l13*	*l11*	*l12*	***l14***	***l3***	***l4***	*l5*	***l1***	*l6*	*l2*	*l7*	*l8*
		t3	*l10*	*l9*	*l13*	*l11*	*l12*	*l14*	***l4***	***l3***	*l5*	*l1*	*l6*	*l2*	*l7*	*l8*
		t4	*l10*	*l9*	*l13*	*l11*	*l12*	*l14*	*l4*	*l3*	*l5*	*l1*	*l6*	*l2*	*l7*	*l8*
		t5	*l10*	*l9*	*l13*	*l11*	*l12*	***l4***	***l14***	*l3*	*l5*	*l1*	***l2***	***l6***	*l7*	*l8*
conf 10			***M1***	***M2***	***M3***	***M4***	***M5***	***M6***	***M7***	***M8***	***M9***	***M10***	***M11***	***M12***	***M13***	***M14***
	test 12	**t1**	*l10*	*l9*	*l13*	*l11*	*l12*	*l4*	*l14*	*l3*	*l5*	*l1*	*l6*	*l2*	*l7*	*l8*
		t2	*l10*	*l9*	*l13*	*l11*	*l12*	***l14***	***l4***	*l3*	*l5*	*l1*	*l6*	*l2*	*l7*	*l8*
		t3	*l10*	*l9*	*l13*	*l11*	*l12*	*l14*	*l4*	*l3*	*l5*	*l1*	*l6*	*l2*	*l7*	*l8*
		t4	*l10*	*l9*	*l13*	*l11*	*l12*	*l14*	*l4*	*l3*	*l5*	*l1*	*l6*	*l2*	*l7*	*l8*
		t5	*l10*	*l9*	*l13*	*l11*	*l12*	*l14*	*l4*	*l3*	*l5*	*l1*	*l6*	*l2*	*l7*	*l8*
conf 11			***M1***	***M2***	***M3***	***M4***	***M5***	***M6***	***M7***	***M8***	***M9***	***M10***	***M11***	***M12***	***M13***	***M14***
	test 14	**t1**	*l10*	*l9*	*l13*	*l11*	*l12*	*l4*	*l14*	*l1*	*l5*	*l3*	*l6*	*l2*	*l7*	*l8*
	test 15	**t2**	*l10*	*l9*	*l13*	*l11*	*l12*	***l14***	***l4***	***l3***	*l5*	***l1***	*l6*	*l2*	*l7*	*l8*
		t3	*l10*	*l9*	*l13*	*l11*	*l12*	*l14*	*l4*	*l3*	*l5*	*l1*	*l6*	*l2*	*l7*	*l8*
		t4	*l10*	*l9*	*l13*	*l11*	*l12*	*l14*	*l4*	*l3*	*l5*	*l1*	*l6*	*l2*	*l7*	*l8*
		t5	*l10*	*l9*	*l13*	*l11*	*l12*	***l4***	***l14***	*l3*	*l5*	*l1*	*l6*	*l2*	*l7*	*l8*
conf 12			***M1***	***M2***	***M3***	***M4***	***M5***	***M6***	***M7***	***M8***	***M9***	***M10***	***M11***	***M12***	***M13***	***M14***
	test 16	**t1**	*l10*	*l9*	*l13*	*l11*	*l12*	*l4*	*l14*	*l3*	*l5*	*l1*	*l2*	*l6*	*l8*	*l7*
		t2	*l10*	*l9*	*l13*	*l11*	*l12*	***l14***	***l4***	*l3*	*l5*	*l1*	*l2*	*l6*	*l8*	*l7*
		t3	*l10*	*l9*	*l13*	*l11*	*l12*	*l14*	*l4*	*l3*	*l5*	*l1*	*l2*	*l6*	*l8*	*l7*
		t4	*l10*	*l9*	*l13*	*l11*	*l12*	*l14*	*l4*	*l3*	*l5*	*l1*	*l2*	*l6*	*l8*	*l7*
		t5	*l10*	*l9*	*l13*	*l11*	*l12*	***l4***	***l14***	*l3*	*l5*	*l1*	*l2*	*l6*	*l8*	*l7*
conf 13			***M1***	***M2***	***M3***	***M4***	***M5***	***M6***	***M7***	***M8***	***M9***	***M10***	***M11***	***M12***	***M13***	***M14***
	test 17	**t1**	*l10*	*l9*	*l13*	*l11*	*l12*	*l4*	*l14*	*l3*	*l5*	*l1*	*l6*	*l2*	*l8*	*l7*
	test 20	**t2**	*l10*	*l9*	*l13*	*l11*	*l12*	***l14***	***l4***	*l3*	*l5*	*l1*	*l6*	*l2*	*l8*	*l7*
		t3	*l10*	*l9*	*l13*	*l11*	*l12*	*l14*	*l4*	*l3*	*l5*	*l1*	*l6*	*l2*	*l8*	*l7*
		t4	*l10*	*l9*	*l13*	*l11*	*l12*	*l14*	*l4*	*l3*	*l5*	*l1*	*l6*	*l2*	*l8*	*l7*
		t5	*l10*	*l9*	*l13*	*l11*	*l12*	***l4***	***l14***	*l3*	*l5*	*l1*	*l6*	*l2*	*l8*	*l7*
conf 14			***M1***	***M2***	***M3***	***M4***	***M5***	***M6***	***M7***	***M8***	***M9***	***M10***	***M11***	***M12***	***M13***	***M14***
	test 18	**t1**	*l9*	*l10*	*l13*	*l11*	*l12*	*l5*	*l14*	*l3*	*l4*	*l1*	*l2*	*l6*	*l7*	*l8*
		t2	*l9*	*l10*	*l13*	*l11*	*l12*	***l14***	***l5***	*l3*	*l4*	*l1*	*l2*	*l6*	*l7*	*l8*
		t3	*l9*	*l10*	*l13*	*l11*	*l12*	*l14*	*l5*	*l3*	*l4*	*l1*	*l2*	*l6*	*l7*	*l8*
		t4	*l9*	*l10*	*l13*	*l11*	*l12*	*l14*	*l5*	*l3*	*l4*	*l1*	*l2*	*l6*	*l7*	*l8*
		t5	*l9*	*l10*	*l13*	*l11*	*l12*	*l14*	*l5*	*l3*	*l4*	*l1*	*l2*	*l6*	*l7*	*l8*
conf 15			***M1***	***M2***	***M3***	***M4***	***M5***	***M6***	***M7***	***M8***	***M9***	***M10***	***M11***	***M12***	***M13***	***M14***

	test 19	***t1***	*l10*	*l9*	*l13*	*l11*	*l12*	*l4*	*l14*	*l3*	*l5*	*l1*	*l2*	*l6*	*l8*	*l7*
	test 23	***t2***	*l10*	*l9*	*l13*	*l11*	*l12*	***l14***	***l4***	*l3*	*l5*	*l1*	*l2*	*l6*	*l8*	*l7*
		t3	*l10*	*l9*	*l13*	*l11*	*l12*	*l14*	*l4*	*l3*	*l5*	*l1*	*l2*	*l6*	*l8*	*l7*
		t4	*l10*	*l9*	*l13*	*l11*	*l12*	*l14*	*l4*	*l3*	*l5*	*l1*	*l2*	*l6*	*l8*	*l7*
		t5	*l10*	*l9*	*l13*	*l11*	*l12*	*l14*	*l4*	*l3*	*l5*	*l1*	*l2*	*l6*	*l8*	*l7*
conf 16			***M1***	***M2***	***M3***	***M4***	***M5***	***M6***	***M7***	***M8***	***M9***	***M10***	***M11***	***M12***	***M13***	***M14***
	test 21	***t1***	*l9*	*l10*	*l13*	*l11*	*l12*	*l4*	*l14*	*l5*	*l1*	*l3*	*l6*	*l2*	*l8*	*l7*
		t2	*l9*	*l10*	*l13*	*l11*	*l12*	***l14***	***l5***	***l4***	*l1*	*l3*	*l6*	*l2*	*l8*	*l7*
		t3	*l9*	*l10*	*l13*	*l11*	*l12*	*l14*	*l5*	*l4*	*l1*	*l3*	*l6*	*l2*	*l8*	*l7*
		t4	*l9*	*l10*	*l13*	*l11*	*l12*	*l14*	*l5*	*l4*	*l1*	*l3*	*l6*	*l2*	*l8*	*l7*
		t5	*l9*	*l10*	*l13*	*l11*	*l12*	***l5***	***l14***	*l4*	*l1*	*l3*	*l6*	*l2*	*l8*	*l7*
conf 17			***M1***	***M2***	***M3***	***M4***	***M5***	***M6***	***M7***	***M8***	***M9***	***M10***	***M11***	***M12***	***M13***	***M14***
	test 24	***t1***	*l9*	*l10*	*l13*	*l11*	*l12*	*l5*	*l14*	*l4*	*l1*	*l3*	*l2*	*l6*	*l7*	*l8*
	test 28	***t2***	*l9*	*l10*	*l13*	*l11*	*l12*	*l5*	*l14*	*l4*	*l1*	*l3*	*l2*	*l6*	*l7*	*l8*
		t3	*l9*	*l10*	*l13*	*l11*	*l12*	*l5*	*l14*	*l4*	*l1*	*l3*	*l2*	*l6*	*l7*	*l8*
		t4	*l9*	*l10*	*l13*	*l11*	*l12*	*l5*	*l14*	*l4*	*l1*	*l3*	*l2*	*l6*	*l7*	*l8*
		t5	*l9*	*l10*	*l13*	*l11*	*l12*	*l5*	*l14*	*l4*	*l1*	*l3*	*l2*	*l6*	*l7*	*l8*
conf 18			***M1***	***M2***	***M3***	***M4***	***M5***	***M6***	***M7***	***M8***	***M9***	***M10***	***M11***	***M12***	***M13***	***M14***
	test 25	***t1***	*l9*	*l10*	*l13*	*l11*	*l12*	*l5*	*l14*	*l4*	*l1*	*l3*	*l6*	*l2*	*l8*	*l7*
		t2	*l9*	*l10*	*l13*	*l11*	*l12*	*l5*	*l14*	*l4*	*l1*	*l3*	*l6*	*l2*	*l8*	*l7*
		t3	*l9*	*l10*	*l13*	*l11*	*l12*	*l5*	*l14*	*l4*	*l1*	*l3*	*l6*	*l2*	*l8*	*l7*
		t4	*l9*	*l10*	*l13*	*l11*	*l12*	*l5*	*l14*	*l4*	*l1*	*l3*	*l6*	*l2*	*l8*	*l7*
		t5	*l9*	*l10*	*l13*	*l11*	*l12*	*l5*	*l14*	*l4*	*l1*	*l3*	*l6*	*l2*	*l8*	*l7*
conf 19			***M1***	***M2***	***M3***	***M4***	***M5***	***M6***	***M7***	***M8***	***M9***	***M10***	***M11***	***M12***	***M13***	***M14***
	tes 26	***t1***	*l9*	*l10*	*l13*	*l11*	*l12*	*l5*	*l14*	*l3*	*l4*	*l1*	*l6*	*l2*	*l8*	*l7*
		t2	*l9*	*l10*	*l13*	*l11*	*l12*	***l14***	***l5***	*l3*	*l4*	*l1*	*l6*	*l2*	*l8*	*l7*
		t3	*l9*	*l10*	*l13*	*l11*	*l12*	*l14*	*l5*	*l3*	*l4*	*l1*	*l6*	*l2*	*l8*	*l7*
		t4	*l9*	*l10*	*l13*	*l11*	*l12*	*l14*	*l5*	*l3*	*l4*	*l1*	*l6*	*l2*	*l8*	*l7*
		t5	*l9*	*l10*	*l13*	*l11*	*l12*	*l14*	*l5*	*l3*	*l4*	*l1*	*l6*	*l2*	*l8*	*l7*
conf 20			***M1***	***M2***	***M3***	***M4***	***M5***	***M6***	***M7***	***M8***	***M9***	***M10***	***M11***	***M12***	***M13***	***M14***
	test 27	***t1***	*l9*	*l10*	*l13*	*l11*	*l12*	*l14*	*l5*	*l3*	*l4*	*l1*	*l6*	*l2*	*l8*	*l7*
		t2	*l9*	*l10*	*l13*	*l11*	*l12*	*l14*	*l5*	*l3*	*l4*	*l1*	*l6*	*l2*	*l8*	*l7*
		t3	*l9*	*l10*	*l13*	*l11*	*l12*	*l14*	*l5*	*l3*	*l4*	*l1*	*l6*	*l2*	*l8*	*l7*
		t4	*l9*	*l10*	*l13*	*l11*	*l12*	*l14*	*l5*	*l3*	*l4*	*l1*	*l6*	*l2*	*l8*	*l7*
		t5	*l9*	*l10*	*l13*	*l11*	*l12*	*l14*	*l5*	*l3*	*l4*	*l1*	*l6*	*l2*	*l8*	*l7*
conf 21			***M1***	***M2***	***M3***	***M4***	***M5***	***M6***	***M7***	***M8***	***M9***	***M10***	***M11***	***M12***	***M13***	***M14***
	test 29	***t1***	*l9*	*l10*	*l13*	*l11*	*l12*	*l5*	*l14*	*l4*	*l1*	*l3*	*l6*	*l2*	*l7*	*l8*
		t2	*l9*	*l10*	*l13*	*l11*	*l12*	*l5*	*l14*	*l4*	*l1*	*l3*	*l6*	*l2*	*l7*	*l8*
		t3	*l9*	*l10*	*l13*	*l11*	*l12*	*l5*	*l14*	*l4*	*l1*	*l3*	*l6*	*l2*	*l7*	*l8*
		t4	*l9*	*l10*	*l13*	*l11*	*l12*	*l5*	*l14*	*l4*	*l1*	*l3*	*l6*	*l2*	*l7*	*l8*
		t5	*l9*	*l10*	*l13*	*l11*	*l12*	*l5*	*l14*	*l4*	*l1*	*l3*	*l6*	*l2*	*l7*	*l8*

APPENDIX D – Case study data

At these appendix, we present the remaining detail data of the case study, for the productive departments.

Table D. 7. 1 – Proximity value, for positions inside facility SP.

SP	l1S	l2S	l3S	l4S	l5S	l6S	l7S	l8S	l9S	l10S	l11S	l12S	l13S	l14S	l15S	l16S	l17S	l18S	l19S
l1S	0	5	3	3	2	1	3	0	0	0	0	0	0	0	0	0	0	0	0
l2S	5	0	4	5	3	2	4	1	1	0	0	0	0	0	0	0	0	0	0
l3S	3	4	0	5	5	3	3	2	2	1	1	0	0	0	0	0	0	0	0
l4S	3	5	5	0	5	3	5	2	1	1	1	0	0	0	0	0	0	0	0
l5S	2	3	5	5	0	5	5	3	3	2	2	1	0	0	0	0	0	0	0
l6S	1	2	3	3	5	0	5	5	3	2	2	1	0	0	0	0	0	0	0
l7S	3	4	3	5	5	5	0	3	3	4	5	3	2	2	1	2	2	0	0
l8S	0	1	2	2	3	4	3	0	5	5	3	3	2	2	1	2	2	1	1
l9S	0	0	1	1	2	3	3	5	0	5	3	3	2	2	1	2	2	0	0
l10S	0	0	1	1	2	3	4	5	5	0	5	5	3	3	2	3	3	1	1
l11S	0	0	0	0	1	2	5	3	3	5	0	5	3	3	3	3	4	2	2
l12S	0	0	0	0	5	2	3	3	3	5	5	0	5	5	3	5	5	2	2
l13S	0	0	0	0	1	2	2	2	2	3	1	5	0	5	4	3	2	3	2
l14S	0	0	0	0	0	1	2	2	2	3	3	5	5	0	5	5	3	3	3
l15S	0	0	0	0	0	0	1	1	1	2	2	3	4	5	0	5	3	5	3
l16S	0	0	0	0	0	1	2	2	2	3	3	5	3	5	5	0	5	5	4
l17S	0	0	0	0	0	0	1	1	1	2	4	5	3	3	3	5	0	4	5
l18S	0	0	0	0	0	0	0	0	0	0	1	1	3	3	5	5	4	0	5
l19S	0	0	0	0	0	0	1	1	1	2	2	2	3	3	3	4	5	5	0

Table D. 7. 2 – Proximity values, for positions inside facility IN.

IN	l1I	l2I	l3I	l4I	l5I	l6I	l7I	l8I	l9I	l10I	l11I	l12I	l13I	l14I	l15I	l16I	l17I	l18I	l19I
l1I	0	3	2	5	3	1	0	2	0	0	0	0	0	0	0	0	0	0	0
l2I	3	0	5	5	3	3	2	3	2	2	2	1	1	1	0	0	0	0	0
l3I	1	5	0	5	3	5	3	4	2	2	2	1	1	1	0	0	0	0	0
l4I	5	5	5	0	5	4	3	5	2	2	2	1	1	1	0	0	0	0	0
l5I	2	3	3	5	0	3	3	5	2	2	2	1	1	1	0	0	0	0	0
l6I	1	3	5	4	3	0	5	5	3	3	2	2	2	1	0	0	0	0	0
l7I	1	2	3	3	2	5	0	5	5	4	2	3	3	1	2	1	0	2	1
l8I	1	3	4	5	5	5	5	0	3	5	5	3	3	3	2	2	1	2	2
l9I	0	1	2	2	2	3	5	3	0	3	2	5	3	2	3	2	1	3	2
l10I	0	1	2	2	2	3	4	5	3	0	5	4	5	3	3	3	2	3	3
l11I	1	2	3	3	3	3	3	5	3	5	0	3	5	5	3	3	2	3	3
l12I	0	2	3	3	3	3	3	3	5	4	3	0	5	2	5	3	2	4	2
l13I	0	1	2	2	2	3	3	3	3	5	5	5	0	5	4	3	2	5	4
l14I	0	2	2	2	2	6	3	3	3	3	5	3	5	0	3	3	2	4	5
l15I	0	0	1	1	1	2	2	2	3	3	3	5	4	3	0	5	3	5	3
l16I	0	0	0	0	0	1	1	1	2	2	2	3	3	3	5	0	5	5	3
l17I	0	0	0	0	0	1	1	1	2	2	2	3	3	3	3	5	0	4	3
l18I	0	0	1	1	1	2	2	2	3	3	3	4	5	4	5	5	4	0	5
l19I	0	0	1	1	1	2	2	2	3	3	3	3	4	5	3	3	3	5	0

Table D. 7. 3 – Proximity values, for positions inside facility PL.

PL	*l1P*	*l2P*	*l3P*	*l4P*	*l5P*	*l6P*	*l7P*	*l8P*	*l9P*	*l10P*	*l11P*
l1P	0	5	3	5	3	3	3	2	1	0	0
l2P	5	0	5	5	3	4	3	3	2	1	0
l3P	3	5	0	4	3	5	3	3	2	1	0
l4P	5	5	4	0	5	5	4	3	2	1	0
l5P	3	3	3	5	0	4	5	2	1	0	0
l6P	3	4	5	5	4	0	5	5	3	2	1
l7P	3	3	3	4	5	5	0	5	5	4	3
l8P	2	3	3	3	3	5	5	0	5	3	2
l9P	1	2	3	2	2	3	5	5	0	5	3
l10P	0	1	2	1	1	2	4	3	5	0	5
l11P	0	0	1	0	0	1	3	2	3	5	0

Table D. 7. 4 – Proximity value between facilities (SP, IN and PL).

facilities	SP	IN	PL
SP	-	2	1
IN	2	-	1
PL	1	1	-

Table D. 7. 5 - Distance between positions inside location *l12S*.

l	*l1*	*l2*	*l3*	*l4*	*l5*	*l6*	*l7*	*l8*	*l9*	*l10*	*l11*	*l12*	*l13*	*l14*	*l15*	*l16*	*l17*	*l18*	*l19*	*l20*	*l21*	*l22*	*l23*	*l24*	*l25*	*l26*	*l27*	*l28*	*l29*	*l30*	*l31*	*l32*	*l33*	*l34*	*l35*
l1	0	2	3	5	7	9	10	12	14	15	17	19	20	22	24	26	27	29	3	4	6	8	9	11	13	14	16	18	20	21	23	25	26	28	30
l2	2	0	2	3	5	7	9	10	12	14	15	17	19	20	22	24	26	27	4	3	4	6	8	9	11	13	14	16	18	20	21	23	25	26	28
l3	3	2	0	2	3	5	7	9	10	12	14	15	17	19	20	22	24	25	6	4	3	4	6	8	9	11	13	14	16	18	20	21	23	25	26
l4	5	3	2	0	2	3	5	7	9	10	12	14	15	17	19	20	22	24	8	6	4	3	4	6	8	9	11	13	14	16	18	20	21	23	25
l5	7	5	3	2	0	2	3	5	7	9	10	12	14	15	17	19	20	22	9	8	6	4	3	4	6	8	9	11	13	14	16	18	20	21	23
l6	9	7	5	3	2	0	2	3	5	7	9	10	12	14	15	17	19	20	11	9	8	6	4	3	4	6	8	9	11	13	14	16	18	20	21
l7	10	9	7	5	3	2	0	2	3	5	7	9	10	12	14	15	17	19	13	11	9	8	6	4	3	4	6	8	9	11	13	14	16	18	20
l8	12	10	9	7	5	3	2	0	2	3	5	7	9	10	12	14	15	17	14	13	11	9	8	6	4	3	4	6	8	9	11	13	14	16	18
l9	14	12	10	9	7	5	3	2	0	2	3	5	7	9	10	12	14	15	16	14	13	11	9	8	6	4	3	4	6	8	9	11	13	14	16
l10	15	14	12	10	9	7	5	3	2	0	2	3	5	7	9	10	12	13	18	16	14	13	11	9	8	6	4	3	4	6	8	9	11	13	14
l11	17	15	14	12	10	9	7	5	3	2	0	2	3	5	7	9	10	12	20	18	16	14	13	11	9	8	6	4	3	4	6	8	9	11	13
l12	19	17	15	14	12	10	9	7	5	3	2	0	2	3	5	7	9	10	21	20	18	16	14	13	11	9	8	6	4	3	4	6	8	9	11
l13	20	19	17	15	14	12	10	9	7	5	3	2	0	2	3	5	7	8	23	21	20	18	16	14	13	11	9	8	6	4	3	4	6	8	9
l14	22	20	19	17	15	14	12	10	9	7	5	3	2	0	2	3	5	7	25	23	21	20	18	16	14	13	11	9	8	6	4	3	4	6	8
l15	24	22	20	19	17	15	14	12	10	9	7	5	3	2	0	2	3	5	26	25	23	21	20	18	16	14	13	11	9	8	6	4	3	4	6
l16	26	24	22	20	19	17	15	14	12	10	9	7	5	3	2	0	2	3	28	26	25	23	21	20	18	16	14	13	11	9	8	6	4	3	4
l17	27	26	24	22	20	19	17	15	14	12	10	9	7	5	3	2	0	2	30	28	26	25	23	21	20	18	16	14	13	11	9	8	6	4	3
l18	29	27	25	24	22	20	19	17	15	13	12	10	8	7	5	3	2	0	30	29	27	25	23	22	20	18	17	15	13	12	10	8	6	5	3
l19	3	4	6	8	9	11	13	14	16	18	20	21	23	25	26	28	30	30	0	33	31	30	28	26	25	23	21	20	18	16	14	13	11	13	14
l20	4	3	4	6	8	9	11	13	14	16	18	20	21	23	25	26	28	29	33	0	2	3	5	7	9	10	12	14	15	17	19	20	22	24	26
l21	6	4	3	4	6	8	9	11	13	14	16	18	20	21	23	25	26	27	31	2	0	2	3	5	7	9	10	12	14	15	17	19	20	22	24
l22	8	6	4	3	4	6	8	9	11	13	14	16	18	20	21	23	25	25	30	3	2	0	2	3	5	7	9	10	12	14	15	17	19	20	22
l23	9	8	6	4	3	4	6	8	9	11	13	14	16	18	20	21	23	23	28	5	3	2	0	2	3	5	7	9	10	12	14	15	17	19	20
l24	11	9	8	6	4	3	4	6	8	9	11	13	14	16	18	20	21	22	26	7	5	3	2	0	2	3	5	7	9	10	12	14	15	17	19
l25	13	11	9	8	6	4	3	4	6	8	9	11	13	14	16	18	20	20	25	9	7	5	3	2	0	2	3	5	7	9	10	12	14	15	17
l26	14	13	11	9	8	6	4	3	4	6	8	9	11	13	14	16	18	18	23	10	9	7	5	3	2	0	2	3	5	7	9	10	12	14	15
l27	16	14	13	11	9	8	6	4	3	4	6	8	9	11	13	14	16	17	21	12	10	9	7	5	3	2	0	2	3	5	7	9	10	12	14
l28	18	16	14	13	11	9	8	6	4	3	4	6	8	9	11	13	14	15	20	14	12	10	9	7	5	3	2	0	2	3	5	7	9	10	12
l29	20	18	16	14	13	11	9	8	6	4	3	4	6	8	9	11	13	13	18	15	14	12	10	9	7	5	3	2	0	2	3	5	7	9	10
l30	21	20	18	16	14	13	11	9	8	6	4	3	4	6	8	9	11	12	16	17	15	14	12	10	9	7	5	3	2	0	2	3	5	7	9
l31	23	21	20	18	16	14	13	11	9	8	6	4	3	4	6	8	9	10	14	19	17	15	14	12	10	9	7	5	3	2	0	2	3	5	7
l32	25	23	21	20	18	16	14	13	11	9	8	6	4	3	4	6	8	8	13	20	19	17	15	14	12	10	9	7	5	3	2	0	2	3	5
l33	26	25	23	21	20	18	16	14	13	11	9	8	6	4	3	4	6	6	11	22	20	19	17	15	14	12	10	9	7	5	3	2	0	2	3
l34	28	26	25	23	21	20	18	16	14	13	11	9	8	6	4	3	4	5	13	24	22	20	19	17	15	14	12	10	9	7	5	3	2	0	2
l35	30	28	26	25	23	21	20	18	16	14	13	11	9	8	6	4	3	3	14	26	24	22	20	19	17	15	14	12	10	9	7	5	3	2	0

Table D. 7. 6 - Proximity values for positions inside location *l12S*.

l	*l1*	*l2*	*l3*	*l4*	*l5*	*l6*	*l7*	*l8*	*l9*	*l10*	*l11*	*l12*	*l13*	*l14*	*l15*	*l16*	*l17*	*l18*	*l19*	*l20*	*l21*	*l22*	*l23*	*l24*	*l25*	*l26*	*l27*	*l28*	*l29*	*l30*	*l31*	*l32*	*l33*	*l34*	*l35*
l1	0	5	3	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	2	1	0	0	0	0	0	0	0	0	0	0	0	0
l2	5	0	5	3	2	1	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	2	1	0	0	0	0	0	0	0	0	0	0	0	0
l3	3	5	0	5	3	2	1	0	0	0	0	0	0	0	0	0	0	0	3	3	3	3	3	2	1	0	0	0	0	0	0	0	0	0	0
l4	2	3	5	0	5	3	2	1	0	0	0	0	0	0	0	0	0	0	2	3	3	3	3	3	2	1	0	0	0	0	0	0	0	0	0
l5	1	2	3	5	0	5	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	3	3	3	3	2	1	0	0	0	0	0	0	0	0
l6	0	1	2	3	5	0	5	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	3	3	3	3	2	1	0	0	0	0	0	0	0
l7	0	0	1	2	3	5	0	5	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	3	3	3	3	2	1	0	0	0	0	0	0
l8	0	0	0	1	2	3	5	0	5	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	3	3	3	3	2	1	0	0	0	0	0
l9	0	0	0	0	1	2	3	5	0	5	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	3	3	3	3	2	1	0	0	0	0
l10	0	0	0	0	0	1	2	3	5	0	5	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	3	3	3	3	2	1	0	0	0
l11	0	0	0	0	0	0	1	2	3	5	0	5	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	3	3	3	3	2	1	0	0
l12	0	0	0	0	0	0	0	1	2	3	5	0	5	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	3	3	3	3	2	1	0
l13	0	0	0	0	0	0	0	0	1	2	3	5	0	5	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	3	3	3	3	2	1
l14	0	0	0	0	0	0	0	0	0	1	2	3	5	0	5	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	3	3	3	3	2
l15	0	0	0	0	0	0	0	0	0	0	1	2	3	5	0	5	3	2	0	0	0	0	0	0	0	0	0	0	1	2	3	3	3	3	3
l16	0	0	0	0	0	0	0	0	0	0	0	1	2	3	5	0	5	3	0	0	0	0	0	0	0	0	0	0	0	1	2	3	3	3	3
l17	0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	5	0	5	0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	3	3
l18	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	3
l19	3	3	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	3
l20	3	3	3	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2
l21	3	3	3	3	3	2	1	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
l22	2	3	3	3	3	3	2	1	0	0	0	0	0	0	0	0	0	0	2	3	5	0	5	3	2	1	0	0	0	0	0	0	0	0	0
l23	1	2	3	3	3	3	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	5	0	5	3	2	1	0	0	0	0	0	0	0	0
l24	0	1	2	3	3	3	3	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	5	0	5	3	2	1	0	0	0	0	0	0	0
l25	0	0	1	2	3	3	3	3	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	5	0	5	3	2	1	0	0	0	0	0	0
l26	0	0	0	1	2	3	3	3	3	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	5	0	5	3	2	1	0	0	0	0	0
l27	0	0	0	0	1	2	3	3	3	3	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	5	0	5	3	2	1	0	0	0	0
l28	0	0	0	0	0	1	2	3	3	3	3	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	5	0	5	3	2	1	0	0	0
l29	0	0	0	0	0	0	1	2	3	3	3	3	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	5	0	5	3	2	1	0	0
l30	0	0	0	0	0	0	0	1	2	3	3	3	3	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	5	0	5	3	2	1	0
l31	0	0	0	0	0	0	0	0	1	2	3	3	3	3	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	5	0	5	3	2	1
l32	0	0	0	0	0	0	0	0	0	1	2	3	3	3	3	3	2	1	0	0	0	0	0	0	0	0	0	1	2	3	5	0	5	3	2
l33	0	0	0	0	0	0	0	0	0	0	1	2	3	3	3	3	3	2	0	0	0	0	0	0	0	0	0	0	1	2	3	5	0	5	3
l34	0	0	0	0	0	0	0	0	0	0	0	1	2	3	3	3	3	3	0	0	0	0	0	0	0	0	0	0	0	1	2	3	5	0	5
l35	0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	5	0

Table D. 7. 7 - Closeness value, between machines of department I1S, considering the need of join machines of the same type.

M	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24	M25	M26	M27	M28	M29	M30	M31
M1	0	5	5	5	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M2	5	0	5	5	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M3	5	5	0	5	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M4	5	5	5	0	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M5	5	5	5	5	0	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M6	5	5	5	5	5	0	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M7	5	5	5	5	5	5	0	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M8	5	5	5	5	5	5	5	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M9	5	5	5	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M10	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M11	0	0	0	0	0	0	0	0	0	5	0	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M12	0	0	0	0	0	0	0	0	0	5	5	0	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M13	0	0	0	0	0	0	0	0	0	5	5	5	0	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M14	0	0	0	0	0	0	0	0	0	5	5	5	5	0	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M15	0	0	0	0	0	0	0	0	0	5	5	5	5	5	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M16	0	0	0	0	0	0	0	0	0	5	5	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5	5	5	0	0	0	0	0	0	0
M18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	5	5	5	5	5	5	0	0	0	0	0	0	0
M19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	0	5	5	5	5	5	0	0	0	0	0	0	0
M20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	0	5	5	5	5	0	0	0	0	0	0	0
M21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	0	5	5	5	0	0	0	0	0	0	0
M22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5	0	5	5	0	0	0	0	0	0	0
M23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5	5	0	5	0	0	0	0	0	0	0
M24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5	5	5	0	0	0	0	0	0	0	0
M25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	0	0	0	0
M26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	5	0	0	0	0
M27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	0	0	0	0	0
M28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
M31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0