Dealing with aisles in manufacturing system layout problems : formulation, exact resolution and simulation based optimization

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Dealing with aisles in manufacturing system layout problems: formulation, exact resolution and simulation based optimization

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ABSTRACT

Facility layout can have significant impacts on the safety, cost, time, and productivity of manufacturing systems. There are several major decisions involved when designing a facility layout. In general, facility layout problems (FLPs) are concerned with the decisions related to the allocation of the facilities such as machines, departments and workstations on the shop floor of a manufacturing system to achieve the given objectives and considering certain constraints. However, the facilities require paths that allow them to be connected. These paths, called aisles, are used for the transportation of materials and workers between the facilities. Since transporting materials between facilities is performed through an aisle network, designing a good aisle structure can contribute to reducing the transportation distance between facilities to cut the material handling cost as well as transportation time and to preparing smooth and safe material transportation. Therefore, designing a good aisle structure is very important for the efficiency of manufacturing systems, and should be included in FLPs. This thesis studies and analysis the problem of designing aisles in facility layout problems and provides an approach that allows designing aisles structure and facilities layout in an integrated manner.

Two novel approaches are developed to find the optimum facility layout and aisle structure. In the first approach, a mixed-integer linear programming model is developed to simultaneously find the optimum structure of the aisles including the number, position and width of the aisles, the position of the facilities, and the position of the entrance/exit doors in unequal area FLPs. A branch-and-cut algorithm, improved by adding optimality cuts and efficient branching and node strategies, is used to solve the problem. The computational experiments show that the proposed approach is able to find the suited position of facilities and aisles structure for manufacturing systems up to 12 facilities.

In the second approach, simulation is fully integrated with an optimization method (i.e., a metaheuristic algorithm), enabling designers to consider various dynamic and stochastic factors such as transportation time, machine and transporters breakdowns, stochastic demand for products and stochastic process time. The great advantage of the proposed simulation-based optimization approach is that it can support a direct connection between simulation and many optimization

algorithms and can handle the mentioned stochastic and dynamic phenomena of the system. Therefore, it can be applied to a wide variety of FLPs in many manufacturing systems.

Keywords: Facility layout problems, Aisle structure, Mixed-integer linear programming, Simulation-based optimization

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LIST OF ABBREVIATIONS

MHC	Material handling costs
WIP	Work-in-process inventory
FLPs	Facility layout problems
MILP	Mixed-integer linear programming
OSHA	Occupational safety and health administration
EA-FLPs	Equal-area facility layout problems
UA-FLPs	Unequal area facility layout problems
MIP	Mixed-integer programming
SFLP	Static facility layout problems
DFLP	Dynamic facility layout problems
I/O	Input/output
P/D	Pick-up/drop-off
TTD	Total transportation distance
B&C	Branch-and-cut
OFV	Objective function value
COM	Component object model
SDEA	Stochastic data envelopment analysis
NSGA-II	Non-dominated sorting genetic algorithm
ANN	Artificial neural network
MFT	Mean flow time
CD	Crowding distance
DCD	Dynamic crowding distance
MNSGA-II	Modified non-dominated sorting genetic algorithm
SC	Similarity coefficient
GQL	Greatest queue-length
S/N	Signal to noise

General introduction

Among the many issues involved within the field of manufacturing systems, the design of facilities layout is an ongoing and interesting research field (Dessens, 2003). Facility layout has a significant effect on the performance of manufacturing systems. Between 20%-50% of operating expenses in a manufacturing facility are related to material handling costs (MHC) and a properly designed facility can reduce these costs by 10-30% (Tompkins et al., 2010). However, the impact of the facility layout goes beyond MHC. In addition to reducing material handling costs, this is also likely to reduce the material handling batch size. By reducing the material handling batch size, work-in-process inventory (WIP) will also decrease. Decreasing WIP has a direct cost implication (likely a large one) and is also likely to improve the lead time. Thus, the impact of layout design goes significantly beyond the impact on material handling expenses (e.g., productivity ratios concerning manufacturing cycle, aisle space, and energy) (Sule, 2008).

Finding the facility layout has been studied by many researchers under the topic of facility layout problems (FLPs). FLPs can be defined as one which aims to place the resources or facilities in optimal locations within the designated space available in accordance with some criteria or objectives, subject to satisfying certain constraints. There are many kinds of FLPs, which will be detailed in the next chapter. A classification of them is given, for example, in (Drira et al., 2007).

Most FLPs aim at finding the best position of facilities in manufacturing systems. In addition to optimizing the facilities' positions, finding a good aisles structure in manufacturing systems is a part of the facility layout. The aisles structure contributes to layout efficiency by reducing MHC, mean flow time and the amount of space needed, and providing smooth transportation. Therefore,

to achieve a good layout, it is essential to not only determine the position of facilities such as machines and workstations, but also the corresponding aisles structure. To optimize the aisles structure, the issues such as accessibility of aisles for facilities, calculating material flow distance through the aisles, smooth material flow in aisles, total space occupied by the aisles and safety of aisles also need to be considered. All these requirements increase the complexities in designing aisles so that, as it can be seen in Chapter 2, the problem of designing aisles structure has less been paid attention to in the literature of FLPs.

In this thesis, designing the aisles structure and layout of facilities is studied simultaneously. To this aim, a comprehensive analysis is performed to identify the main requirements and characteristics of aisles structure in manufacturing systems. Through this investigation, it is revealed how a good and efficient aisles structure can be designed. Then, an exact approach based on the mixed-integer linear programming (MILP) model is proposed to find the best positions of facilities and best aisles structure in an unequal area FLP (UA-FLP. The proposed model is solved by a branch and cut algorithm and the global optimum solution is found.

However, it should be mentioned that the design of a layout in manufacturing systems should take into consideration various dynamic and stochastic factors such as transportation time, machine and transporters breakdown, stochastic demand for products and stochastic process time. Therefore, in the rest of the thesis, dynamic and stochastic phenomena of manufacturing systems are taken into account to obtain a more realistic layout. To this aim, a simulation based optimization approach is proposed. Simulation optimization refers to the optimization of a problem subject to constraints, in which the performance criteria are evaluated through a simulation model. It has also been referred in the literature as simulation-based optimization, stochastic optimization, and optimization via simulation (Amaran et al., 2014). In the rest of this manuscript, the term simulation optimization is used. For a FLP, in simulation optimization approaches, layouts are generated by an optimization algorithm and evaluated by a simulation model in an iterative process. Unfortunately, making a connection between simulation and optimization has risen as a big challenge for these types of approaches. Connecting an optimization tool to a simulation tool using an interface can cause a lot of computational time to transfer data. The proposed simulation-

based optimization approach can support a direct connection to handle stochastic and dynamic phenomena of the system in a reasonable computational time and so it is possible to evaluate more solutions. Also, in the proposed simulation optimization the optimization environment is open source. This caused many optimization algorithms such as metaheuristic, heuristic and exact optimization algorithms can be used. The possibility of using different optimization algorithms causes that several layout problems can be model and solved by the proposed approach.

The basic research question answered in this dissertation is how to design an aisles structure in a manufacturing system under the requirements of an efficient layout in a more realistic context and avoiding restrictive assumptions. To achieve the research aim and address this research question, the following sub-questions are introduced each of which is answered in one of the chapters:

1. What are FLPs, aisles and how aisles affect facility layout performance? What are the requirements and characteristics of a good aisles structure in a manufacturing system? To answer these questions, in Chapter 1, different types of FLPs are presented and the problem of aisles in the layout of manufacturing systems is analyzed.
2. What has been done in the literature regarding the optimization of aisles structure in facility layout problems? To answer this question, in Chapter 2, a comprehensive literature review is conducted to study the latest research and developments on optimizing aisles in FLPs.
3. How the optimal position of facilities and aisles structure in manufacturing systems can be found? This question is answered in Chapter 3. First, the decision variables and constraints that best represent the optimal aisles structure and layout parameters are identified. Then, the problem is formulated as a MILP model to generate an optimal solution based on minimizing total transportation distance. An effective optimization technique is applied to solve the model.
4. How the dynamic and stochastic phenomena of manufacturing systems can be taken into account so that a more realistic layout can be achieved? How a suited simulation optimization environment can be useful for this? This question is answered in Chapter 4. To this aim, first, different types of stochastic and dynamic phenomena in manufacturing systems that can be influenced by layout are determined. Then, to consider these phenomena, a simulation model is

developed. This simulation model is connected to a multi-objective metaheuristic algorithm to optimize the problem in terms of two objectives of minimizing total transportation distance and mean flow time.

In order to address these issues, the manuscript is organized as follows. In Chapter 1, we try to explain FLPs, how aisles structure can affect FLP and the necessity of optimizing aisles and FLPs at the same time. In Chapter 2, we conduct a comprehensive review of the literature published in the research area of FLP, focusing on the researches that considered aisles in their FLPs. In Chapter 3, we develop a novel optimization model and an exact optimization algorithm for generating optimal aisles structure and facility layout to minimize the total transportation distance. In Chapter 4, we develop a multi-objective metaheuristic algorithm and a simulation model. In Chapter 5, the findings of the research are explained and the limitations and recommendations for future research work are described.

Chapter 1: Facility Layout Problems and Aisle Structure

1.1 Introduction

In this chapter, the basic concepts of facility layout and different types of facility layout problems are explained. There are many classifications for different types of FLP in the literature. The classification presented in this chapter emphasis on the way of classification based on the characteristics of layout that affect the aisles. These characteristics include the size of the facilities, discrete or continuous formulation of the problem, the time horizon under consideration (static or dynamic layout) and having predefined or un-predefined layout pattern. In the rest of this chapter, the issue of aisles in manufacturing systems is investigated. Through this investigation, the requirements and characteristics of aisles structure in manufacturing systems are revealed.

1.2 Facility Layout

Defining the position of facilities that are required to manufacture a product or deliver service in a given space is called facility layout (FL) (Drira et al., 2007). Any physical entity that facilitates the performance of any job may be considered as a facility; A facility can be a machine, workstation, inspection station, washing station, locker room, manufacturing cell, warehouse, office, lounge, restroom, etc (Heragu, 2018). Since the facility includes a widespread definition, FL arises in manufacturing, warehousing, hospitals, and schools, fire station, police stations, etc. Layout of facilities is an important and fundamental strategic issue in any manufacturing and service system and can have a significant impact on its viability and productivity (Singh & Sharma, 2006a). When developing a facility layout, designers should take into account several constraints such as:

- Certain facility pairs need to be in adjacent sites for safety reasons regardless of the volume of material flow between them. An example is the forging and heat-treatment stations. Due to fire hazards, these two stations must be next to each other even if relatively few parts pass between them (kouki Amri et al., 2016).
- Certain facility pairs need to be located in nonadjacent sites. Sometimes technological reasons dictate that two or more facilities cannot be close together even if a large number of parts have to visit them for successive operations. Because the welding station generates sparks that could possibly ignite flammable solvents in the painting station, the two stations should be in nonadjacent sites, as far apart as possible, although there may be much interaction between them.
- Certain facilities have to be in specific locations. Consider this real-world example: A manufacturing machine uses a fuel that enters the factory through a tube. The tube and the fuel inside it are dangerous and the machine must be always located in the positions where the tube enters the building. If this company plans a layout change, it cannot justify changing the position of the machine.
- Local governmental regulations and hazard insurance company regulations must be observed. For example, fire codes may require a certain number of fire exits. The

occupational safety and health administration (OSHA) regulations include entrance and exits to the manufacturing facility, health and safety norms, requirements that hazardous processes or equipment be located so that employee contact is minimal, and so on.

As a consequence, facility layout is complex to solve. Due to the variety of considerations found in the articles, researchers do not agree about a common and exact definition of layout problems. In this thesis, Facility Layout Problems (FLPs) are defined as finding the best position of facilities in a given space subject to certain design criteria and area limitations, with one or multiple objectives. FLPs are known to be complex and are generally NP-Hard (Garey & Johnson, 1979). It has been tremendously studied as a field in operational research. The most common objectives of the research works in this area include reducing material handling costs, utilizing the available space effectively and efficiently, providing a safe and pleasant environment for personnel, reducing congestion to permit a smooth flow of people and material, and facilitating communication and supervision (Heragu, 2018).

1.3 Different types of facility layout problems

Different types of FLPs have been introduced in the literature. The problems addressed in research works differ depending on factors such as size and shape of the facilities, input data and manner of formulation (Drira et al., 2007). Any combination of these factors determines a different type of FLP.

1.3.1 Equal vs. unequal area facility layout problems

In equal-area facility layout problems (EA-FLP) facilities are considered to have the same size. Therefore, in this type of FLPs, in many cases, the potential locations of facilities are known in advance and facilities are mapped to the locations to find the optimum layout based on the objective function (Xie & Sahinidis, 2008) (see Figure 1.1 (a)).

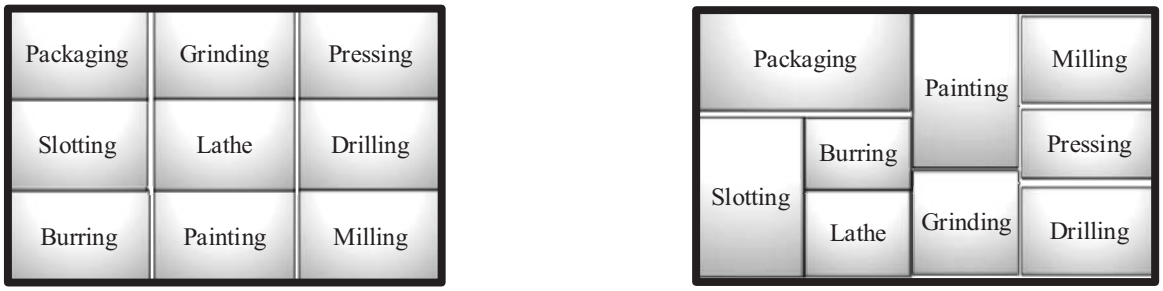

Figure 1.1: (a) A layout with equal size facilities, (b) A layout with unequal size facilities

Unlike EA-FLPs, unequal area facility layout problems (UA-FLPs) do not restrict to consideration of facilities with equal size (see Figure 1.1 (b)). The facilities are placed anywhere within the space available without overlapping (García-Hernández et al., 2015). The focus of this thesis is UA-FLP. In UA-FLP a facility is generally defined as rectangular-shaped with a fixed-length l_i and a fixed width w_i. In this case, the facility is called fixed or rigid block (Chwif et al., 1998). According to Chwif et al. (1998), a facility may be also represented by its area (A_i) and its aspect ratio (α_i). The aspect ratio of facility i is defined as $\alpha_i = {}^{l_i}/_{w_i}$. Therefore, the length and width of the facilities can be changed within an upper bound and a lower bound of α_i. UA-FLP may be formulated as a mixed integer programming (MIP) problem (Dunker et al., 2005). Advantages, disadvantages, and applications of EA-FLP and UA-FLP can be found in (Hungerländer & Rendl, 2013; Keller & Buscher, 2015; Saravanan & Kumar, 2015).

1.3.2 Discrete vs. continuous layout problems

In discrete FLP problems, the potential locations of facilities are known in advance and facilities are allocated to the locations to find the optimum layout based on the objective function (Xie & Sahinidis, 2008). If the locations are capable of accommodating all the facilities, it is categorized as an EA-FLP; otherwise, it is UA-FLP (H. Li & Love, 2000). However, generally, discrete FLP problems is not suited for unequal-area facility layout because unequal-area layout problems introduce different types of additional constraints into the problem formulation.

Discrete FLP problems are often formulated by quadratic assignment problem (QAP) with the objective of minimizing a given function cost. There are two main assumptions in QAP: firstly all facilities are equal size; secondly, the locations of facilities are known in a priori. If there are fewer than *m* facilities to be assigned to *n* locations, then to use the QAP formulation, we can create *n* – *m* dummy facilities and assign a zero flow between each of these and all others (including the other dummy departments). If there are fewer locations than departments, the problem is infeasible. An illustration of nine locations, nine departments, and the assignment of each facility to a specific location is shown in Figure 1.1 (a). A QAP formulation is presented as follows:

$$X_{ik} = \begin{cases} 1 & \text{if facility } i \text{ is at location } k \\ 0 & \text{otherwise} \end{cases}$$

N: Number of locations and facilities

f_{ij}: Flow of material between facilities i and j

d_{kl}: Distance between the locations k and l.

$$Min \sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=1}^{N}\sum_{l=1}^{N} f_{ij} d_{kl} X_{ik} X_{jl} \qquad (1\text{-}1)$$

Subject to:

$$\sum_{k=1}^{N} X_{ik} = 1 \qquad \forall\, i \qquad (1\text{-}2)$$

$$\sum_{i=1}^{N} X_{ik} = 1 \qquad \forall\, k \qquad (1\text{-}3)$$

$$X_{ik} \in \{0,1\} \qquad \forall\, i,k \qquad (1\text{-}4)$$

The objective function (1) minimizes the total material handling cost. Constraint 2 ensures that each facility is assigned to one location and constraint 3 ensures that each location has one facility assigned to it. Finally, constraint 4 indicates that the decision variable is binary

Unlike the discrete facility layout problem, the continuous formulation does not allocate the facilities to locations. The departments are placed anywhere within the space available without overlapping (Dunker et al., 2005). According to Tompkins et al. (2010), for the continuous formulation, the coordinates of the centroid and sides are generally used to define a facilities' position and shape. Continuous facility layout problem may be formulated as a mixed-integer programming (MIP) problem. The MIP formulation can be found in (Dunker et al., 2005).

Dong et al. (2009) described two approaches for representing coordinates, namely discrete and continual, which can be used in the continuous approach. In discrete representations, the underlying grid structure is used for representing the facility, while, in continual representations, continuous coordinates (x,y) are used to represent the location of the facilities, which serves to enhance accuracy but makes the model more complex (Dong et al., 2009). Advantages, disadvantages, and applications of these two methods can be found in (Hungerländer & Rendl, 2013; Keller & Buscher, 2015; Saravanan & Kumar, 2015).

1.3.3 Static vs. dynamic facility layout problems

Facility layout problems can be either classified as static facility layout problems (SFLP) or dynamic facility layout problems (DFLP), depending on the nature of input requirements and the time horizon under consideration. The SFLP arises when the flow of materials between the facilities is deterministic and constant during a planning horizon (Kuppusamy, 2001). A planning horizon encompasses the duration of time considered while solving the layout problem. Material flow is calculated based on the product demand and product mix. Product demand is the quantity of each part type to be produced and the product mix refers to a set of part types to be produced. The SFLP approach is a suitable method for analyzing a single period layout problem by considering that the product demand is stable for a long time period (Balakrishnan & Cheng, 1998).

On the contrary, a DFLP approach generally arrives when flows of material between facilities change during the planning horizon. In DFLP, the planning horizon is divided into some periods and in each period the flow between facilities is known. The layout for each period can be

optimized based on its corresponding material flow. Therefore, the layout may be changed between periods. Figure 1.2 presents a DFLP for nine equal-area facilities in three periods. During the process of changing the layout rearrangement costs arise. Rearrangement costs can be defined as the cost of shifting from one layout in one period to another in the next and depends on the departments involved in this shift. A comprehensive review of the DFLP can be found in (Balakrishnan & Cheng, 1998; Kulturel-Konak, 2007; Moslemipour et al., 2012; Zhu et al., 2018).

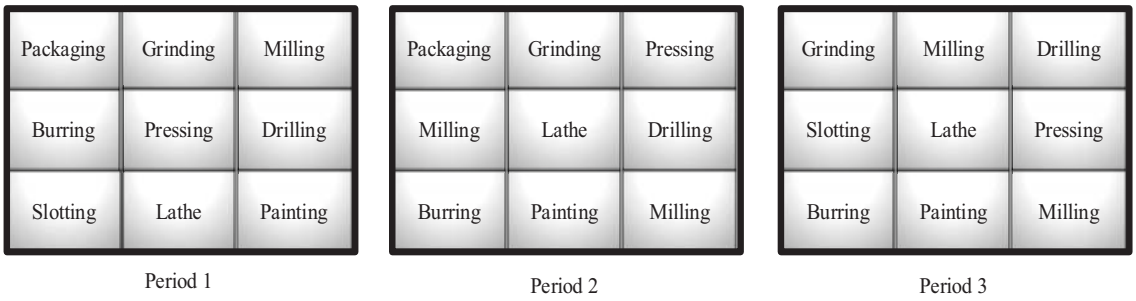

Figure 1.2: An example of changing the layout in each period in DFLP

1.3.4 Predefined vs. un-predefined layout patterns

Sometimes facilities have to be placed on the shop floor in a predefined pattern. For example, they are placed consecutively in a straight line. This means that the layout pattern is predetermined as a straight line. There are different types of predefined layout patterns such as single-row layout, loop layout and multi-rows layout (Yang et al., 2005). In a single-row layout, the facilities are better to be placed according to the sequence of products operations. In this situation, materials typically flow from one facility directly to the next adjacent one. Figure 1.3 shows several types of predefined patterns (Tompkins et al., 2010).

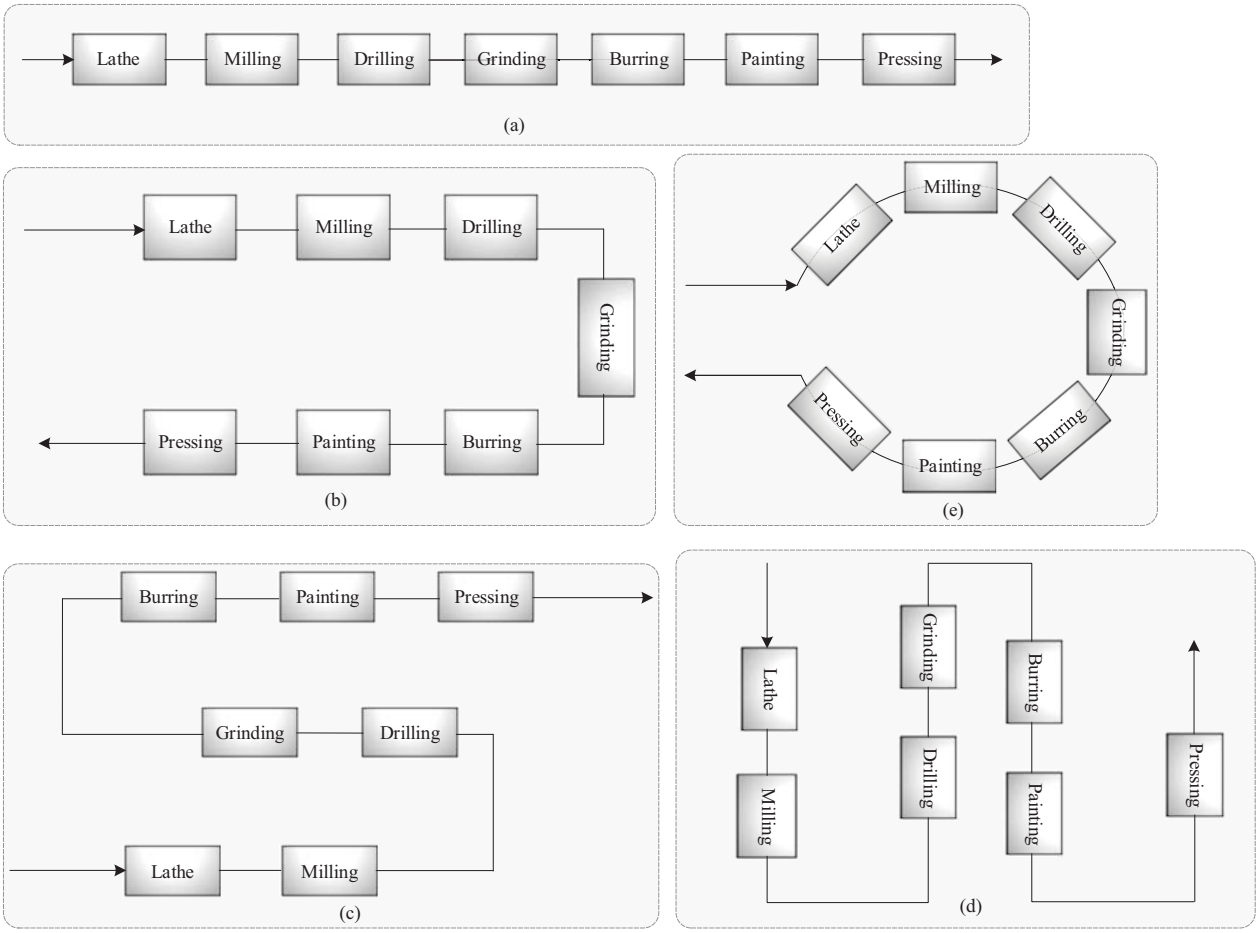

Figure 1.3: Predefined layout patterns for single-row FLP. a) straight-line, b) U-shape, c) S-shape, d) W-shape, e) circular-shape

A common type of predefined layout pattern is the loop layout pattern. The loop layout is characterized by the presence of a loop that services the facilities around it. The facilities are positioned either in the inside of the loop or along the outside area of the loop. A multi-row layout deals with several rows of facilities taking into consideration that the material handling flow can be among facilities from the same row or different rows (Cheng et al., 2001; Kim et al., 1996; Ficko et al., 2004). If the pattern of the layout is predefined, it can be mathematically modeled as a discrete FLP in which the problem is simplified to finding the optimum sequence of facilities.

On the contrary of predefined layout patterns, there are un-predefined layout patterns. The un-predefined layout patterns correspond to the situations where the general pattern of the layout is unknown in advance. In an un-predefined layout pattern, the problem is generally modeled as a continuous formulation in which the problem is finding the optimum coordinates of the facilities. In this thesis, the continuous formulation of an un-predefined layout pattern is studied.

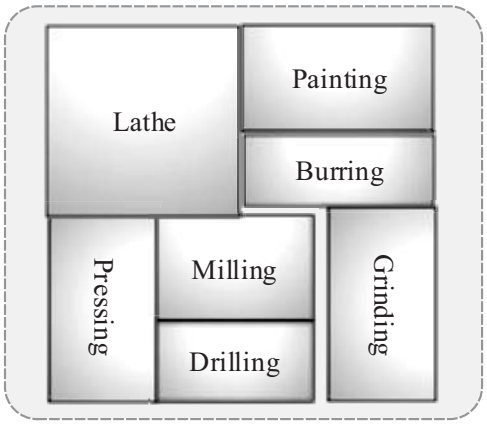

Figure 1.4: An example of an undefined layout.

1.4 Aisles

1.4.1 Function of aisles

Inside a manufacturing system materials need to be moved between facilities to be processed. Aisles are the areas on the shop floor that are used for material and human transportations. An aisles structure is defined as a set of aisles that are connected together. Determining the aisles structure means determining the position, shape, width and length of each aisle. An aisles structure has fundamental effects on system performance. Aisles may or may not be the major material carrier routes. It depends on the type of MHE used. If equipment such as fork-lifts, AGVs, tow-tractors, mobile cranes, and conveyors are used, aisles are required (conveyors need aisle space for rails) and aisles form the main artery of the material movement. The manufacturing system with bridge cranes or gantry cranes does not need aisles for material handling. Nevertheless, aisles

in these types of systems are required in particular for the movement of workers. The aisles are also required for quick evacuation in case of an emergency. The next subsections describe and analyze the characteristics and requirements of the aisles. Some of them are absolutely necessary and must be considered in designing the aisles and some others are required to increase the efficiency of the aisle.

1.4.2 Accessibility of aisles

Accessibility is the initial requirement of any aisles structure. Accessibility means that transportation devices and workers can reach every facility through the aisles structure. This connection happens between the aisle and Pick-up/dropoff (P/D) points of the facility. P/D points, shown in figure 1.5 by red circles, are some places around the facility where the material handling system loads or unloads the material required for that facility (Rajagopalan & Heragu, 1997). In this way, it is feasible for all facilities to receive new products and deliver processed products. Without careful attention to aisles accessibility, some facilities may have no possibility to receive and to send the products. For example, as shown in Figure 1.5 the facility 4 has no access to the aisles.

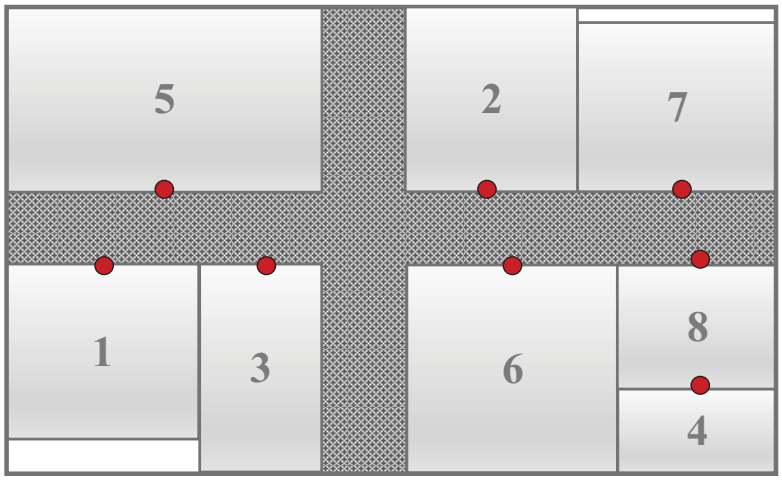

Figure 1.5: An example of accessibility of aisles

Also, aisles structure must be designed in a way that between each pair of facilities there is a path through aisles. For example, in Figure 1.6, facilities 1, 7 and 8 have no access to facilities 2, 5 and 9. Therefore, for instance, it is impossible to produce a product with processing route 1→9→3.

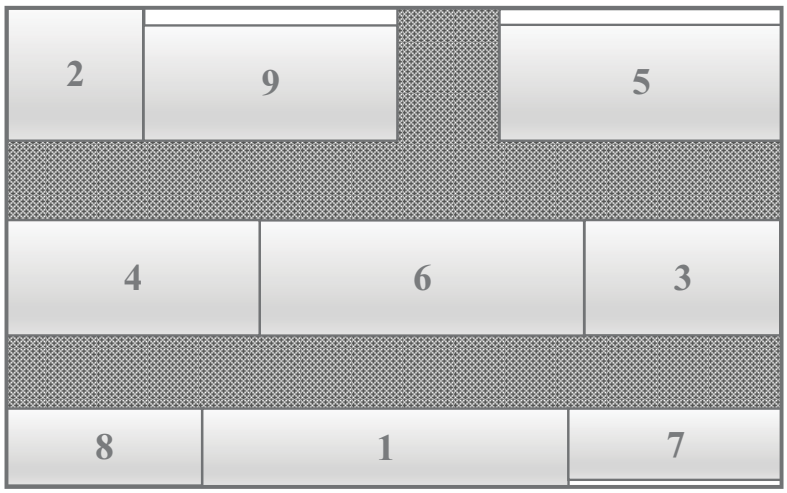

Figure 1.6: An example of accessibility of aisles

Another issue concerning aisle accessibility is related to entrance and exit doors. Entrance and exit doors are locations where the parts, the raw material, and the transportation devices enter and exit from the manufacturing system. When products enter the system, they should have access to the first facility in their processing route. Consequently, the aisle structure is necessary. In fact, determining the location of entrance/exit doors and connecting them to the aisles structure is strongly associated with the FLP. The entrance/exit doors need enough space for loading/unloading operations. Sometimes constructing entrance/exit doors in some parts around the building is not possible. For example, if there is a parking lot next to one side of the building or some parts of the building are in the vicinity of another building so that there is not enough space for loading/unloading operation. These technical and environmental limitations cause all the points around the building not suitable to be considered as potential points for entrance/exit doors. In this situation, only some segments around the building are feasible for constructing entrance/exit doors. Therefore, determining the best position of the entrance/exit door is an important part of the layout problem.

1.4.3 Aisles based distance

Since transportation is done through the aisles, the aisles should be so as to reduce transportation times. This is one of the most important objectives in designing the aisles. In most approaches, which do not take aisles into consideration, Euclidean or rectilinear distances are used to calculate the distance between facilities (Friedrich et al., 2018). Euclidean distance measures the direct distance in the form of a straight line while rectilinear distance is the sum of the differences in Cartesian coordinates. Neither of these two measurement techniques can be considered accurate (Besbes et al., 2020), especially in the form of centroid-to-centroid, because of two reasons. First, the flow from a facility to another does not typically start or end at the facility's center. Second, these measurements assume flow through other facilities rather than through the aisles which is not typical in an actual factory. According to Minier (2019) using a none aisle-based distance to calculate flow distances results in a layout with a 35% to 230% loss of optimality. Figure 1.7 shows this inaccuracy to calculate the distance between facilities 4 and 9. In this figure, the black line shows the rectilinear distance and the white line shows the aisles based distance. An aisle-based distance ensures flow feasibility is implemented when calculating the distance between facilities. Therefore, it is of great importance to include aisles structures in the layout and simultaneously determining aisles structure and positions of facilities.

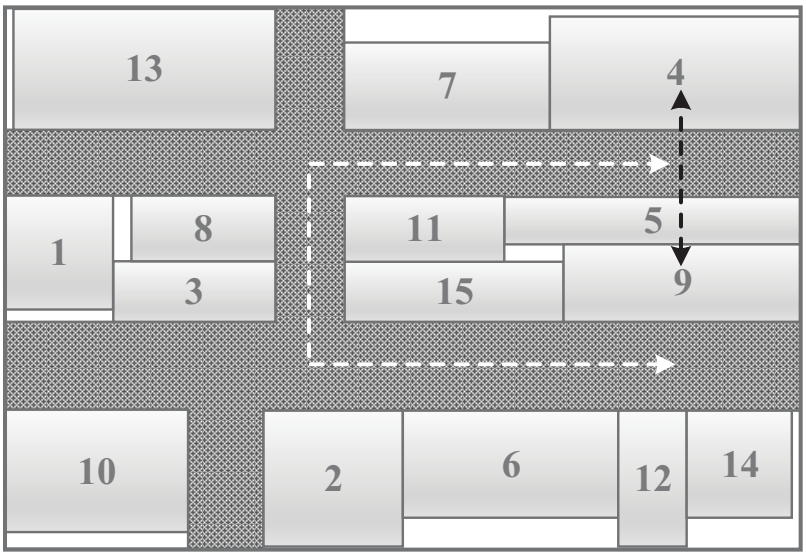

Figure 1.7: A comparison between aisle-based distance and rectilinear distance

1.4.4 Smooth material flow in aisles

One of the objectives of the aisles is to prepare a smooth flow of materials between facilities. To this aim, transporters need to move between facilities without being blocked or interrupted. The most effective factor in blocking the transporters is the width of the aisles. Aisle width refers to the lateral distance between two opposing sides of an aisle. It determines the number of transporters that can pass each other within the aisle. The wider aisles are good because they help to smooth the flow by allowing two or more transporters to pass through an aisle at the same time otherwise one of them has to wait until the aisles get empty. The width of the aisle must be large enough so that when a transporter waits on the aisle to complete a load/unload process, the path does not get blocked. According to Tompkins (2010), aisle widths should be determined by considering the type and volume of flow to be handled by the aisle.

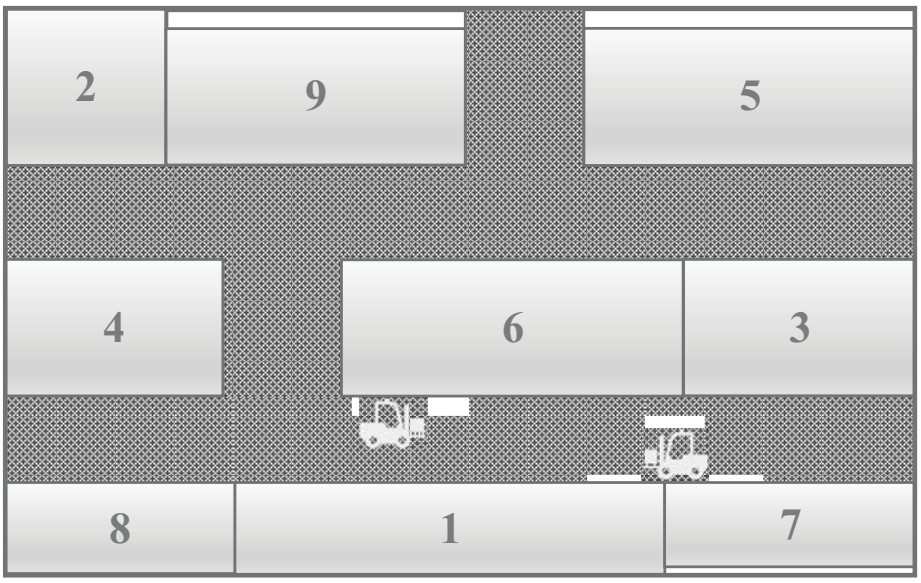

Figure 1.8: An example of passing two transporters through an aisle at the same time

Another issue concerning smooth material flow in aisles is intersections. The intersections in the aisles cause workflow interference and weaken the smooth flow of materials. Several authors have identified workflow interference as a major concern in traditional facility layout design (Chiang et al., 2006). Tompkins and White (1984) discussed the importance of minimizing

interruptions on aisles and recognized that the effect of interruptions results in undesirable congestion. Apple (1972) acknowledged taking the necessary precautions to avoid cross traffic. Luggen (1991) also noted the benefits of eliminating complex material flow patterns, stating ‘‘complex material flow patterns create an extensive part move and queue time, result in lost or misplaced parts, and contribute to damaged parts due to excessive movement’’. Therefore, the number and position of the aisles should be determined so as to avoid intersections and interruptions. Also, since the transporters have to decelerate to turn around, the transportation time will increase and this yields security problems. Hence, as Tompkins et al. (2010) mentioned, curves, jogs, and non-right angle intersections should be avoided in designing the aisles structure and aisles should be as straight as possible and unnecessary turns should be eliminated. Figure 1.9 is an example of an aisles structure with numerous turns. However, as we will see in the next chapter, many articles have proposed aisles structure with a high number of turns.

According to the Health and Safety Executive (HSE), sharp or blind turns in aisles should be avoided. Otherwise, equipment such as mirrors should be used to improve vision if these turns are unavoidable.

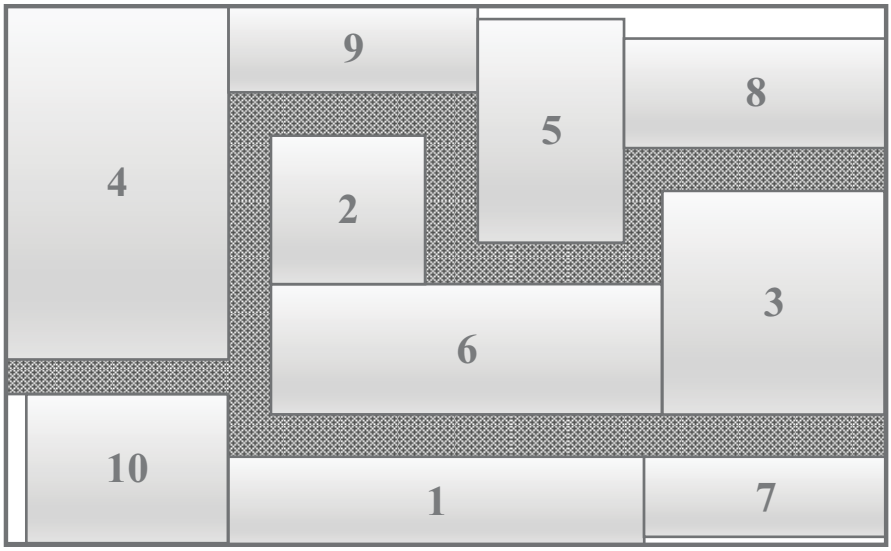

Figure 1.9: An example of an aisles structure with a high number of turns

1.4.5 Aisle space

Aisles spaces are defined as the spaces on the floor that are specifically assigned to aisles where no facilities are placed. Facilities and aisles must not overlap. The space between workstations or machinery, should not be considered as aisle space because of safety or maintenance access (Lin & Sharp, 1999). The aisle space is calculated based on the number of aisles and the length and width of each of them. According to Tompkins et al., 2010 a designer needs to consider that generally between 5% and 40% of the total floor space is occupied by aisles which is valuable floor space. Designing aisles that are too wide may result in wasted space. Conversely, designing aisles that are too narrow may result in congested facilities and safety problems. So it is important to balance the floor that is space dedicated to aisles. For higher space utilization, aisles along the wall of a manufacturing plant should be avoided. Figure 1.10 (a) and Figure 1.10 (b) are two examples for designing too narrow and too wide aisles, respectively.

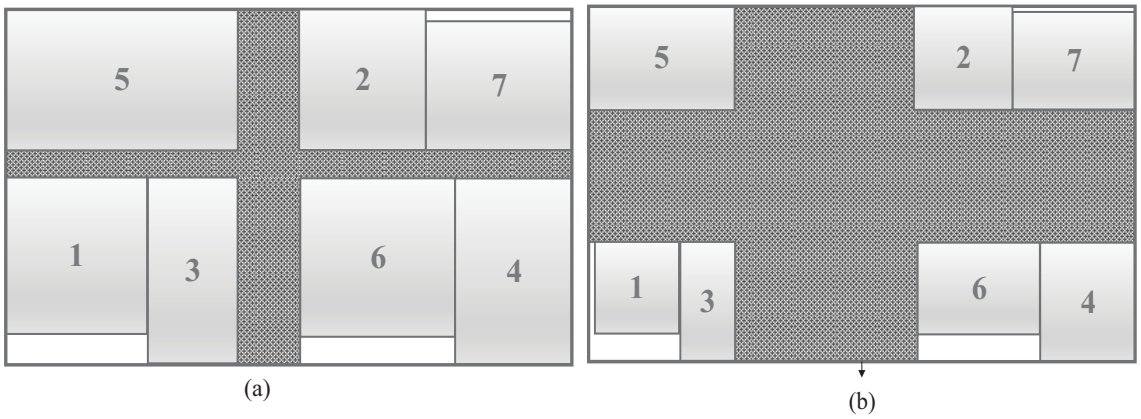

Figure 1.10: (a) An example of a too narrow aisles structure (b) An example of a too wide aisles structure

Aisles are used not only for handling the materials between facilities but also for moving the facilities. In case of a facility breakdown (machine breakdown, AGV breakdown, etc.) if it is not possible to repair it at the place, the facility should be moved out of the manufacturing plant. Therefore, aisles should be wide enough to make it possible to transfer the whole facility or the largest disassembled part of the facility out.

1.4.6 Aisle orientation

Diagonal aisles should be avoided because they can cause unusable space within the shop floor if the angle between aisles at an intersection is too small (see Figure 1.11). As shown in Figure 1.11, diagonal aisles would lead to an asymmetric structure and so the unused space would increase. Besides, extreme aisle angles could also hinder usable aisle space as transportation devices may not be capable of making a sharp turn.

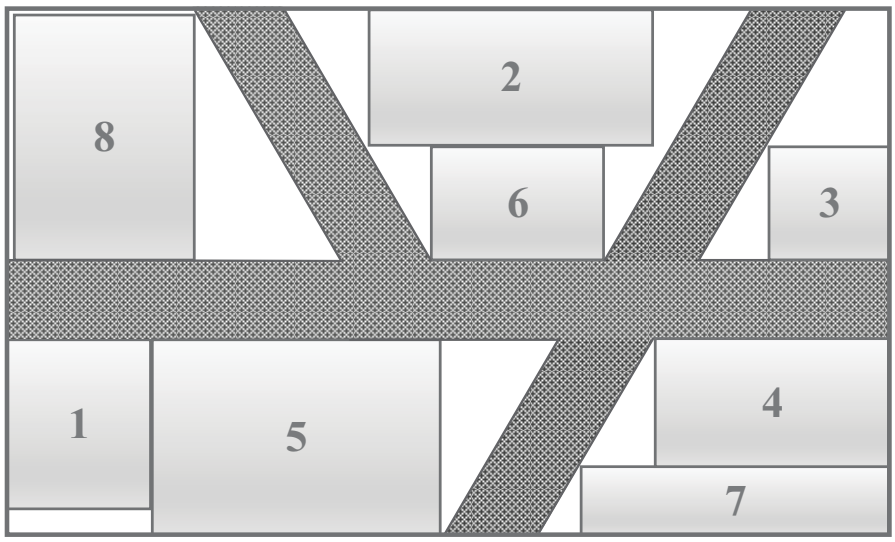

Figure 1.11: An example of diagonal aisles that lead to wasting the space on the floor

1.4.7 Aisles and safety

Another issue concerning the aisles is safety issues. The safety issues come forth when people and material handling equipment use the same aisles. According to HSE, aisles must be far enough away from doors or gates that workers use, or from pedestrian routes. This way, the safety of workers is not threatened. A common practice is to clearly mark the paths used by the people. According to OSHA, an aisle marking with a width of 2 inches or more is acceptable.

A simpler structure that has longer aisles with fewer corners will increase safety (Tretheway & Foote, 1994). Complex aisle structures with short aisles and excessive turns also increase the probability of an accident and are undesirable from a safety point of view (Kim, 1992). According to Health and Safety Executive (HSE), aisles should avoid passing close to any edge, or anything that is likely to collapse or be left in a dangerous state unless it is fenced or adequately protected.

1.4.8 Aisles and alternative routes

The alternative routes are defined as the number of possible routes that can be used to transfer a part between two facilities. Once a layout has a good aisles structure design, it supports alternative routes to access a facility. This is useful in a situation where an aisle is blocked because of unforeseen events. By blocking an aisle, the pathway will be shut and transporters need to access facilities through another pathway. There are two alternatives to eliminate this undesirable situation. Either the aisles should be wide enough so that no blocking happens or the aisles be designed in such a way that facilities can be accessed through alternative pathways. Figure 1.12 shows how the effect of blocking can be removed by having a wide aisle or an aisle structure with alternative routes.

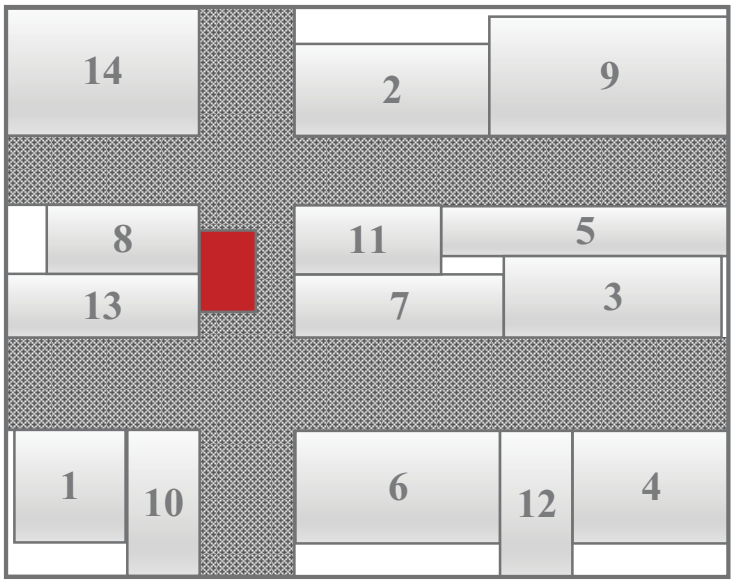

Figure 1.12: An example of blocking in the aisles

1.4.9 Aisles for predefined layout patterns

According to subsection 1.3.4, in predefined layout patterns, the facilities cannot freely be placed on the shop floor and they should be placed consecutively. This results that the aisle structure in these types of layout problems is somewhat predefined and is align and parallel to the boundary of facilities. Figure 1.13 shows a possible aisles structure in predetermined FLPs.

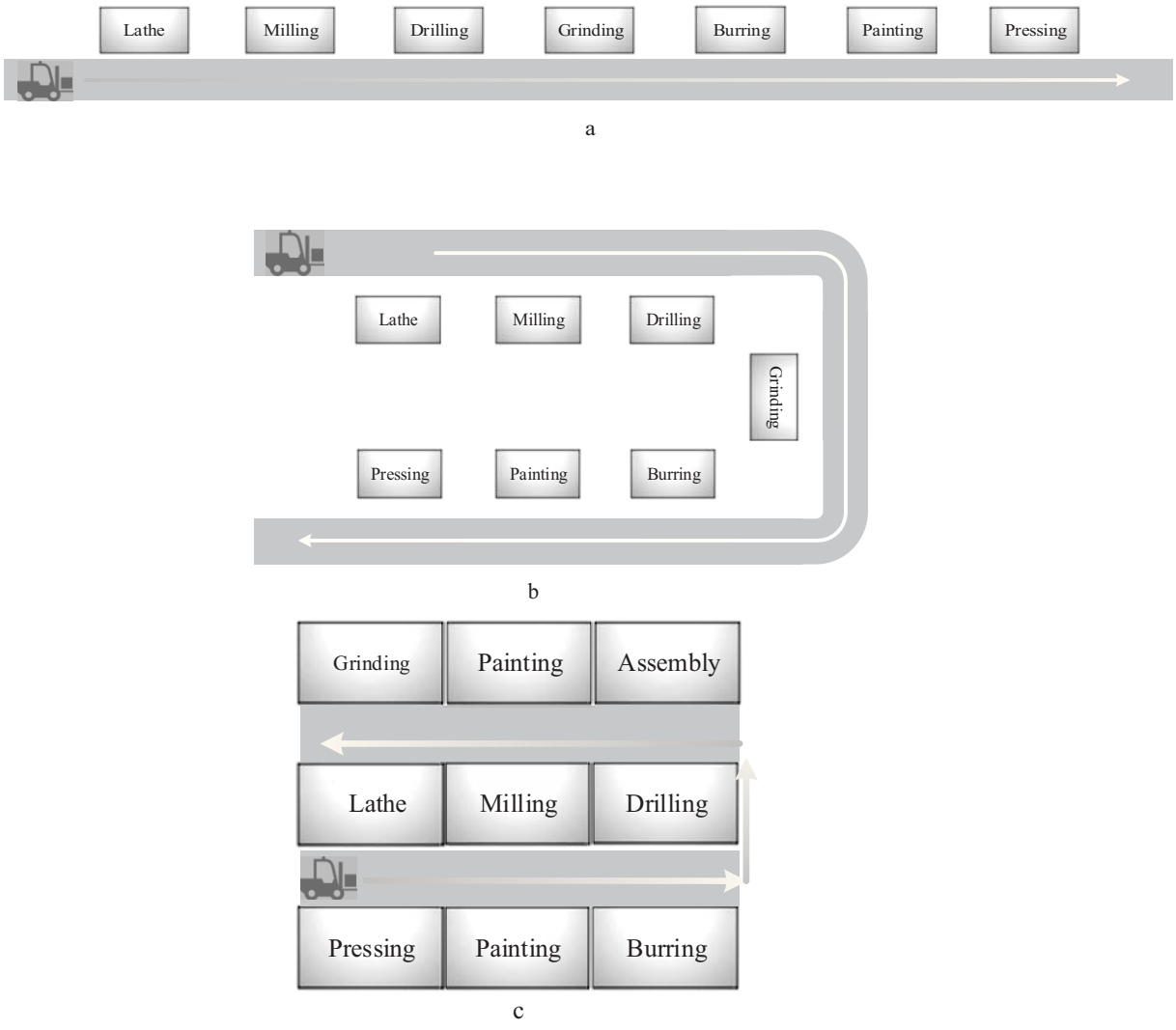

Figure 1.13: Aisle structure in predetermined layout. (a-b) single-row and (c) multi-row layout

The problem of optimizing aisles structure in FLPs with un-predefined layout patterns, which is the main focus of this thesis, is complex because in these problems, facilities are allowed to be placed in any possible position on the shop floor and so aisles can be placed in any possible position of the floor. Therefore, we need to determine the exact coordinate of each facility and aisles.

1.5 Conclusion

In this chapter, first, different types of FLPs were presented. Second, the issue of aisles structure in manufacturing systems was analyzed and the main characteristics and requirements of the aisles structure were investigated. Through this investigation, it was shown that aisles structure has an important effect on the system performance and should be optimized as a part of the facility layout. Therefore, not only the position of facilities but also the structure of the aisles should be determined. However, the complexity of this problem depending on the type of FLP can be medium to very high. The highest complexity happens when the facilities have unequal sizes, the layout pattern is unknown in advance and the problem is solved in a continuous manner. In this type of FLPs, the facilities are allowed to be placed anywhere on the shop floor. This leads that aisles can be placed anywhere on the shop floor as long as the aisles requirements are satisfied. The rest of this thesis is focused on this problem, after analyzing the literature and understanding the gaps.

Chapter 2: Literature review

2.1. Introduction

Many articles have been published in the area of FLPs. Therefore, the literature of FLPs is rich and there are many survey articles in this area (see the articles by Drira et al. 2007; Kusiak & Heragu, 1987; Meller & Gau, 1996; Singh & Sharma, 2006b). We are interested in the articles that have taken aisles into consideration in FLPs. The problem of designing aisles structure in FLPs depends on whether the layout pattern is predefined or un-predefined. Since the main focus of this thesis is on the incorporation of aisles structure into FLPs with un-predefined layout patterns, this chapter covers only the studies that have addressed the optimization of aisles structure in FLPs where the general layout pattern is not predetermined. The analysis of the published literature in this area is performed in accordance with:

1. Whether the aisles space is considered or not. As it was mentioned in chapter 1, the aisles occupy considerable space on the shop floor. However, in many articles, it is assumed that the aisles do not occupy a space and borders around the facilities are considered as a candidate aisles structure.
2. Whether the optimization of the facility layout and the aisles structure are performed in an integrated or non-integrated manner. The non-integrated here means that the layout of

facilities and the aisles structure are optimized in two separate steps. To elaborate, in the first step, the facilities are placed on the shop floor and in the second step, some of the borders of facilities are considered as aisles.

Based on the two mentioned issues, the literature is classified into three groups which are explained in the next subsections.

2.2. Non-integrated approaches without aisle space requirements

The articles in this group consider that the borders of facilities are used as aisles, and so assume that aisles occupy no space or a negligible space on the shop floor. In these articles, the position of facilities and aisle structure are determined in two separate steps and are not optimized simultaneously. In all of these articles, except Tretheway and Foote (1994), the position of facilities is first optimized, and then some parts of the borders of the facilities are selected as aisles. In Tretheway and Foote (1994), first, the aisle structure was determined and then the departments were located around the aisle structure. The aisle structure consisted of the main aisles in conjunction with sub-aisles. The main aisles were single-direction parallel aisles running the full length of the plant. Sub-aisles were perpendicular to the main aisles and did not cross any main aisles. Norman, Arapoglu, and Smith (2001) presented a tractable method for concurrently optimizing the shapes and location of the departments and the number and the position of input/output (I/O) points for each department. In their model, they identified an aisle structure that contains un-capacitated, bidirectional aisles. A genetic algorithm (GA) was applied to select the best departmental boundaries to be used as aisles. Wu and Appleton (2002) proposed a two-stage method for designing a facility layout and an aisle structure. In the first stage, the location of the facilities was determined so that MHC was minimized, and all the borders around the facilities were considered as the aisle structure. In the second stage, the aisle structure was modified to minimize the number of aisles. In this way, by taking into account the pick-up/drop-off (P/D) points of facilities, the redundant aisles were removed. Minimizing the MHC was considered as an objective function (OF) in which the shortest path between the P/D points of two departments

via the aisle structure was used to calculate the distance between facilities. GA and random search methods were applied and compared to optimize both stages. In Alagoz, Norman, and Smith (2008), the borders around the departments were considered as the candidate aisles and a hierarchy algorithm was used to select the final aisles. In their approach, first, a layout based on a flexible bay structure was obtained, and then a heuristic procedure was applied to construct candidate aisles without significantly changing the areas of the departments. Lastly, the final aisle structure was obtained through an enumeration algorithm. Xiao, Xie, Kulturel-Konak, and Konak (2017) presented a MILP model for the dynamic facility layout problem. The objective of the model was to minimize the total MHC and re-layout costs over multiple planning periods. The authors considered a rectangular area for each facility and mentioned that the zone boundaries of the facilities are possible locations to place aisles and material-handling equipment. Friedrich et al. (2018) presented an approach for the efficient arrangement of facilities and their I/O locations within a floor area to minimize the total transportation distance. In their research, the boundaries of the departments were considered as the aisles and each facility had one I/O point next to an aisle.

The approaches reviewed in this subsection do not take into account the spaces occupied by the aisles. As Friedrich et al. (2018) mentioned, the space in use by the aisles is an important consideration in designing the aisle structure. Aisles spaces are passages between workstations or machines to allow free movement of workers and transportation devices on the floor. In a real layout, aisles require significant floor space and ignoring this issue may lead to a layout with low efficiency in terms of workers' and transportation devices' movements.

2.3. Non-integrated approaches with aisle space requirements

The articles reviewed in this subsection consider the use of non-integrated approaches but take into account the space required for the aisles. Benson and Foote (1997) considered locating the I/O points for the departments and selected the best aisle structure among a set of aisle structures, with both vertical and horizontal aisles. A genetic algorithm was applied to find the best location of I/O

points on several pre-determined aisle structures. Zhou, Ye, Cao, and Ye (2006) discussed a particular multi-objective facility layout problem with aisles. The first objective was to minimize the total material handling costs. The second objective was to maximize the adjacency requirements between the facilities, which means, for example, placing some facilities as far apart as possible (due to some factors such as noise, dust, or safety reasons). The problem was formulated as a bi-criteria nonlinear mixed-integer programming model. They fixed some spaces and considered them as aisles for moving the transportation devices. A multi-objective genetic algorithm with a local search method was developed to obtain the Pareto solutions. Li (2011) studied the problem of the optimization of aisle structure and department allocation for the layout of a retail area. First, a set of potential aisle structures were defined. These structures were evaluated by exposure metric. The exposure metric is the probability that a point in the retail area is noticed by customers. Then the department allocation problem was solved. They considered central aisles and branch aisles, which divided the entire retail area into a number of sub-areas. Wang and Chang (2015) developed a two-stage model called spine bay layout to allocate the workstations to several inter-bay systems to minimize the MHC. In their approach, a central vertical aisle was used for inter-bay material handling. This vertical aisle was connected to a set of horizontal aisles that were used for intra-bay material handling. To optimize the spine bay layout, a two-stage mixed-integer programming (MIP) model was developed. In the first stage, each workstation was allocated to a bay, and in the second stage, the exact position of the workstations inside their relevant bay was determined. Allahyari and Azab (2018) proposed a mathematical model for FLP which considered operations sequence, parts demand and aisle structure. They used one central horizontal aisle or one central vertical aisle in the middle of the shop floor. The position and the width of the aisles were predefined. By considering a horizontal aisle in the center of the floor, the floor was divided into two horizontal levels. Minimizing the total distance traveled by materials between facilities was considered as the objective function. A multi-start search simulated annealing algorithm was developed to solve large instances of the problem, in which a unique heuristic algorithm was used for initialization. Even if the second group's articles were concerned with the aisle structure, where aisles occupied spaces on the floor, they did not explicitly address how to define the problem of designing the aisle structure and the position of facilities simultaneously. Solving these problems sequentially can result in solutions that are far from the global optimum solution (Hu et al., 2007).

2.4. Integrated approaches with aisle space requirements

The previously discussed articles tried to find an aisle structure before or after determining the position of facilities. In these articles, the aisle structure and the facility layout were determined in two separate steps. The articles reviewed in this subsection study the problem of optimizing the aisle structure and facility position in an integrated manner. Peters and Yang (1997) investigated the position of facilities and aisles for a material handling system design integration problem in the semiconductor manufacturing industry. They proposed a methodology to solve this integrated design problem. In their approach, the aisle structure was limited to having aisles around the floor or one central aisle. Gomez, Fernandez, De la Fuente García, and Garcıa (2003) designed a GA that incorporates vertical aisles in the plant layout problem. Their aisle structure was limited to a set of vertical aisles. Lee, Roh, and Jeong (2005) proposed an improved GA for multi-floor FLP considering vertical and horizontal aisles. The best position of facilities and aisles on each floor was determined to satisfy the two objectives of minimizing total transportation costs and maximizing adjacency requirements between facilities. They assumed that the number and width of each vertical and horizontal aisle on each floor were given by the designer. Chang, Lin, and Lin (2006) addressed an optimal multiple-floor layout with aisles. In their study, the aisle structure was determined during the layout construction stage simultaneously. A K-means clustering algorithm was applied in order to group the departments which were allocated to the same floor. Then a hybrid genetic algorithm was used to improve the layout on each floor. Klausnitzer and Lasch (2016) proposed an MIP approach to simultaneously optimize the aisle structure and the position of facilities. They assumed that the aisles have a predefined width and can be placed around the facilities and next to the floor space borders. By this assumption, they used the rectilinear distance metric to calculate the distances between facilities. Table 2.1 is a summary of the reviewed researches.

2.5. Conclusion

It is evident from the literature that only a few pieces of research have dealt with optimizing aisles in FLPs. Even though these researches have taken the issue of optimizing aisles into account,

many essential requirements of the aisles structure, described in chapter 1, have not been taken into account. In fact, none of these researches have explicitly addressed the dos and don'ts in designing the aisles structure. Therefore, many requirements of the aisles have not been studied in them. For example, regarding the accessibility issue, the previous research works have not considered the locations of entrance and exit doors and how to connect them to the aisles. Also, optimizing the aisles' width, which affects the issue of smooth material flow, aisle space and safety have not yet been considered. Besides, they often have used very simple structures for the aisles (such as one central aisle or aisles located only on the borders of the shop floor). Moreover, only very few of these researches have addressed more complex aisle structures that combine vertical and horizontal aisles. These researches either have used a predefined number of aisles, have not provided an exact approach, or have not optimized the position of facilities and the design of the aisles structure simultaneously.

As a consequence of these limitations, in the next chapter, an exact approach is proposed to simultaneously determine the layout of facilities as well as the aisle structure satisfying the requirements related to the design of aisle structure.

Chapter 3: An exact approach

3.1. Introduction

The main aim of this chapter is to propose an exact approach to simultaneously find optimum aisles structure and layout of facilities. In this approach, the problem is described and then is modeled through a mixed-integer mathematical programming technique. Afterward, an exact optimization algorithm is applied to solve the model and obtaining a global optimum solution. In this regard in Section 3.2, characteristics of the layout problem under study are described. In Section 3.3, the model outline, notation set and formulations are presented. Section 3.4 presents the designated algorithm to solve the model. The computational experiments are shown in Section 3.5.

3.2. Problem description

We define a set of characteristics for the aisles structure and facilities. Through these characteristics, the requirements of aisles structure, mentioned in chapter one, are fulfilled. The aisle structure consists of vertical and horizontal aisles where the horizontal aisles are extended to the boundaries of the shop floor and a single vertical aisle connects two consecutive horizontal aisles. Extending horizontal aisles to the boundaries of the shop floor creates long and straight aisles that are desirable in manufacturing systems (Kim, 1992; Stephens & Meyers, 2013). Furthermore, this structure helps to reduce the number of turns and provides smoother, faster and safer transportation (Friedrich et al., 2018; Leno, Saravanasankar, & Ponnambalam, 2012). Also, vertical and horizontal aisles cause that available space for placing the facilities are rectangle which leads to decreasing unused space. Therefore, this type of aisles structure contributes to a smooth material flow in aisles and better utilization of the space and increases safety.

It should be determined entrance/exit doors on the top and down side of the manufacturing system so that the aisles structure is connected to. It should be noticed that due to technical or environmental limitations, some possible points are only allowed for constructing entrance/exit doors. Determining the entrance and exit door is concerned with the issue of aisle accessibility as an initial requirement of the aisles structure. Each machine along with its required surrounding space is considered as a rectangular-shaped facility. There is a fixed point at each facility that is used to pick-up/drop-off the products from/to that facility, named P/D point. Facilities can be rotated clockwise with one of four angles: 0°, 90°, 180°, and 270°. Hence, they can be placed either in a horizontal orientation, where the longer side of the facility is parallel to the x-axis or in a vertical orientation, where the longer side of the facility is parallel to the y-axis (Figure 3.1).

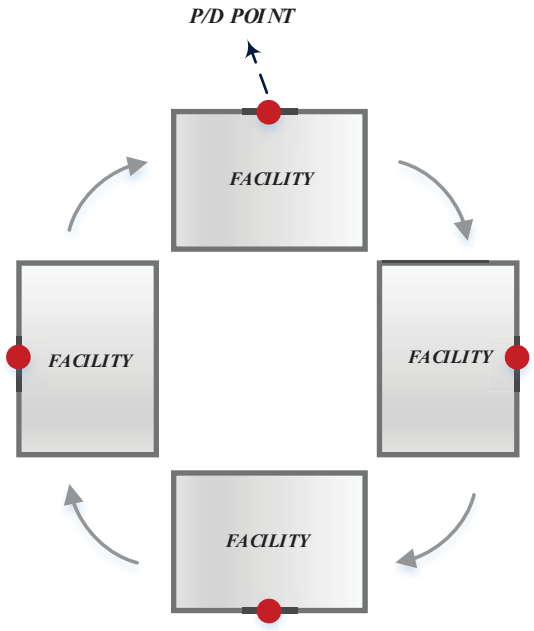

Figure 3.1. Location of P/D point according to facility rotation

Based on the analysis, the essential decision to accomplish the objectives and requirements of the problem are identified as follows:

1) Number of aisles.
2) Position and orientation of aisles.
3) Width and length of the aisles.
4) Position of the facilities
5) Orientation of the facilities

In addition to the above-mentioned decision variables the position of entrance and exit doors should be determined so that they are connected to the aisles and so the following decision variable needs to be determined:

6) Position of the entrance and exit doors

By optimality making these decisions, the optimum design of the floor of the manufacturing system concerning aisle structure and facility layout is achieved.

Figure 3.2 illustrates a typical layout according to the problem characteristics, decision variables and constraints. In this figure, the green lines on the edges of the shop floor are possible areas to construct the entrance/exit doors. In this layout, for example, facilities 7, 10, 12, 19 and 20 are supplied by a horizontal aisle and facilities 9, 5 and 25 are supplied by a vertical aisle. Some facilities such as 2, 4 and 9 are placed in their horizontal orientation and others, such as 1, 3 and 20, are rotated and placed in their vertical orientation. Since facilities can be located in any position in the continuous space of the shop floor, placing the facilities with a suitable orientation to minimize transportation distances is merely a complex problem. Integrating the aisles and entrance/exit doors into the problem increases this complexity. In the next section, a mathematical model is proposed to address this problem.

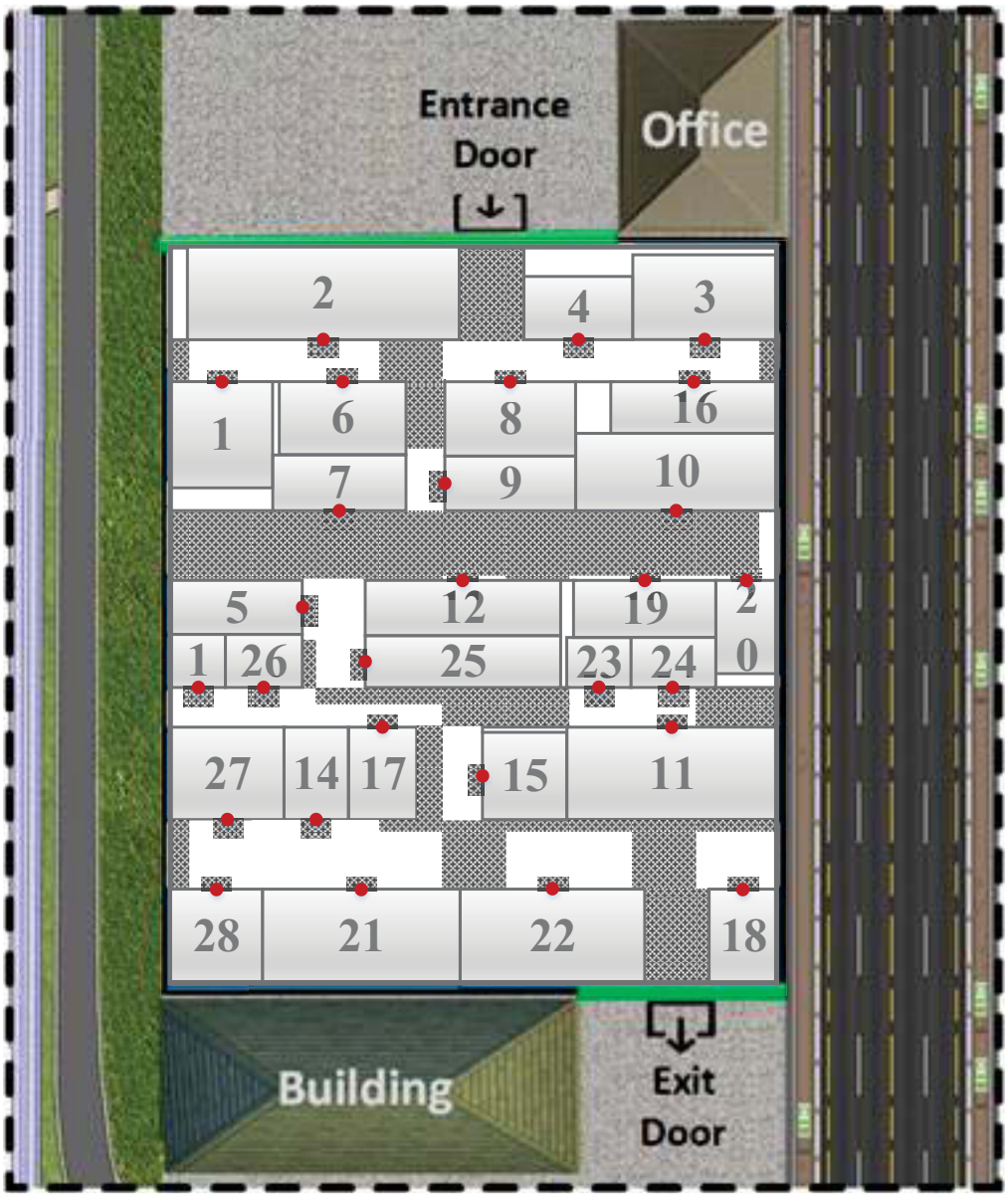

Figure 3.2. An example of a layout of facilities, aisles structure and location of entrance/exit doors.

3.3. Problem formulation

In this subsection, a mathematical model that copes with the considerations discussed in subsection 3.2 is proposed. It is shown that the problem can be formulated using a mixed-integer linear mathematical model.

3.3.1. Notations

The notations used in the model are presented in Tables 3.1-3.3. In particular, Table 3.1 gives the notation for the sets adopted. Table 3.2 outlines the parameters used in the model. Table 3.3 presents the variables within the model

Table 3.1: Notation of Sets and Indexes

i, j	Index set of facilities $i, j = 1, 2, \dots, N$
k, l	Index set of horizontal aisles $k, l = 1, 2, \dots, K$
m, n	Index set of vertical aisles $m, n = 1, 2, \dots, K-1$
p	Index set of levels $p = 1, 2, \dots, K+1$

Table 3.2: Notation of defined Parameters

$length$:	Length of the plant floor along the *x*-axis
$width$:	Width of the plant floor along the *y*-axis
$f_{i,j}$:	Total material flow between facilities *i* and *j*
sh_i^M:	Length of the shorter side of facility *i*
lng_i^M:	Length of the longer side of facility *i*
(l^{ENT}, u^{ENT}):	Starting and ending point of the allowable area for constructing entrance door
(l^{EXT}, u^{EXT}):	Starting and ending point of the allowable area for constructing exit door

m_w^H:	Minimum width of horizontal aisles
m_w^V:	Minimum width of vertical aisles
α:	Coefficient of traffic impact for determining the width of horizontal aisles
β:	Coefficient of traffic impact for determining the width of vertical aisles
$PD_i =$	$\begin{cases} 1 & \text{If the P/D point of facility } i \text{ is on its longer side} \\ 0 & \text{Otherwise} \end{cases}$
M:	A large positive number

Table 3.3: Notation of Continuous and Binary Decision variables

(x_i^C, y_i^C):	The centroid (or position) of facility *i*
x_m^V:	The centroid of vertical aisle *m* in the *x*-axis
y_k^H:	The centroid of horizontal aisle *k* in the *y*-axis
$d_{i,j}^{MM}$:	The distance between the P/D point of facility *i* and *j* through aisles
$(d\_x_{i,j}^{MM}, d\_y_{i,j}^{MM})$:	The distances between the P/D point of facilities *i* and *j* in the *x* and *y*-axis directions
(x_i^{PD}, y_i^{PD}):	The *x* and *y*-axis coordinate of the P/D point of facility *i*
$d\_x_{k,l}^{HH}$:	The horizontal distance required to travel from horizontal aisle *k* to horizontal aisle *l*
$d\_x_{m,n}^{VV}$:	The horizontal distance required to travel from vertical aisle *m* to vertical aisle *n*
$d\_x_{i,m}^{MV}$:	The horizontal distance between the P/D point of facility *i* and the centroid of vertical aisle *m*
$(l\_x_i^M, l\_y_i^M)$:	The length of facility *i* in the *x* and *y*-axis directions
w_k^H:	The width of horizontal aisle *k*
w_m^V:	The width of vertical aisle *m*
$traffic_k^H$:	The amount of traffic in the horizontal aisle *k*
$traffic_m^V$:	The amount of traffic in the vertical aisle *m*
$h_i =$	$\begin{cases} 1 & \text{If facility } i \text{ has a horizontal orientation} \\ 0 & \text{Otherwise} \end{cases}$
$left_{i,j}^{MM} =$	$\begin{cases} 1 & \text{if facility } i \text{ is to the left of facility } j \\ 0 & \text{Otherwise} \end{cases}$
$below_{i,j}^{MM} =$	$\begin{cases} 1 & \text{if facility } i \text{ is below facility } j \\ 0 & \text{Otherwise} \end{cases}$

$above_{i,k}^{MH} = \begin{cases} 1 & \text{if facility } i \text{ is above the horizontal aisle } k \\ 0 & \text{Otherwise} \end{cases}$

$below_{i,k}^{MH} = \begin{cases} 1 & \text{if facility } i \text{ is below the horizontal aisle } k \\ 0 & \text{Otherwise} \end{cases}$

$left_{i,m}^{MV} = \begin{cases} 1 & \text{if facility } i \text{ is to the left of vertical aisle } m \\ 0 & \text{Otherwise} \end{cases}$

$right_{i,m}^{MV} = \begin{cases} 1 & \text{if facility } i \text{ is to the right of vertical aisle } m \\ 0 & \text{Otherwise} \end{cases}$

$u_{i,p}^{MP} = \begin{cases} 1 & \text{if facility } i \text{ is placed in level } p \\ 0 & \text{Otherwise} \end{cases}$

$z_{i,k}^{MH} = \begin{cases} 1 & \text{if facility } i \text{ is supplied via horizontal aisle } k \\ 0 & \text{Otherwise} \end{cases}$

$z\_a_{i,k}^{MH} = \begin{cases} 1 & \text{if facility } i \text{ is supplied via horizontal aisle } k \text{ which is located above it} \\ 0 & \text{Otherwise} \end{cases}$

$z\_b_{i,k}^{MH} = \begin{cases} 1 & \text{if facility } i \text{ is supplied via horizontal aisle } k \text{ which is located below it} \\ 0 & \text{Otherwise} \end{cases}$

$z_{i,m}^{MV} = \begin{cases} 1 & \text{if facility } i \text{ is supplied via vertical aisle } m \\ 0 & \text{Otherwise} \end{cases}$

$z\_l_{i,m}^{MV} = \begin{cases} 1 & \text{if facility } i \text{ is supplied via vertical aisle } m \text{ which is located left of it} \\ 0 & \text{Otherwise} \end{cases}$

$z\_r_{i,m}^{MV} = \begin{cases} 1 & \text{if facility } i \text{ is supplied via vertical aisle } m \text{ which is located right of it} \\ 0 & \text{Otherwise} \end{cases}$

$c_{k,i,j}^{H} = \begin{cases} 1 & \text{if horizontal aisle } k \text{ is in the path of materials transported between facilities } i \text{ an} \\ 0 & \text{Otherwise} \end{cases}$

$c_{m,i,j}^{V} = \begin{cases} 1 & \text{if vertical aisle } m \text{ is in the path of materials transported between facilities } i \text{ and} \\ 0 & \text{Otherwise} \end{cases}$

3.3.2. Objective function

Determining the aisles structure and layout of facilities so that total transportation distance (TTD) between facilities is minimized is an efficient metric to measure the efficiency of facility layout and aisles structure. Through this metric, it can be specified if the facilities, aisles and entrance and exit door are placed in the optimum position or not. TTD is defined as the sum of the material flow between each pair of facilities, f_{ij}, multiplied by the corresponding transportation

distances, $d_{i,j}^{MM}$, is considered as the objective function. It should be mentioned that the distance between facilities and entrance and exit doors is not considered in Eq. 3.1. The updated version of the objective function is presented in section 3.3.10.

$$Min\ TTD = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} f_{i,j} d_{i,j}^{MM} \tag{3.1}$$

Since the product route and demand is known, f_{ij} can be calculated easily. To calculate $d_{i,j}^{MM}$, the total vertical path plus the total horizontal path that should be traveled through the aisles to connect the P/D points of facilities *i* and *j* must be calculated. Figure 3.3 illustrates the aisle-based distances for facility pairs (3,6), (10,5) and (16,14). As shown in Figure 3.3, the total vertical distances between P/D points of a facility pair are not dependent on the aisle structure and can be obtained by calculating the difference between the *y*-coordinates of their P/D points.

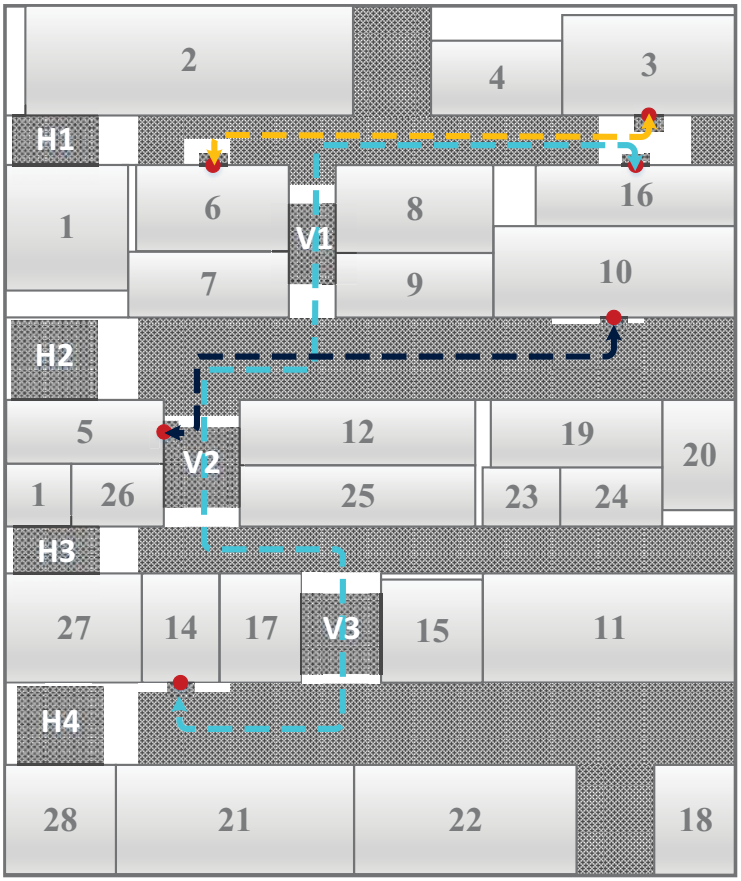

Figure 3.3. An example of the aisle-based distances between the P/D points of three pairs of facilities.

To calculate the horizontal distances, each horizontal aisle along with its connected vertical aisle, which is below it, is considered as a class of aisle. For example, in Figure 3.3, horizontal aisle 1 (H1) and vertical aisle 1 (V1) are in one class, horizontal aisle 2 (H2) and vertical aisle 2 (V2) are in one class and so on.

If two facilities are supplied by an identical class of aisle (e.g., facility pairs (3,6) and (10,5) in Figure 3.3), their horizontal distance is equal to the difference between the x-coordinates of their P/D points. It can be stated that in this situation, the aisle-based distance between each pair of facilities is equal to the rectilinear distance between their P/D points. This distance is calculated

using constraints (2)-(6). The first two parts of the right-hand side of constraint (2) calculate the rectilinear distance between the P/D points of facilities *i* and *j* and the last part is to control if both facilities *i* and *j* are supplied through an identical class of aisle.

$$d_{i,j}^{MM} \geq d\_x_{i,j}^{MM} + d\_y_{i,j}^{MM} - M(2 - z_{i,k}^{MH} - z_{j,l}^{MH} - z_{i,m}^{MV} - z_{j,n}^{MV}) \qquad \forall i < j, \forall\, k = l = m = n \qquad (3.2)$$

$$d\_x_{i,j}^{MM} \geq x_i^{PD} - x_j^{PD} \qquad \forall i, j \qquad (3.3)$$

$$d\_x_{i,j}^{MM} \geq x_j^{PD} - x_i^{PD} \qquad \forall i, j \qquad (3.4)$$

$$d\_y_{i,j}^{MM} \geq y_i^{PD} - y_j^{PD} \qquad \forall i, j \qquad (3.5)$$

$$d\_y_{i,j}^{MM} \geq y_j^{PD} - y_i^{PD} \qquad \forall i, j \qquad (3.6)$$

Calculating the horizontal distance between facilities *i* and *j* that are not supplied by the same class of aisle is more complicated. Let us consider the path that should be traveled between two facilities 16 and 14 in Figure 3.4. The transportation device has to move through arcs a-b, c-d, e-f and g-h in the horizontal direction. The sum of these arcs determines the horizontal traveling distance between facilities 16 and 14. The lengths of these arcs are different and depend on the position of the aisles and facilities. To deal with this difficulty, the distance between facilities *i* and *j,* which are not supplied through an identical class of aisles, is split into two distance types.

1. The first type comprises the horizontal distances that should be traveled inside the aisles that supply facilities *i* and *j*. Arcs a-b and g-h in Figure 3.4 are examples of this type of distance and are calculated using Eqs. (3.11) and (3.12).
2. The second type comprises the horizontal distances that should be traveled through the aisles other than the ones that supply facilities *i* and *j*. These distances, shown by arcs c-d and e-f in Figure 3.4, are calculated by Eq. 3.7. In fact, these distances are equal to the horizontal distances required to travel from horizontal aisle *k* to horizontal aisle *l.*

$$d\_x_{k,l}^{HH} = \sum_{m=k}^{l-2} d\_x_{m,m+1}^{VV} \qquad \forall k < l-1 \qquad (3.7)$$

$$d\_x_{m,n}^{VV} \geq x_m^V - x_n^V \qquad \forall m,n \qquad (3.8)$$

$$d\_x_{m,n}^{VV} \geq x_n^V - x_m^V \qquad \forall m,n \qquad (3.9)$$

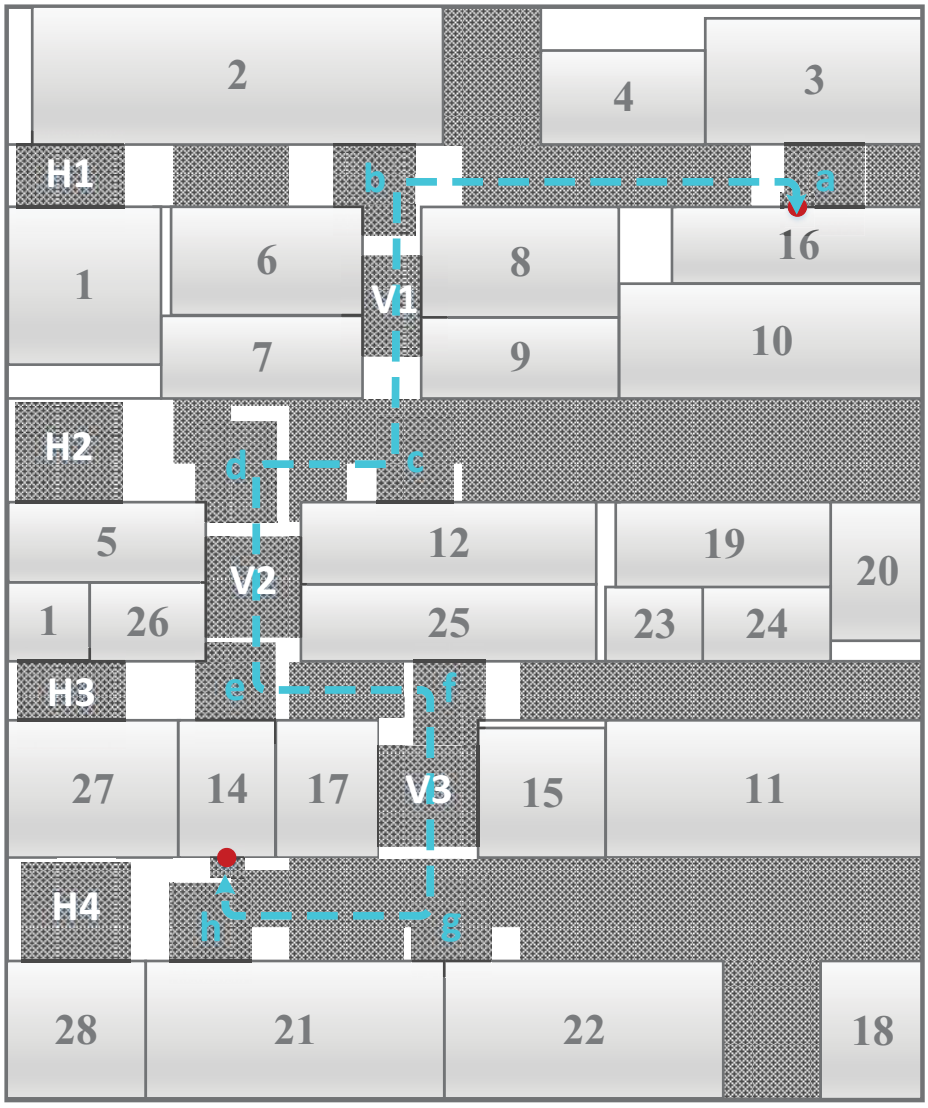

Figure 3.4. Aisle-based distance between facilities 16 and 14.

The total distances between facilities through aisles are calculated using constraints (3-10). In constraints (3-10) $d\_x_{i,m}^{MV}$ and $d\_x_{j,n}^{MV}$ are type 1 horizontal distances, $d\_x_{k,l}^{HH}$ are type 2 horizontal distances, and $d\_y_{i,j}^{MM}$ is a vertical distance.

$$d_{i,j}^{MM} \geq d\_x_{i,m}^{MV} + d\_x_{j,n}^{MV} + d\_x_{k,l}^{HH} + d\_y_{i,j}^{MM} - M\left(2 - z_{i,k}^{MH} - z_{j,l}^{MH} - z_{i,m}^{MV} - z_{j,n}^{MV}\right) \qquad \forall i \neq j, k < l, \; m = k, n = l - 1 \tag{3.10}$$

$$d\_x_{i,m}^{MV} \geq x_i^{PD} - x_m^{V} \qquad \forall i, m \tag{3.11}$$

$$d\_x_{i,m}^{MV} \geq x_m^{V} - x_i^{PD} \qquad \forall i, m \tag{3.12}$$

It should be noticed that in constraints (10) k is less than l. This means that it calculates the distance between a facility and its downstream facilities. In this way, only half of the distance matrix is calculated, which is not necessarily a lower/upper triangular matrix. Since the distance between facilities *i* and *j* is exactly equal to the distance between facilities *j* and *i*, the distance matrix is symmetrical and the unfilled parts can easily be obtained using constraints (3-13). In this way, repetitive computations are avoided and computational complexity is reduced.

$$d_{i,j}^{MM} \geq d_{j,i}^{MM} \qquad \forall i, j \tag{3.13}$$

3.3.3. Within-site boundary constraints

These groups of constraints, similar to those used in Dunker, Radons, and Westkämper (2005), guarantee that all the facilities and aisles are placed inside the boundaries of the shop floor. First, it is necessary to determine the length of each facility in the *x* and *y*-axis directions. Facilities are allowed to take either a horizontal or vertical orientation. If a facility is placed in the horizontal direction, its length along the *x*-axis is equal to its longer side and its length along the *y*-axis is equal to its shorter side (Figure 3.5). Eqs. (3.14) and (3.15) are used to control the length of the facilities considering their orientations.

$$l\_x_i^M = lng_i^M h_i + sh_i^M (1 - h_i) \qquad \forall i \qquad (3.14)$$

$$l\_y_i^M = lng_i^M (1 - h_i) + sh_i^M h_i \qquad \forall i \qquad (3.15)$$

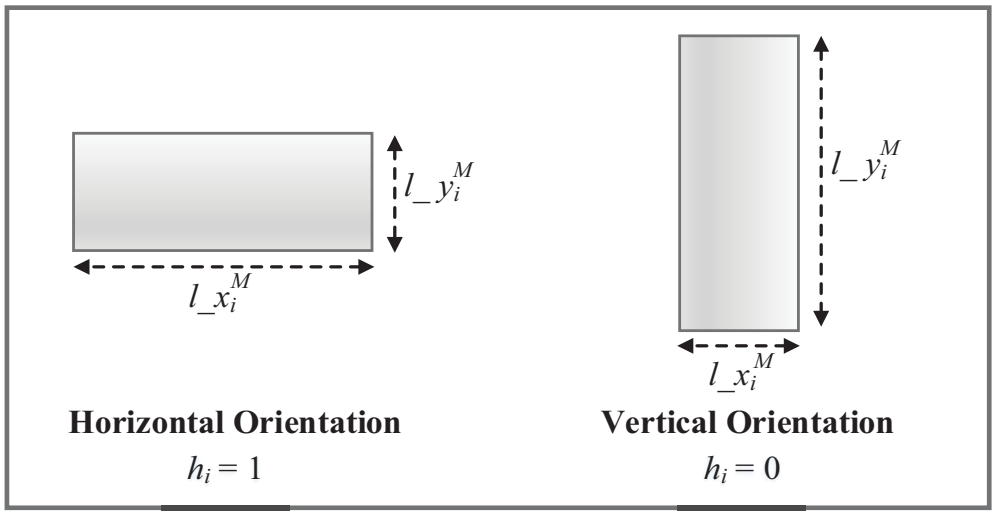

Figure 3.5. The orientation of facilities.

Constraints (3.16)-(3.19) guarantee that facilities are located inside the boundaries of the shop floor.

$$x_i^C + 0.5 l\_x_i^M \leq length \qquad \forall i \qquad (3.16)$$

$$x_i^C - 0.5 l\_x_i^M \geq 0 \qquad \forall i \qquad (3.17)$$

$$y_i^C + 0.5 l\_y_i^M \leq width \qquad \forall i \qquad (3.18)$$

$$y_i^C - 0.5 l\_y_i^M \geq 0 \qquad \forall i \qquad (3.19)$$

Constraints (3.20)-(3.23) guarantee that aisles are placed within the boundaries of the shop floor. This group of constraints is the same as the ones used for the facilities. In line with our

assumptions, the horizontal aisles are extended to the *x*-axis boundaries of the floor and thus they should only be verified as being located inside the *y*-axis boundaries of the floor. In the same way, the vertical aisles are verified as being placed inside the *x*-axis boundaries of the floor.

$$y_k^H + 0.5w_k^H \leq width \qquad \forall k \qquad (3.20)$$

$$y_k^H - 0.5w_k^H \geq 0 \qquad \forall k \qquad (3.21)$$

$$x_m^V + 0.5w_m^V \leq length \qquad \forall m \qquad (3.22)$$

$$x_m^V - 0.5w_m^V \geq 0 \qquad \forall m \qquad (3.23)$$

3.3.4. Non-overlapping constraints

Constraints (3.24)-(3.26), similar to those presented in Meller, Narayanan, and Vance, (1998), are used to guarantee non-overlapping between facilities. If two facilities are located at the same level on the shop floor, the right-hand side of constraints (3.24) is equal to 1, and consequently one of the left-side variables has to take the value 1. As an example, if facility *i* is to the left of facility *j*, $left_{i,j}^{MM} = 1$, constraint (3.25) is imposed and constraint (3.26) is relaxed. Therefore, the *x*-coordinate of the centroid of facility *i* plus half of its length in the *x*-axis direction ($x_i^C + 0.5l\_x_i^M$) should be less than the *x*-coordinate of the centroid of facility *j* minus half of its length in the *x*-axis direction ($x_j^C - 0.5l\_x_j^M$).

$$below_{i,j}^{MM} + below_{j,i}^{MM} + left_{i,j}^{MM} + left_{j,i}^{MM} \geq u_{i,p}^{MP} + u_{j,p}^{MP} - 1 \qquad \forall i \neq j, p \qquad (3.24)$$

$$x_i^C + 0.5l\_x_i^M \leq x_j^C - 0.5l\_x_j^M + M(1 - left_{i,j}^{MM}) \qquad \forall i \neq j \qquad (3.25)$$

$$y_i^C + 0.5l\_y_i^M \leq y_j^C - 0.5l\_y_j^M + M(1 - below_{i,j}^{MM}) \qquad \forall i \neq j \qquad (3.26)$$

The following constraints guarantee non-overlapping between facilities and horizontal aisles. Each facility has two states relative to the horizontal aisles, above or below. If facility i is above horizontal aisle k, $above_{i,k}^{MH} = 1$, constraints (3.28) are relaxed and constraints (3.29) are imposed (Figure 3.6).

$$below_{i,k}^{MH} + above_{i,k}^{MH} = 1 \qquad \forall i,k \qquad (3.27)$$

$$y_k^H - 0.5w_k^H \geq y_i^C + 0.5l\_y_i^M - M(1 - below_{i,k}^{MH}) \qquad \forall i,k \qquad (3.28)$$

$$y_k^H + 0.5w_k^H \leq y_i^C - 0.5l\_y_i^M + M(1 - above_{i,k}^{MH}) \qquad \forall i,k \qquad (3.29)$$

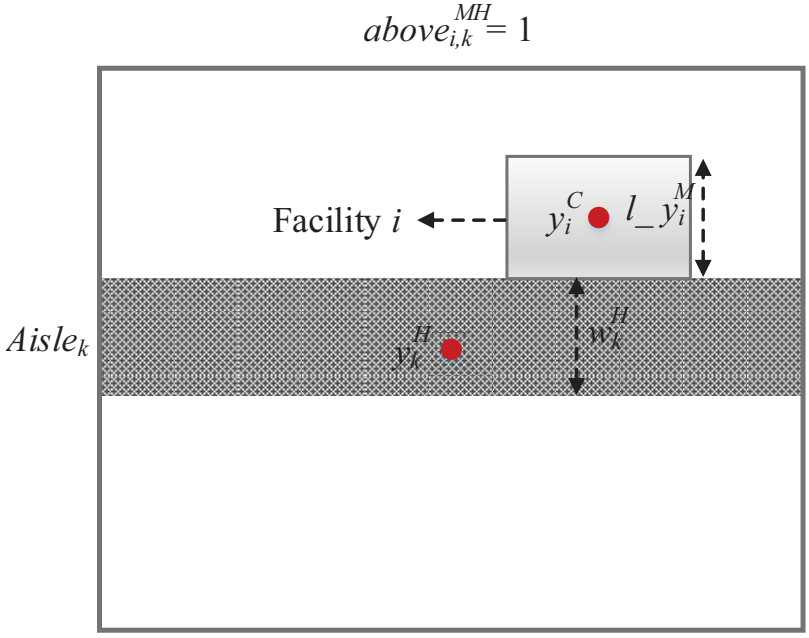

Figure 3.6. Non-overlapping between facilities and horizontal aisles.

The following constraints guarantee that at the same level the facilities and the vertical aisles do not overlap. Each facility has two states relative to vertical aisles, left or right. If facility i is located on the right side of vertical aisle n, $right_{i,m}^{MV} = 1$, then constraints (3.31) are relaxed and constraints (3.32) are imposed (Figure 3.7).

$$left_{i,m}^{MV} + right_{i,m}^{MV} \geq u_{i,p}^{MP} \qquad \forall i, m = p - 1, \quad 1 < p < K + 1 \qquad (3.30)$$

$$x_m^V - 0.5w_m^V \geq x_i^C + 0.5l\_x_i^M - M(1 - left_{i,m}^{MV}) \qquad \forall i, m \qquad (3.31)$$

$$x_m^V + 0.5w_m^V \leq x_i^C - 0.5l\_x_i^M + M(1 - right_{i,m}^{MV}) \qquad \forall i, m \qquad (3.32)$$

$right_{i,m}^{MV} = 1$

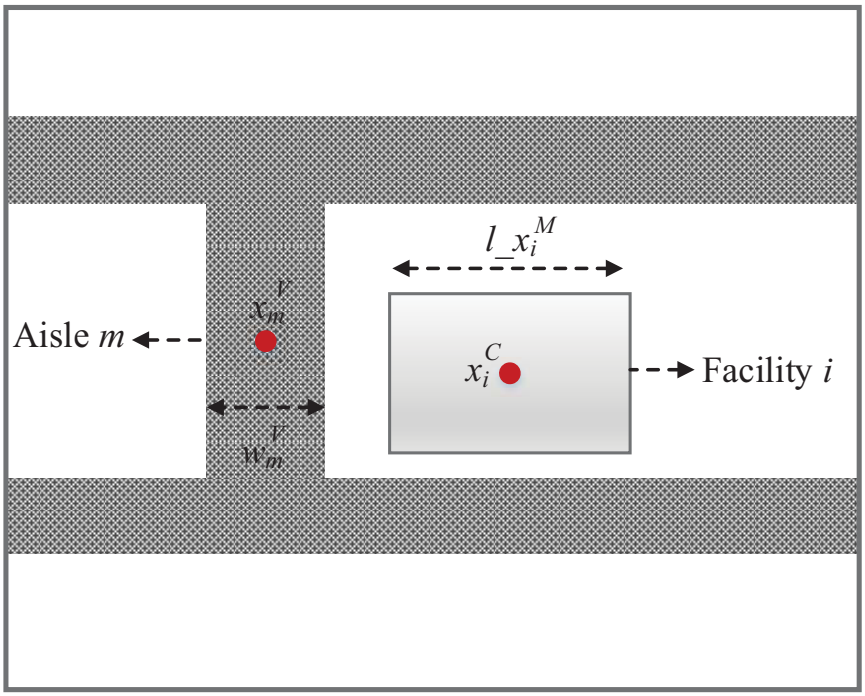

Figure 3.7. Non-overlapping between facilities and vertical aisles.

Constraints (3.33) guarantee non-overlapping between horizontal aisles.

$$y_k^H - 0.5w_k^H \geq y_l^H + 0.5w_l^H \qquad \forall k > l \qquad (3.33)$$

3.3.5. P/D points and aisle accessibility constraints

According to the accessibility principle, each facility should be connected to the aisles structure. This connection happens between the aisle and Pick-up/dropoff (P/D) points of the facility. It is assumed to have one fixed P/D point in the center of one of its sides. To connect a facility to the aisle structure, the facility's P/D point should be at the edge of a horizontal or vertical aisle. Depending on a facility's orientation and the location of its P/D point, one of the following situations can occur, as illustrated in Figure 3.8:

1. The facility is placed horizontally and its P/D point is on its longer side.
2. The facility is placed vertically and its P/D point is on its shorter side.
3. The facility is placed horizontally and its P/D point is on its shorter side.
4. The facility is placed vertically and its P/D point is on its longer side.

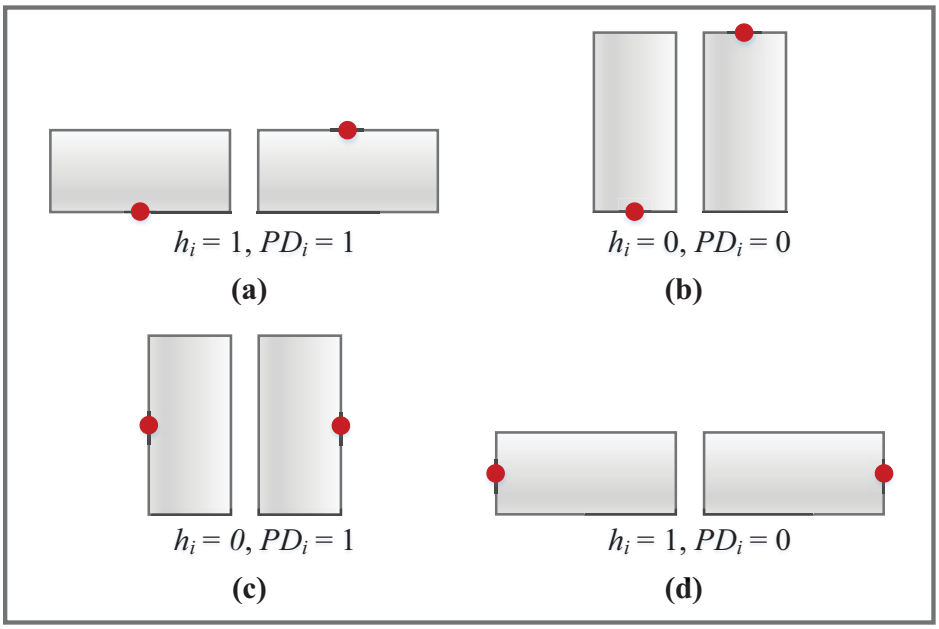

Figure 3.8. Facility orientation and position of P/D point

A facility should be supplied by a horizontal aisle if its situation matches one of the conditions shown in Figure 3.8 (a) and Figure 3.8 (b), and it should be supplied by a vertical aisle if its situation matches one of the conditions shown in Figure 3.8 (c) and Figure 3.8 (d). Taking into account facility orientations and the positions of their P/D points, constraints (3.34)-(3.36) guarantee that each facility is supplied by only one aisle.

$$\sum_{k=1}^{K} z_{i,k}^{MH} + \sum_{m=1}^{K-1} z_{i,m}^{MV} = 1 \qquad \forall i \qquad (3.34)$$

$$z_{i,k}^{MH} \geq h_i PD_i + (1 - h_i)(1 - PD_i) \qquad \forall i, k \qquad (3.35)$$

$$z_{i,m}^{MV} \geq 1 - h_i PD_i - (1 - h_i)(1 - PD_i) \qquad \forall i, m \qquad (3.36)$$

As shown in Figure 3.9, if a facility is supplied by a horizontal (vertical) aisle, it can be placed above/below (to the left/right of) the corresponding aisle. Eqs. (3.37) and (3.38) determine the position of a facility relative to the aisle that supplies it.

$$z\_a_{i,k}^{MH} + z\_b_{i,k}^{MH} = z_{i,k}^{MH} \qquad \forall i, k \qquad (3.37)$$

$$z\_l_{i,m}^{MV} + z\_r_{i,m}^{MV} = z_{i,m}^{MV} \qquad \forall i, m \qquad (3.38)$$

By knowing four variables $z\_a_{i,k}^{MH}$, $z\_b_{i,k}^{MH}$, $z\_l_{i,m}^{MV}$, and $z\_r_{i,m}^{MV}$, the coordinates of a facility's P/D point can be calculated. As shown in Figure 3.9, if a facility is supplied by a horizontal aisle, the *x*-coordinate of its P/D point is equal to the *x*-coordinate of the facility's centroid. This is guaranteed by constraints (3.39) and (3.40).

$$x_i^{PD} \leq x_i^C + M(1 - z_{i,k}^{MH}) \qquad \forall i, k \qquad (3.39)$$

$$x_i^{PD} \geq x_i^C - M(1 - z_{i,k}^{MH}) \qquad \forall i, k \qquad (3.40)$$

Determining the *y*-coordinate of the P/D point of a facility that is supplied by a horizontal aisle depends on the position of the facility relative to that aisle. If a facility is supplied by a horizontal aisle that is above it, $z\_a_{i,k}^{MH} = 1$, the *y*-coordinate of its P/D point should be equal to the *y*-coordinate of its centroid plus one-half of its length in the *y*-axis direction (see Figure 3.9). Constraints (3.41) and (3.42) are responsible for controlling this issue. In the same way, the *y*-coordinate of the P/D point of a facility that is supplied by a horizontal aisle situated below it is calculated through constraints (3.43) and (3.44).

$$y_i^{PD} \leq y_i^C + 0.5l\_y_i^M + M(1 - z\_a_{i,k}^{MH}) \qquad \forall i,k \qquad (3.41)$$

$$y_i^{PD} \geq y_i^C + 0.5l\_y_i^M - M(1 - z\_a_{i,k}^{MH}) \qquad \forall i,k \qquad (3.42)$$

$$y_i^{PD} \leq y_i^C - 0.5l\_y_i^M + M(1 - z\_b_{i,k}^{MH}) \qquad \forall i,k \qquad (3.43)$$

$$y_i^{PD} \geq y_i^C - 0.5l\_y_i^M - M(1 - z\_b_{i,k}^{MH}) \qquad \forall i,k \qquad (3.44)$$

Constraints (3.45)-(3.50) are similar to constraints (3.39)-(3.44), yet are used to determine the P/D point coordinates of the facilities that are supplied through vertical aisles. As shown in Figure 3.9, the *y*-coordinate of the P/D points of these facilities is equal to the *y*-coordinate of their centroid. Determining the *x*-coordinate of the P/D points of these facilities depends on the position of the facilities relative to their supplying vertical aisles. According to constraints (3.47) and (3.48), if a facility is supplied by a vertical aisle that is located on its left side, $z\_l_{i,m}^{MV} = 1$, the *x*-coordinate of its P/D point should be equal to the *x*-coordinate of the facility's centroid minus one-half of its length in the *x*-axis direction. In the same way, the *x*-coordinate of the P/D point of a facility supplied by a vertical aisle on its right side is calculated through constraints (3.49) and (3.50).

$$y_i^{PD} \leq y_i^C + M(1 - z_{i,m}^{MV}) \qquad \forall i,m \qquad (3.45)$$

$$y_i^{PD} \geq y_i^C - M(1 - z_{i,m}^{MV}) \qquad \forall i,m \qquad (3.46)$$

$$x_i^{PD} \leq x_i^C + 0.5l\_x_i^M + M(1 - z\_l_{i,m}^{MV}) \qquad \forall i, m \qquad (3.47)$$

$$x_i^{PD} \geq x_i^C + 0.5l\_x_i^M - M(1 - z\_l_{i,m}^{MV}) \qquad \forall i, m \qquad (3.48)$$

$$x_i^{PD} \leq x_i^C - 0.5l\_x_i^M + M(1 - z\_r_{i,m}^{MV}) \qquad \forall i, m \qquad (3.49)$$

$$x_i^{PD} \geq x_i^C - 0.5l\_x_i^M - M(1 - z\_r_{i,m}^{MV}) \qquad \forall i, m \qquad (3.50)$$

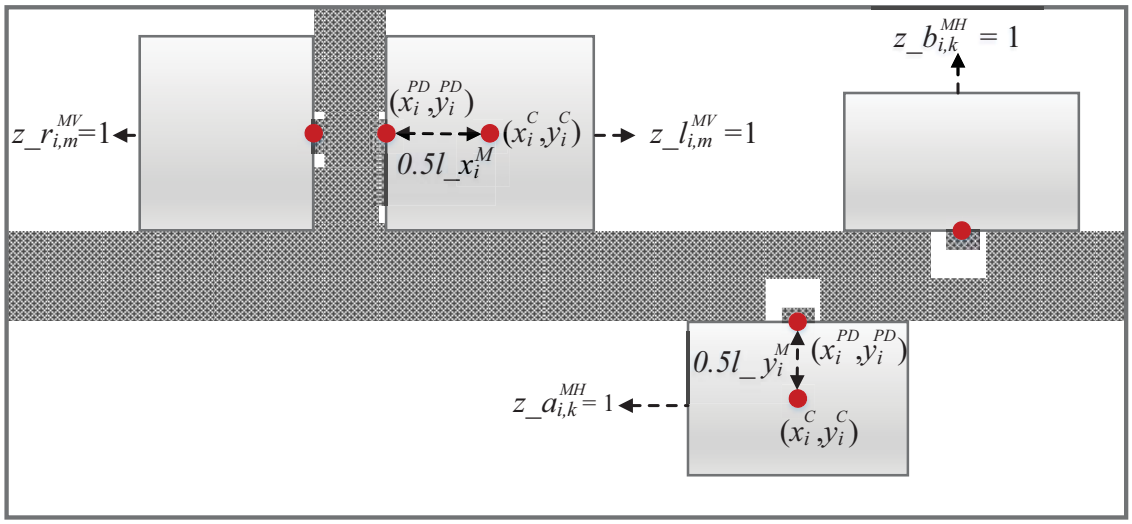

Figure 3.9. Coordinates of P/D points of facilities relative to the aisles that supply them

Constraints (3.51)-(3.54) guarantee that if a facility is supplied by a horizontal aisle, its P/D point should be located at the common border with that aisle. Two decision variables, $z\_a_{i,k}^{MH}$ and $z\_b_{i,k}^{MH}$, determine whether facility i is supplied by horizontal aisle k. For example, if facility i is supplied by horizontal aisle k which is above it, variable $z\_a_{i,k}^{MH}$ will be equal to 1 and variable $z\_b_{i,k}^{MH}$ will be equal to 0. This means that constraints (3.51) and (3.52) are imposed and constraints (3.53) and (3.54) are relaxed. Thus the y-coordinate of the P/D point of facility i, y_i^{PD} should be equal to the y-coordinate of the lower side of aisle k, $y_k^H - 0.5w_k^H$.

$$y_i^{PD} \leq y_k^H - 0.5w_k^H + M(1 - z\_a_{i,k}^{MH}) \qquad \forall i,k \qquad (3.51)$$

$$y_i^{PD} \geq y_k^H - 0.5w_k^H - M(1 - z\_a_{i,k}^{MH}) \qquad \forall i,k \qquad (3.52)$$

$$y_i^{PD} \leq y_k^H + 0.5w_k^H + M(1 - z\_b_{i,k}^{MH}) \qquad \forall i,k \qquad (3.53)$$

$$y_i^{PD} \geq y_k^H + 0.5w_k^H - M(1 - z\_b_{i,k}^{MH}) \qquad \forall i,k \qquad (3.54)$$

Similar to constraints (3.51)-(3.54), constraints (3.55)-(3.58) are used to ensure that if a facility is supplied by a vertical aisle, its P/D point should be located at the edge of that aisle.

$$x_i^{PD} \leq x_m^V - 0.5w_m^V + M(1 - z\_r_{i,m}^{MV}) \qquad \forall i,k \qquad (3.55)$$

$$x_i^{PD} \geq x_m^V - 0.5w_m^V - M(1 - z\_r_{i,m}^{MV}) \qquad \forall i,k \qquad (3.56)$$

$$x_i^{PD} \leq x_m^V + 0.5w_m^V + M(1 - z\_l_{i,m}^{MV}) \qquad \forall i,k \qquad (3.57)$$

$$x_i^{PD} \geq x_m^V + 0.5w_m^V - M(1 - z\_l_{i,m}^{MV}) \qquad \forall i,k \qquad (3.58)$$

3.3.6. Facility level constraints

Constraints (3.59) ensure that each facility is allocated to only one level, and constraints (3.60) and (3.61) control the level of each facility.

$$\sum_{\forall p} u_{i,p}^{MP} = 1 \qquad \forall i \qquad (3.59)$$

$$y_k^H - 0.5w_k^H \geq y_i^C + 0.5l\_y_i^M - M(1 - u_{i,p}^{MP}) \qquad \forall i, k = p-1, 1 < p \leq K+1 \qquad (3.60)$$

$$y_k^H + 0.5w_k^H \leq y_i^C - 0.5l\_y_i^M + M(1 - u_{i,p}^{MP}) \qquad \forall i, k = p,\ 1 \leq p < K+1 \qquad (3.61)$$

3.3.7. Aisle width constraints

Aisles width is connected to the principles of aisle space, smooth material flow and aisles safety. Aisle width refers to the lateral distance between two opposing sides of an aisle. Generally, aisles are not necessarily supposed to have the same width, and aisles with more traffic should be wider. In the proposed formulation, the traffic in an aisle is considered as the sum of the material flow which uses that aisle to reach its destination. Constraints (3.62)-(3.65) calculate the amount of traffic in each horizontal and vertical aisle.

$$traffic_k^H = \sum_i \sum_j f_{ij} c_{k,i,j}^H \qquad \forall k \qquad (3.62)$$

$$c_{k,i,j}^H \geq z_{i,l}^{MH} + z_{j,l'}^{MH} + z_{i,m}^{MV} + z_{j,n}^{MV} - 1 \qquad \forall i \neq j, l, m \leq k \leq l', n \qquad (3.63)$$

$$traffic_m^V = \sum_i \sum_j f_{ij} c_{m,i,j}^V \qquad \forall m \qquad (3.64)$$

$$c_{m,i,j}^V \geq z_{i,k}^{MH} + z_{j,l}^{MH} + z_{i,n}^{MV} + z_{j,n'}^{MV} - 1 \qquad \forall i \neq j, k, n \leq m \leq l, n' \qquad (3.65)$$

It is assumed that if an aisle is created, its width should be at least equal to a minimum value. This value is determined such that the aisles are wide enough to allow the largest disassembled part of a facility to be transported in case of breakdown. In addition, the space needed for walkways is considered to determine the minimum aisle width. An aisle with more traffic needs to be wider. Therefore, the width of the aisles should be equal to a minimum value plus a traffic-based value. Constraints (3.66) and (3.67) are defined to determine the width of each aisle based on the traffic passing through it. Coefficients α and β are determined by the opinions of expert designers. It can be noted that any other strategies can be defined, based on expert designers' ideas to determine the width of the aisles.

$$w_k^H \geq m\_w^H + \alpha\, traffic_k^H - M(1 - c_{k,i,j}^H) \qquad \forall\, k \qquad (3.66)$$

$$w_m^V \geq m\_w^V + \beta\, traffic_m^V - M(1 - c_{m,i,j}^V) \qquad \forall m \qquad (3.67)$$

According to constraints (3.66) and (3.67), if no facility uses a horizontal aisle *k* in its travel path ($c_{k,i,j}^H = 0, \forall i, j$), then its width is set to be equal to zero. By determining the width of the horizontal aisles, the number of aisles can be obtained. In this way, horizontal aisles with a width >0 are included in the layout and those with a width of 0 are not taken into account. The number of vertical aisles is equal to the number of horizontal aisles minus one.

3.3.8. The entrance and exit door constraints

Another important consideration in a manufacturing system is the entrance/exit doors through which the materials and transportation devices enter or exit the system. Usually, there are technical and environmental restrictions that limit the possible locations around the building for the construction of entrance/exit doors. In this research, the environmental restrictions are assumed to be such that the entrance/exit doors can only be constructed in some parts of the top/bottom side of the building (see green line in Figure 3.10).

In the mathematical model, the entrance/exit doors are considered as two virtual facilities indexed by *0* and *N+1*. Thus the P/D point of the entrance door, x_0^{PD}, and the P/D point of the exit door, x_{N+1}^{PD}, have to satisfy the following constraints.

$$l^{ENT} \leq x_0^{PD} \leq u^{ENT} \qquad (3.68)$$

$$l^{EXT} \leq x_{N+1}^{PD} \leq u^{EXT} \qquad (3.69)$$

The *y*-coordinate of the entrance/exit doors is equal to the *y*-coordinate of the top/bottom side of the shop floor (see Figure 3.10). After locating the entrance and exit doors on the top and bottom

sides of the building, two new vertical aisles are required to connect the aisle network to the entrance and exit doors. Since there are *K-1* normal vertical aisles in the system, the two new vertical aisles, called entrance and exit aisles, are indexed by 0 and *K*. As shown in, Figure 3.10, the *x*-coordinate of the centroid of the entrance (exit) aisle is equal to the *x*-coordinate of the entrance (exit) door.

$$x_0^{PD} = x_0^V \tag{3.70}$$

$$x_{N+1}^{PD} = x_K^V \tag{3.71}$$

The two new vertical aisles are treated in the same way as other vertical aisles. The facilities should have no overlap with these new vertical aisles. This is guaranteed by constraint (3.30)-(3.32) for $m = 0$ and $m = K$.

By determining the position of the entrance and the exit doors, the distances between these doors and the facilities can be calculated and considered when calculating the TTD. Constraints (3.72)-(3.75) are used to calculate the distances between the facilities and the entrance/exit doors. These constraints are similar to constraints (3.2) and (3.10).

$$d_{0,i}^{MM} \geq d\_x_{0,i}^{MM} + d\_y_{0,i}^{MM} - M\left(1 - z_{i,1}^{MH} - z_{i,1}^{MV}\right) \qquad \forall i \tag{3.72}$$

$$d_{0,i}^{MM} \geq d\_x_{0,1}^{MV} + d\_x_{i,m}^{MV} + d\_x_{1,k}^{HH} + d\_y_{0,i}^{MM} - M\left(1 - z_{i,k}^{MH} - z_{i,m}^{MV}\right) \qquad \forall i, 1 < m = k - 1 \tag{3.73}$$

$$d_{i,N+1}^{MM} \geq d\_x_{i,N+1}^{MM} + d\_y_{i,N+1}^{MM} - M\left(1 - z_{i,K}^{MH} - z_{i,K-1}^{MV}\right) \qquad \forall i \tag{3.74}$$

$$d_{i,N+1}^{MM} \geq d\_x_{N+1,K-1}^{MV} + d\_x_{i,m}^{MV} + d\_x_{k,K}^{HH} + d\_y_{i,N+1}^{MM} - M\left(1 - z_{i,k}^{MH} - z_{i,m}^{MV}\right) \qquad \forall i, m = k < K \tag{3.75}$$

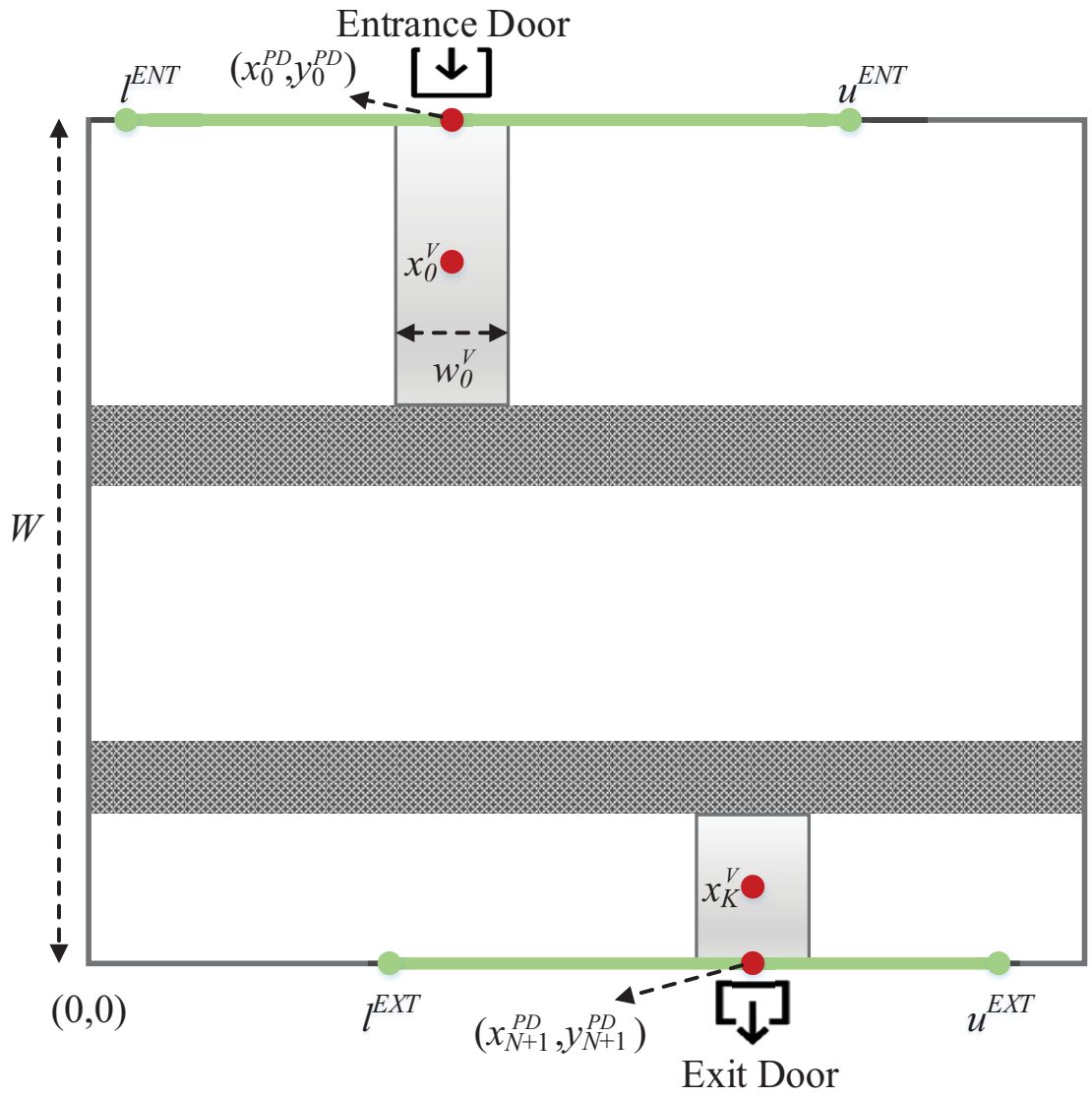

Figure 3.10. Possible areas for placing the entrance and exit doors and their corresponding vertical aisles.

3.3.9. Domain constraints

The decision variables are defined by constraints (3.76) and (3.77).

$$x_i^C, y_i^C, x_m^V, y_k^H \geq 0 \qquad \forall i, j, k, m \qquad (3.76)$$

$$h_i, left_{i,j}^{MM}, below_{i,j}^{MM}, above_{i,k}^{MH}, below_{i,k}^{MH}, left_{i,m}^{MV}, right_{i,m}^{MV}, \qquad \forall i, j, k, m, p \qquad (3.77)$$

$$u_{i,p}^{MP}, z_{i,k}^{MH}, z\_a_{i,k}^{MH}, z\_b_{i,k}^{MH}, z_{i,m}^{MV}, z\_l_{i,m}^{MV}, z\_r_{i,m}^{MV}, c_{k,i,j}^{H}, c_{m,i,j}^{V} \in \{0, 1\}$$

3.3.10. Updated objective function

The objective function, shown in Eq. (3.1), calculates the transportation distance between each pair of facilities and does not consider the transportation distance between the facilities and the entrance and exit doors. The updated objective function calculates the total transportation distance between each pair of facilities and between the facilities and the entrance and exit doors.

$$Min\ TTD = \sum_{i=0}^{N} \sum_{j=i+1}^{N+1} f_{ij} d_{i,j}^{MM} \qquad (3.78)$$

In Eq. (78), $f_{0,j}$ shows the quantity of materials that are moved from the entrance door to facility *j*, and $f_{i,N+1}$ shows the quantity of materials that are moved from facility *i* to the exit door. This new objective function, along with constraints (3.2)-(3.77), shapes the model. Let us note that our problem is very complex. As a matter of fact, without considering the aisle problem, complexity is reduced to an unequal area facility layout problem, which is NP-Hard (Anjos & Vieira, 2017), with *2N* continuous. In our case, *2* continuous variables are needed to determine the position of the entrance/exit doors, *K* for the center of the horizontal aisles and *K-1* for the vertical aisles. In total, there are *2N+2K+1* continuous decision variables for the positioning of facilities

and aisles. In addition to these continuous decision variables, there are continuous variables for the width of the aisles, and many binary variables in the model to satisfy the non-overlapping and aisle accessibility constraints.

However, since the objective function and the constraints are represented entirely by linear equations, this model is linear and hence it is possible to achieve a global optimum solution. Given the complexity of our model, in the next section, we propose a branch-and-cut algorithm, along with improvement mechanisms.

3.4. Proposed optimization algorithm

The branch-and-cut (B&C) method has successfully been used to solve a variety of MILP problems (Karaoğlan, Erdoğan, & Koç, 2018) and it can also guarantee global optimality. The B&C algorithm follows the general scheme of the branch-and-bound (B&B) algorithm. In the B&C algorithm, some cuts are added to the problem to limit the possible value of the continuous relaxed variables. Cuts are additional constraints that may remove the feasible points of the continuous relaxed problem while leaving the feasible set of MIP unchanged, which is very efficient for solving MILP. Interested readers can consult Caccetta (2000), Mitchell (2002) and Conforti, Cornuéjols, and Zambelli (2014) for more details about the B&C algorithm. Even though the B&C algorithm is an effective method to solve MILP, some mechanisms are applied to improve the B&C algorithm in solving the proposed model. These mechanisms consist of 1) adding optimality cuts, 2) defining the branching order of variables and 3) choosing the best node selection strategies.

3.4.1. Optimality cuts

Four families of valid inequalities are introduced to strengthen the model through the implementation of the B&C algorithm. These inequalities are called optimality cuts. The optimality cuts applied here are quite simple yet very efficient. The first group of optimality cuts are used as follows:

$$\sum_{\forall i} z\_a_{i,k}^{MH}\, l\_x_i^M \leq length \qquad \forall k \qquad (3.79)$$

$$\sum_{\forall i} z\_b_{i,k}^{MH}\, l\_x_i^M \leq length \qquad \forall k \qquad (3.80)$$

Inequalities (3.79) and (3.80) prevent variables $z\_a_{i,k}^{MH}$ and $z\_b_{i,k}^{MH}$ from taking the value one if this results in generating an unfeasible layout that violates the limitation of shop floor length. The following two inequalities are used as the second group of cuts:

$$z\_a_{i,k}^{MH} \leq u_{i,p}^{MP} \qquad \forall i, \forall p = k+1 \qquad (3.81)$$

$$z\_b_{i,k}^{MH} \leq u_{i,p}^{MP} \qquad \forall i, \forall p = k \qquad (3.82)$$

Constraints (3.81) imply that if facility *i* is supplied by aisle *k,* which is above it, facility *i* is certainly placed in level *k+1*. Constraints (3.82) imply that if facility *i* is supplied by aisle *k,* which is below it, facility *i* is certainly placed in level *k*.

3.4.2. Branching strategy

Selecting a branching variable is an essential task in any B&C algorithm, since it can significantly affect its computational time. Ideally, it is preferable to select a branching variable that helps to explore the minimum number of nodes. In this study, the objective function is strongly dependent on the variables related to the position of the facilities. At the same time, the decision variable of the position of each facility is directly influenced by the decision variable that is concerned with the aisle that supplies it. Hence, it is reasonable to focus on the variables that determine which aisle is supplying each facility. Consequently, two variables, $z\_a_{i,k}^{MH}$ and $z\_b_{i,k}^{MH}$, are the first priorities for branching. Once variables $z\_a_{i,k}^{MH}$ and $z\_b_{i,k}^{MH}$ are set, variables $u_{i,p}^{MP}$, $above_{i,k}^{MH}$ and $below_{i,k}^{MH}$ will be fixed.

Through this strategy, when the problem is solved as a relaxed linear programming problem at each node and the integer variables are relaxed, some relaxed integer variables are derived to take integer value. Furthermore, by first branching on $z\_a_{i,k}^{MH}$ certain other variables will be relatively determined. For example, if we know the value of $z\_a_{i,k}^{MH}$ for two facilities then this implies that the variable $left_{i,j}^{MM}$ should take value 1.

3.4.3. Node selection strategies

Another important task in any B&C algorithm is to select the node that should be branched at each iteration. Node selection strategies aim to prune open nodes and end the queue as quickly as possible. Depth-first, best-bound, breadth-first, or best-first search strategies are the most commonly used strategies. The depth-first strategy is suitable for problems where a feasible solution is difficult to find. Since finding a feasible solution in which facilities have no overlap is difficult, the depth-first search strategy is implemented. In this strategy, the most recent node added to the tree is chosen for branching. The advantage of this strategy is that a feasible solution, and

consequently a lower bound, can be found quickly (Belov & Scheithauer, 2006). The obtained lower bound is used to keep the list of open nodes minimal and thus memory usage is low.

3.5. Computational experiments

In this section, a set of test instances is used to verify and evaluate the proposed approach. The B&C described in section 3.4 is compared with the general B&C. In the general version of the B&C algorithm, the default settings of CPLEX were used, in which CPLEX chooses a variable to branch on. The node selection strategy is the best-bound search in which the node with the best objective function for the associated LP relaxation is selected. The five following versions of the B&C algorithm are used for this comparison:

- The B&C1, which is the general version of the B&C algorithm.
- The B&C2, which is the B&C1 algorithm plus the proposed branching strategy.
- The B&C3, which is the B&C2 algorithm plus the proposed node selection strategy.
- The B&C4, which is the B&C3 algorithm plus the proposed first group of optimality cuts (Eqs. 3.79, 3.80).
- The B&C5, which is the B&C4 algorithm plus the proposed second group of optimality cuts (Eqs. 3.81, 3.82).

All these versions of B&C algorithms are implemented using GAMS modeling language (version 28.2.0), and CPLEX (version 12.9) is used as the solver. The numerical tests are conducted on a laptop computer with an Intel Core i7 CPU (2.3 GH) and 8 GB of memory under the Windows 10 operating system.

3.5.1. Test instances

Since none of the reviewed studies in Chapter 2 address our problem, using their test instances would not provide an appropriate comparison for the proposed approach. Therefore, new test instances inspired by a real manufacturing system are designed, and the facility dimensions are taken from a real case study (Zhou et al., 2006). Table 3.4 shows 12 facilities and their sizes.

Table 3.4: Facilities and their dimensions.

No.	Facility name	Area (m×m)
1	Raw material warehouse	30×10
2	Casting	18×15
3	Heat-treat	12×10
4	Mechanical	20×15
5	Precision	14×10
6	In-process product	24×20
7	Assembly	14×8
8	Performance testing	18×12
9	Final product warehouse	20×16
10	Maintenance	12×10
11	Service houses	40×30
12	Depot	30×30

In the test instances, the width of the largest disassembled part of the facilities is 3.5 meters (m). In addition, 0.5 m is added for the space needed for walkways. The minimum width for the aisles is therefore considered to be 4 m. The aisles can become wider, based on their traffic. The values of α and β are set to 0.0033. Based on the number of facilities, the test instances are classified into six groups of 7, 8, 9, 10, 11 and 12 facilities. For each group, four instances are generated. These instances have different sizes for the plant floor and different possible positions for the entrance/exit doors that are presented in Table 3.5. For example, test instance 1 corresponds

to a problem with 7 facilities (facilities 1 to 7 in Table 3.1) where the plant length is 45m, the plant width is 55m, the width of the entrance door is 4m and it can be placed on the upper side of the plant in the range 20m to 45m, and the width of the exit door is 4m and can be located on the bottom side of the plant in the range 10m to 40m. These instances are designed so that the total area of all the facilities is around 70% of the total plant area. The material flow between facilities is determined using a uniform distribution on the interval [30, 50].

Table 3.5: General data of the test instances.

Problem No.	No. of facilities	Plant area (m^2)	Entrance door		Exit door	
			Possible position	width(m)	Possible position	width(m)
1	7	45×55	Up. 20m-45m	4	Down. 10m-40m	4
2		40×52	Down. 20m-40m	4	Up. 20m-40m	4
3		43×51	Up. 10m-43m	4	Bottom. 0m-20m	4
4		41×58	Down. 20m-41m	4	Up. 30m-41m	4
5	8	50×58	Up. 10m-40m	4	Down. 30m-40m	4
6		52×55	Down. 30m-52m	4	Up. 20m-40m	4
7		48×60	Up. 10m-40m	4	Down. 0m-48m	4
8		50×60	Down. 10m-50m	4	Up. 0m-30m	4
9	9	50×65	Up. 10m-40m	5	Down. 30m-50m	5
10		52×63	Down. 10m-50m	5	Up. 0m-40m	5
11		48×68	Up. 10m-48m	5	Down. 10m-40m	5
12		50×68	Down. 30m-50m	5	Up. 0m-50m	5
13	10	55×65	Up. 30m-40m	6	Down. 10m-40m	6
14		52×70	Down. 20m-52m	6	Up. 20m-40m	6
15		50×70	Up. 10m-40m	6	Down. 20m-50m	6
16		53×68	Down. 20m-53m	6	Up. 10m-40m	6
17	11	70×70	Up. 30m-40m	6	Down. 0m-40m	6
18		68×72	Down. 50m-60m	6	Up. 50m-68m	6
19		65×75	Up. 0m-50m	6	Down. 10m-65m	6
20		67×74	Down. 0m-50m	6	Up. 10m-67m	6
21	12	75×90	Up. 0m-50m	7	Down. 0m-40m	7
22		67×93	Down. 20m-67m	7	Up. 40m-67m	7
23		65×95	Up. 40m-65m	7	Down. 0m-50m	7
24		68×90	Down. 50m-68m	7	Up. 0m-50m	7

3.5.2. Branch-and-cut experiments

In this subsection, the performance of five different B&C algorithms (B&C1- B&C5) is evaluated. For all versions of the B&C algorithms, a maximum time of 36000 seconds is allowed for CPLEX to find the global optimum solution. If no global optimum solution is found, the algorithm stops and the best solution found is recorded, along with the optimality gap (the gap between the best possible solution with relaxed integrality constraints and the best feasible solution found). Table 3.3 presents the computational results of the algorithms and Figure 3.11 illustrates the mean objective function value (OFV) of the algorithms for each problem size. As can be seen in Table 3.6, for problems with seven facilities ($N = 7$), the performance of all the algorithms with respect to OFV is similar and they obtain the global optimum solution. If the number of facilities increases to eight or more, B&C1 cannot find the global optimum solution in the allowed computation time. The average OFV obtained by B&C1 for problems with eight facilities ($N = 8$) is 24485 with an average optimality gap of 26.32%. However, for this problem size, all the other algorithms reach the global optimum solution. For problems with nine facilities ($N = 9$), B&C3, B&C4 and B&C5 can provide optimal solutions with zero optimality gap, whereas B&C1 and B&C2 find solutions with an average optimality gap of 88.61% and 30.67%, respectively. As the number of facilities increases, the difference between the algorithms becomes more and more apparent. The average optimality gaps of B&C1 and B&C2 for problems with more than nine facilities are more than 75.00% and so their poor performance is quite obvious. This makes these two algorithms out of competition for problems with 10,11, and 12 facilities.

For problems with 10 facilities ($N = 10$) and 11 facilities ($N = 11$), only B&C5 can reach the global optimum solution. For problems with 10 facilities, the average OFV of B&C3 and B&C4 is respectively 77846 and 74987 with an average optimality gap of 31.80% and 13.39%. This shows that the performance of B&C4 is slightly better than B&C3 for finding the global optimum solution. The superiority of B&C4 over B&C3 in terms of OFV can also be seen in larger-sized problems with 11 facilities and 12 facilities ($N = 12$) which is due to the use of the

first group of optimality cuts. However, this group of cuts does not lead to a noticeable improvement in OFV and so the average OFV of B&C3 and B&C4 are very close to each other. Even though the average OFV of B&C3 and B&C4 are close, there is a significant difference between their average optimality gaps. Since the gap is calculated by comparing the current possible solution with a bound, obtained by relaxing integrality constraints, it can be concluded that the bound obtained by B&C3 is dramatically unfeasible concerning integrality constraints.

For problems with 12 facilities ($N = 12$), B&C5 can reach solutions with an average optimality gap of 12.05%. There are many real manufacturing systems with less than 13 facilities (Tompkins et al. 2010) and hence, B&C5 with a relatively low optimality gap can prepare acceptable solutions for them. B&C3 and B&C4, with average optimality gaps of 100.00% and 42.15% respectively, cannot be considered suitable solutions for problems with 12 facilities. Consequently, analysis proves that B&C5 provides the best performance in terms of OFV.

Table 3.6: Comparison between the algorithms.

Problem No.	No. of facilities	B&C1		B&C2		B&C3		B&C4		B&C5	
		OFV	Opt Gap	OFV	Opt Gap	OFV	Opt Gap	OFV	Opt Gap	OFV	Opt Gap
1	7	23887	0.00%	23887	0.00%	23887	0.00%	23887	0.00%	23887	0.00%
2		20753	0.00%	20753	0.00%	20753	0.00%	20753	0.00%	20753	0.00%
3		21652	0.00%	21652	0.00%	21652	0.00%	21652	0.00%	21652	0.00%
4		20789	0.00%	20789	0.00%	20789	0.00%	20789	0.00%	20789	0.00%
Average		21770	0.00%	21770	0.00%	21770	0.00%	21770	0.00%	21770	0.00%
5	8	24647	25.47%	20038	0.00%	20038	0.00%	20038	0.00%	20038	0.00%
6		24537	22.44%	20276	0.00%	20276	0.00%	20276	0.00%	20276	0.00%
7		24214	28.38%	19387	0.00%	19387	0.00%	19387	0.00%	19387	0.00%
8		24540	29.00%	19411	0.00%	19411	0.00%	19411	0.00%	19411	0.00%

Average		24485	26.32%	19778	0.00%	19778	0.00%	19778	0.00%	19778	0.00%
9	9	51921	89.00%	37226	35.00%	27899	0.00%	27899	0.00%	27899	0.00%
10		49084	81.00%	33051	28.27%	27407	0.00%	27407	0.00%	27407	0.00%
11		45116	97.28%	29833	29.39%	23608	0.00%	23608	0.00%	23608	0.00%
12		46464	87.17%	32613	30.00%	25348	0.00%	25348	0.00%	25348	0.00%
Average		48146	88.61%	33181	30.67%	26066	0.00%	26066	0.00%	26066	0.00%
13	10	129697	100.00%	92915	78.48%	82690	25.90%	80142	12.36%	73960	0.00%
14		122859	100.00%	84191	81.00%	72507	30.72%	69710	14.16%	63858	0.00%
15		126679	100.00%	91560	78.47%	80555	34.57%	77456	15.50%	72055	0.00%
16		123603	100.00%	87502	72.85%	75632	36.00%	72639	11.56%	66912	0.00%
Average		125710	100.00%	89042	77.70%	77846	31.80%	74987	13.39%	69196	0.00%
17	11	210796	100.00%	163078	100.00%	95262	100.00%	90896	27.58%	74761	0.00%
18		219616	100.00%	179359	100.00%	110341	100.00%	105965	24.04%	89016	0.00%
19		217338	100.00%	167402	100.00%	101935	100.00%	97742	29.23%	78050	0.00%
20		224677	100.00%	175981	100.00%	108303	100.00%	103827	22.97%	88011	0.00%
Average		218107	100.00%	171455	100.00%	103960	100.00%	99608	25.96%	82460	0.00%
21	12	247113	100.00%	209478	100.00%	159673	100.00%	154272	32.73%	123682	7.14%
22		250830	100.00%	219967	100.00%	175377	100.00%	169590	48.29%	134697	14.54%
23		248214	100.00%	213115	100.00%	169856	100.00%	163736	44.48%	129631	12.29%
24		249256	100.00%	211079	100.00%	170700	100.00%	164707	43.08%	131693	14.24%
Average		248853	100.00%	213410	100.00%	168902	100.00%	163076	42.15%	129926	12.05%

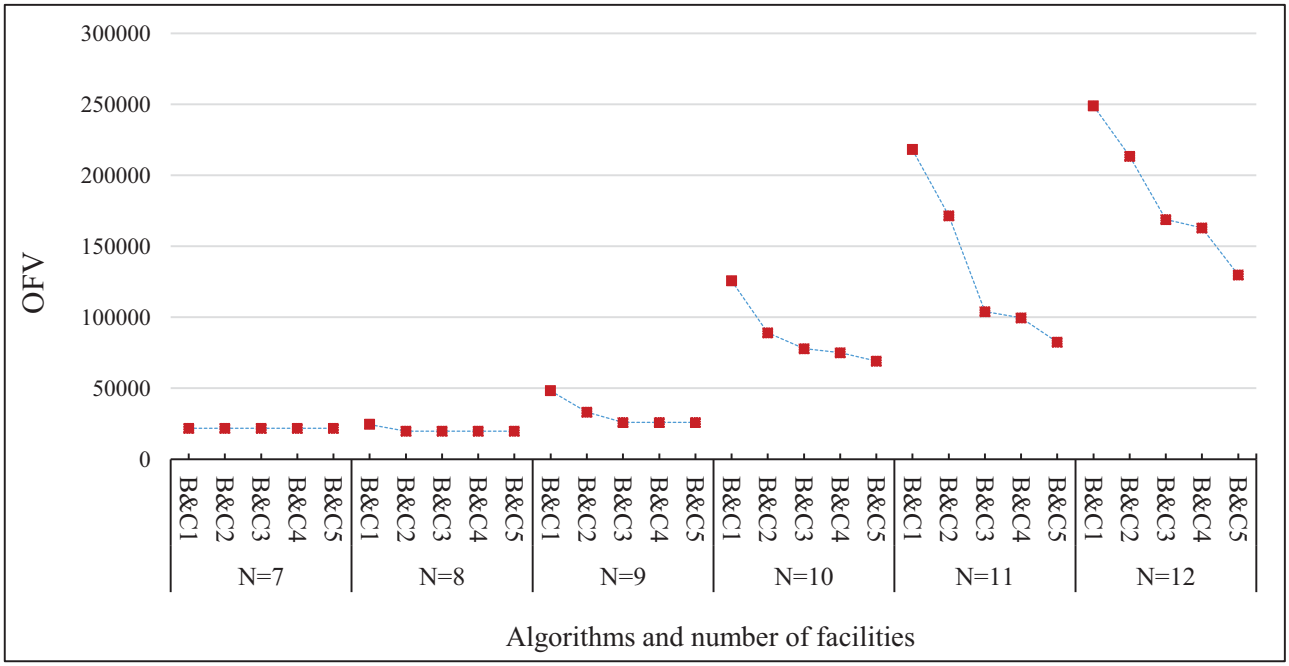

Figure 3.11. Mean OFV of the algorithms for each problem size.

In addition to the OFV, the performance of the algorithms is evaluated in terms of computation time. This comparison is made for problems that the algorithms can reach the zero optimality gap. Figure 3.12 shows the average computation time for each problem size. For problems with seven facilities, to which all the algorithms find the global optimum solution, B&C1, with a computation time of around 7085s, has the worst performance. For this problem size, the computation time of B&C2 is 2024s and that of the other algorithms is less than 2000s. By increasing the problem size to eight facilities, the computation time of B&C2 increases significantly and it reaches the optimum solution in 7677s, whereas the B&C3, B&C4 and B&C5 find the global optimum solution in 2503s, 956s and 807s respectively. For problems with nine facilities, the performance of B&C3 in terms of computation time decreases, and the algorithm requires 13877s to find the global optimum solution. However, B&C4 and B&C5 find the global optimum solution in 1435s and 1379s, respectively, which are much better performances.

Therefore, even though B&C3 and B&C4 achieve similar results in terms of OFV, B&C4 performs much better than B&C3 in terms of computation time. This superiority of B&C4 is due to the use of optimality cuts that help the algorithm to avoid searching the unfeasible nodes. It can be said that even though the cuts in B&C4 do not increase the performance of the algorithm to solve larger-sized problems, they can reduce computation time. For problems with 10 and 11 facilities, B&C5 can reach the global optimum solution in 3011s and 10261s respectively.

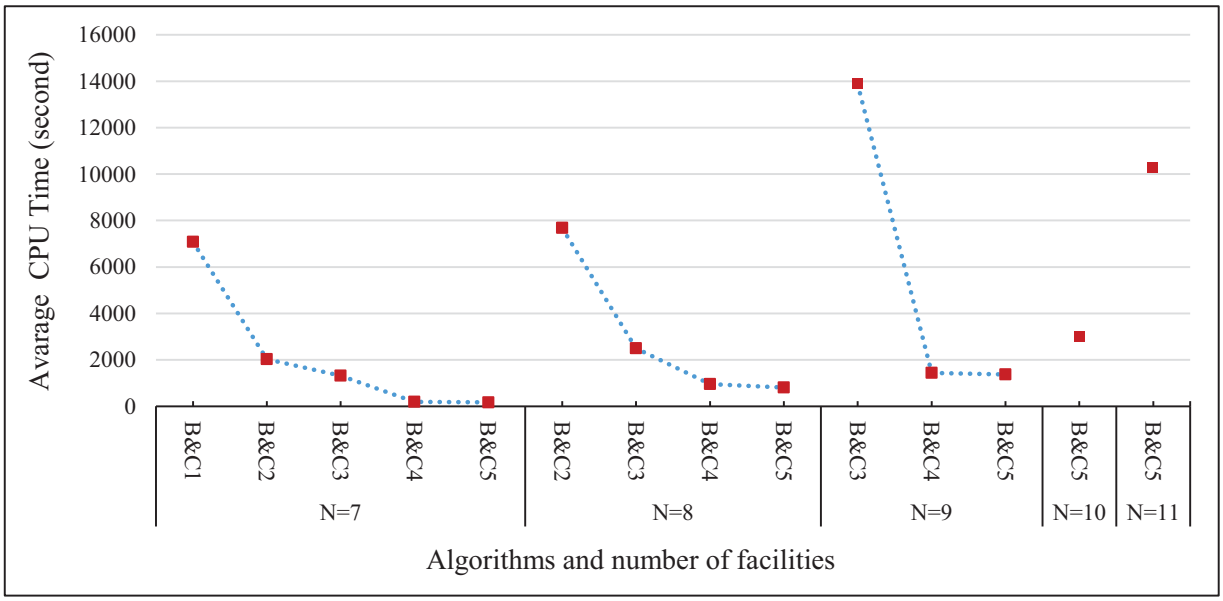

Figure 3.12. Computation times of the algorithms to find global optimum solution.

The best layout obtained via the B&C5 algorithm for problem 21 is illustrated in Figure 3.13. In this layout, 12 facilities are placed on three levels. The aisle structure consists of two horizontal aisles, one vertical aisle between the horizontal aisles, and two vertical aisles connected to the entrance/exit doors. Via this aisle structure, all the facilities have access to each other and to the entrance/exit doors. The upper horizontal aisle is busier than the lower horizontal aisle because it supplies six facilities; therefore it is wider. The central vertical aisle is the busiest aisle because it directly supplies facilities 2 and 5 and is also the communication aisle between two other horizontal aisles. Thus, it is the widest aisle. Since the facilities are allowed to rotate and be placed in their

optimal orientation, the layout is coherent with a minimum of unused space. The area of the shop floor is 6300m^2 and the total space occupied by the facilities and aisles is 4487m^2 and 1573m^2, respectively. Thus, around 3.8% of the area is unused. A large portion of this unused space is related to the zone in the top-left corner. From a practical point of view, since this space has a regular rectangular shape, it could be used efficiently according to the needs of the manufacturing system (e.g., to install new facilities or an office).

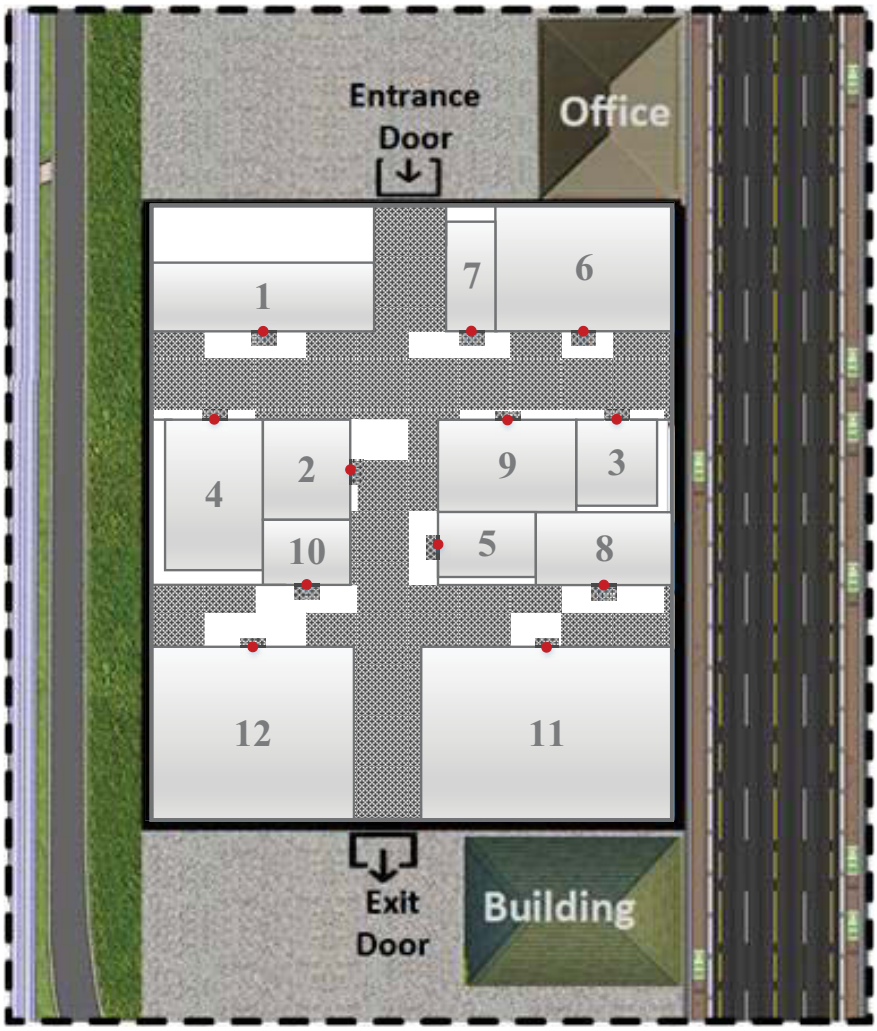

Figure 3.13. The best layout obtained for test instance 21.

3.6. Conclusions

The approach we have presented in this chapter addressed optimizing the position of facilities and aisles structure an integrated manner. The proposed mathematical model pointed out both practical considerations (e. g. to be able to access every facility, to be able to move them for maintenance, and to avoid turns) and theoretical requirements (e. g. where to place the exit and entrance doors, what should be the width of aisles, what is the best aisles structure), which have to be taken into account when designing the layout. All of these considerations were formulated through linear equations which gave us the possibility to reach to global optimum solution. To globally optimized the model an enhanced B&C algorithm was used. This approach was successfully applied to a set of FLP with 7 to 11 facilities of different sizes and the optimum solutions were found in a reasonable amount of time.

Chapter 4: Simulation optimization approach

4.1. Introduction

In the previous chapter, an exact approach was developed to simultaneously design aisles structure and finding the best position of facilities. Nonetheless, the optimality of a layout is influenced by various dynamic and stochastic factors such as transportation time, facilities (machines) and transporters breakdown, stochastic demand of products and stochastic process time. These factors have a great effect on the waiting time of facilities for transporters, the waiting time of transporters to load the products from facilities, and the simultaneous usage of an aisle by transporters which leads to the traffic in the aisles.

Therefore, to reach a more realistic layout, it is required to take into account these stochastic and dynamic phenomena. Queueing theory can be an interesting approach to take into account

these phenomena (Pourvaziri & Pierreval, 2017). Unfortunately, restrictive assumptions limit its applicability to certain particular types of systems and the complex dynamic behavior of the system cannot be modeled by queueing theory. Contrary to queueing theory, simulation-based approaches can take into account various types of stochastic and dynamic phenomena. Simulation is the most popular tool for systems with high uncertainty and dynamics (Ding et al., 2005). However, simulation is not able to search for optimal layout and when we use simulation to solve layout problems, we need to connect it to an optimization algorithm. In fact, in simulation approaches, in an iterative process, layouts are generated by an optimization algorithm and evaluated by a simulation model. Unfortunately, making a connection between simulation and optimization requires time and programming efforts for these types of approaches. The objective of this chapter is to develop a simulation optimization approach that can support a direct connection to handle the mentioned stochastic and dynamic phenomena of the system. The proposed approach is capable to use any metaheuristic algorithm for optimization. In this approach, a direct connection is implemented by using Matlab-Simulink. The applicably of the proposed approach is illustrated through an example.

4.2. The need for stochastic and dynamic analysis of layout problems

Deterministic models of facility layout problems assume that all the required data are deterministic. For example, we do not know what the demand for each product is to be produced, and therefore we do not know exactly what the material-handling requirements are. Even if the required data are available, many of these data are not deterministic. For example, the service rate of machines and transportation time can be stochastic. Thus, it is more relevant to develop stochastic models for layout analysis.

Furthermore, many factors, deterministic as well as stochastic, have a complex interaction with each other. For example, the time to transport a product from one facility to another is a function of where the material handling device is and whether it is busy or not, transporter failure,

and transporter blockages due to traffic congestion. As a result of transportation systems' behavior and interactions among various activities in a manufacturing system, layout problems are dynamic in nature.

Under such circumstances, we need tools that can design and analyze a layout with respect to stochastic and dynamic phenomena. Queuing-based and simulation models are useful tools in this situation. However, queuing-based models are restricted to certain probability distributions for modeling situations in which the stochastic phenomena, such as breakdowns, processing times and transportation time follow a particular statistical distribution, especially that non-exponential distribution rules are not possible with these models.

On the other hand, the dynamic behavior of the systems is not tracked over time by queueing-based models. Therefore, the complexities of the stochastic and dynamic behavior of the system cannot be perfectly addressed by queueing-based models. The simulation approach is attractive because it can capture an unlimited number of complexities in one system. In fact, a simulation model can very closely reflect reality.

By simulation, we can address a broader set of stochastic phenomena with any probability distribution. Furthermore, simulation allows the study of the interactive effects of many components in a dynamic and stochastic environment. For example, the effects of failing a facility (machine) on the waiting time of a transporter to load a product. Therefore, simulation is a relevant and interesting tool to see how dynamic and stochastic aspects of the problem impact the performance of the layout with respect to chosen operational performance measures. In the next section, we are going to study the literature of layout problems to see how simulation has been applied in different approaches in FLPs.

4.3. The literature of simulation in layout

This section reviews and discusses the literature body of knowledge related to the optimizing facility layout problem with the assistance of simulation. Azadivar & Wang (2000) presented a facility layout optimization technique that took into consideration the dynamic characteristics of the system. The cycle time and productivity were considered as the system's performance measures to solve the facility layout design problem. They used a GA package for optimization, a simulation package for simulation, an automatic simulation model generator, and a graphical user interface to connect the optimization and simulation. There was no systematic connection between these packages and their approach was limited to solve small-sized problems. Heilala et al. (2007) evaluated and optimized a layout problem in a production system. The objective was to make a balance between multiple parallel customer orders and finite resources. They mentioned that there is a need for a quick response tool to evaluate alternatives and scenarios before decisions are made. Raute[1] was used to simulate the problem. Raute is the plywood factory design and operative manufacturing simulation case, with Visual Components[2] 3DCreate® component-based simulation software. The connection between simulation and optimization was done using text-formatted files. A simulation optimization methodology was proposed by Wang et al. (2008) to resolve the facility layout problem with the objective of minimizing the total costs of material handling. The layouts were evaluated by simulation model and then they were returned to the GA to be utilized in the selection of the next generation of candidate facility layout. The simulation model was built in simulation software eM-Plant, which provides the development language SimTalk and supports to program the control logic of the production process.

Zhou et al. (2009) implemented a site layout optimization system within a simulation environment. Their approach integrated the general purpose simulation for modeling space, logistics and resource dynamics with genetic algorithms for optimizing the layout based on various

[1] https://www.raute.com/
[2] https://www.visualcomponents.com/

constraints and rules. The approach presented in their article was created in Simphony[3], a simulation engine for building general and special purpose simulation models. Simphony uses GA as a simulation engine. Shahin & Poormostafa (2011) proposed an approach by combining simulation, fuzzy analytic hierarchy process and quality function deployment, and multiple criteria decision making technique for facility layout design. In their approach, a systematic layout design procedure was used to generate a considerable number of layout alternatives. The computer simulation was used to determine quantitative measures such as total cost, waiting time and cycle time. The simulation models were implemented in the Arena simulation software. A multiple criteria decision making technique was used to optimize the layout problem. Lee (2012) proposed an integrated model to optimize a facility layout problem with the objective of minimizing the total walking time. Pedestrian behavior was simulated in VISSIM, which allows the facility layout combination data to be rewritten as a .inp file and also controls the simulation through the component object model (COM) interface. The COM is designed to be used with external programming environments. Thus, it is available to be connected to an external program for doing optimization purposes. In the optimization process, an ant colony optimization was used to determine the optimal locations for the facilities. Abu Bakar (2013) concentrated on the design and optimization of layout for flexible manufacturing systems. ARENA was used to build the simulation model and optimize it.

Butakov et al. (2015) proposed a framework for detectors layout optimization based on a multi-agent simulation. They utilized a special agent-based simulation engine. Their framework consists of three main components: PULSE agent-based simulation engine data structure optimization module, detector layout optimization module based on a genetic algorithm and auxiliary optimization module, which includes interactive visualization. Azadeh et al. (2015) presented a simulation optimization approach to deal with the job shop facility layout design problem. The computer simulation was used for performance modeling of each layout such as average time-in-system, average queue length and average machine utilization. The stochastic data envelopment analysis (SDEA) method was applied for the optimization. SDEA is able to find the

[3] https://www.simphony-project.eu/

optimal layout solution through ranking decision-making variables. Visual SLAM was used as the simulation language for solving the layout optimization problem. Simulation provides a systematic method for evaluating different layout scenarios based on generated data and the objective function to assist the decision-maker.

Pourhassan & Raissi (2017) proposed a simulation optimization for a dynamic facility layout problem (DFLP) with the two objectives of minimizing the material handling cost (MHC) and the number of possible collisions between transporters. Their approach was based on response surface methodology in which a set of scenarios is defined and simulated. Then a regression metamodel is developed to fit a second-order polynomial equation between decision variables and the second objective function. To search the solution space, a NSGA-II was applied. In NSGA-II the regression equation was used to calculate the second objective function. RazaviAlavi & AbouRizk (2017) outlined a framework employing GA and simulation for decision making for site layout planning. The simulation model was built in the Simphony environment and had in manual connection with GA. A limited number of layouts were selected as elite layouts to be imported into the simulation model to find the optimum layout. Azimi & Soofi (2017) proposed a simulation optimization framework, which integrated the simulation, artificial neural network (ANN) and a metaheuristic optimization algorithm. In this approach, a set of scenarios was generated that each scenario showed a layout design. Then, the simulation model was used to calculate the MFT of each scenario as the output of the scenario. This data was used to train an ANN to approximate the objective function. In fact, ANN worked as MFT estimator inside the metaheuristic algorithm.

Garcia et al. (2018) studied the conceptual modeling activities of simulation optimization for facility layout design in conditions of high uncertainty. They considered three cases in two manufacturing companies. The companies in this study were chosen based on whether they were using simulation optimization in their facility layout design or not. Binhomaid (2019) developed a construction site layout planning framework that used agent-based simulation technology to analyze the workers' movements and behaviors on site and to study the impact of those on site

productivity and safety. NetLogo[4] was applied as a multi-agent programming language and modeling environment. The objective function represented the total number of trips associated with a given site layout. Simulation model read and imported the coordinates of these locations from a CSV file. CSV files transferred the data to a GA optimization model to determine the optimum locations of all facilities on site. Masoud et al. (2019) presented a simulation optimization framework to simultaneously find the optimal facility layout design and resource allocation. They used a heuristic algorithm to optimize the problem with the objective of maximizing the production capacity. Several layout scenarios were evaluated by Arena and the optimal layout was selected. Chen et al. (2021) presented a simulation-optimization approach to solve the sortation conveyor layout problem. To design the simulation model, a practical sortation system framework was employed using Plant Simulation[5] which is a 3D dynamic simulation software. A genetic algorithm with local search was proposed to find the optimal design. Simtalk, the scripting language in Plant Simulation, was used to change the behavior of the objects.

According to the reviewed literature, limitations in the available simulation optimization approaches are as follows:

- Some approaches have used simulation to generate a metamodel based on RSM or ANN. In these approaches, all the stochastic and dynamic characteristics of the system are shown in a linear (or quadratic) polynomial regression model or in an ANN. Even if these approaches replace simulation with an explicit deterministic metamodel, they are just an approximation of the performance of the real systems and unfortunately, in many cases, the metamodel approximation is far from the real system performance. Also, these approaches are time-consuming because, in case of a change in the problem characteristics, a new metamodel should be created.
- Some approaches have used optimization tools in simulation software; each of these optimization tools utilizes one or more optimization algorithm. For example, OptQuest (embedded

[4] https://ccl.northwestern.edu/netlogo/
[5] https://www.plm.automation.siemens.com.

in AnyLogic, Arena, Crystal Ball, Enterprise Dynamics and SimFlex) uses tabu search, neural networks and integer programming. These packages are limited to a few optimization approaches. Considering the fact that some problems are better to be optimized by a specific optimization algorithm, approaches that use the optimization tools in simulation software are not well-fitted for the optimization propose. Moreover, since most of the optimization engines embedded in commercial simulation software act like a black box optimization (Ait El Cadi et al., 2016), the optimization process is not accessible to be modified for conducting a better search or eliminating infeasible solutions that cannot satisfy the problems' constraints. Also, because of limitations in programming, these approaches are only able to be applied to simple layout problems.

- Some other approaches use two separate tools and connect the tools using an interface. Connecting optimization and simulation using an interface needs for transferring data between two separate tools that is very time-consuming and so these methods only allow a limited number of solutions to be evaluated. Therefore, there is a need for a more integrated approach.

In the next section, we are going to develop a simulation optimization approach that can support a direct connection between simulation and optimization. The proposed approach is able to use several types of optimization algorithms to do the search process in the most effective manner.

4.4. Proposed simulation optimization approach

In this section, we suggest a simulation optimization approach and then use it to solve a problem of facility layout and aisles structure. We use Matlab because of its ability to provide both a simulation environment and an optimization environment. Because the optimization environment is open source, many optimization algorithms can be used. Therefore, the proposed approach has the ability to be based on metaheuristic, heuristic and exact optimization algorithms. These optimization algorithms can be codded so that all the problem constraints are satisfied as much as possible. All the stages of the optimization process are accessible for modification. It is

possible to check the feasibility of the solutions before given to simulation. This helps to save computational time. The simulation is done by Simulink. Simulink has the capability to simulate any system with any type of dynamic and stochastic phenomena of the system. Matlab provides an integrated environment for simulation and optimization. Therefore, making a connection between simulation and optimization algorithm through direct connection available in Matlab. Consequently, a direct connection between simulation and optimization is implemented. The procedure of the proposed simulation optimization approach is illustrated in Figure 4.1.

To show how the proposed simulation approach can be applied to optimize the problem of facility layout and aisle structure, an application example is described in section 4.5. In section 4.5.1 we show how the aisles are designed. Section 4.5.2 presents the mathematical model. Section 4.5.3 is concerned with the optimization phase, in which a multi-objective metaheuristic algorithm is adopted to find the optimal solution. In section 4.5.4, simulation phase, a simulation model is constructed in Simulink to simulate the example problem.

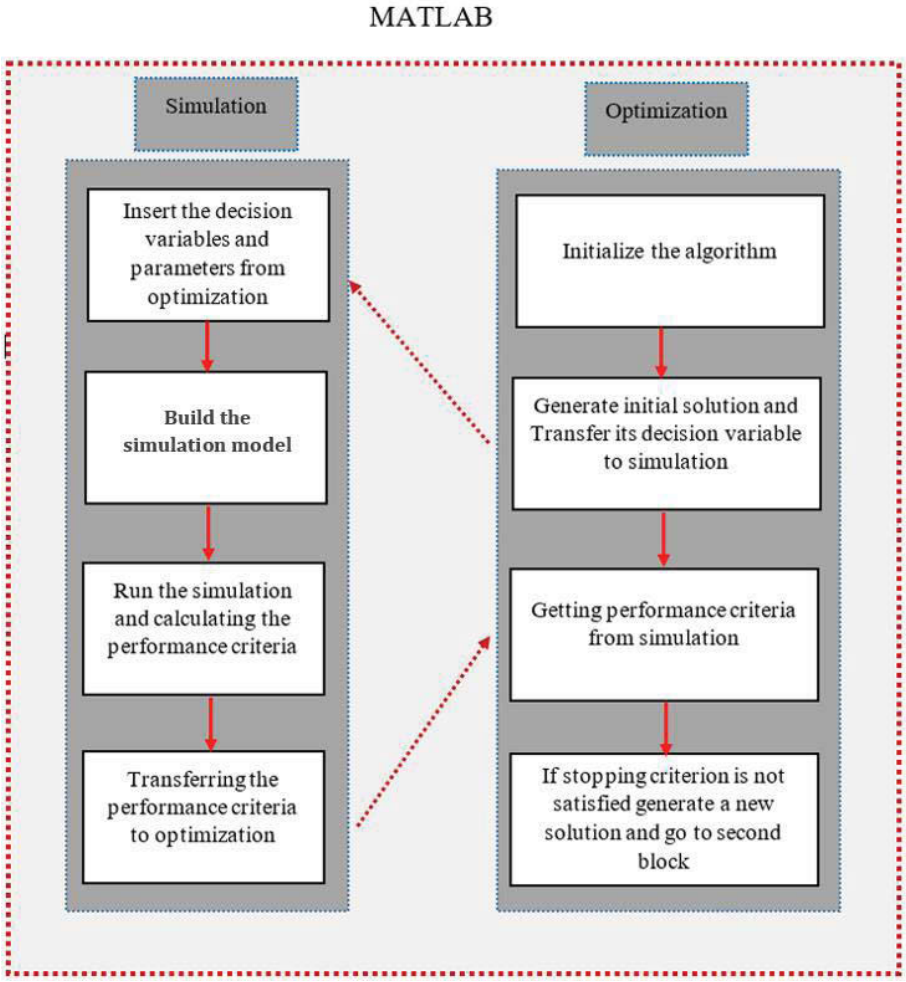

Figure 4.1. Simulation optimization approach

4.5. Applying the proposed approach on a layout problem with aisles

We are interested in determining the layout of facilities and aisles structure in a manufacturing system. Each facility is considered as a processing machine. There are M facilities with dimension $l_m \times w_m$ and the size of the shop floor is $L \times W$. There are transporters in the system that move on the aisle and transport materials between facilities. The facilities (machines) process times and transportation time are stochastic. To apply the proposed simulation optimization approach, in the first stage, the aisles structure is designed. We use a simple version of the aisles structure that is

used to design the aisles through a heuristic. A series of positions are created and the facilities should be allocated to these positions. This implies that the problem turns to a discrete problem of allocating facilities to locations. However, since in the proposed approach the optimization is done in a powerful and totally independent programming language and can be unconditionally connected to the simulation model, it can be used for continuous problems with any form of aisles structure. Since the width of the aisles cannot be infinite, each aisle is given a capacity that shows the number of transporters that can pass an aisle at the same time. After designing the aisles, a multi-objective metaheuristic algorithm is used to find the optimum location of facilities. Two objectives of minimizing material handling cost (MHC) and mean flow time (MFT) are used as the performance criteria. The simulation model is used to calculate the MFT.

4.5.1. Heuristic method to design the aisles

In our approach, several strategies to define the aisles can be used, so that the approach has a big potential. We use a heuristic method to design the aisles. To describe how the heuristic is used to define the aisles consider a shop floor of the manufacturing system that has a rectangular shape with length *L* and width *W*. The facilities are equal and have rectangular shapes with predetermined orientations. There are vertical and horizontal aisles. The width of the aisles is equal to *wa*. The aisles divide the shop floor into sections, called positions. The length of vertical aisles is equal to *W* and the length of horizontal aisles is equal to *L* and so the aisles are extended to the boundaries of the shop floor. With such consideration, we avoid creating triangular or odd-shaped positions. Therefore, each possible position of the facility will have a rectangular shape. Facilities are assigned to possible positions. The aisle network must be so that there is enough space for facilities to be assigned inside the positions. To satisfy this first we determine the maximum number of vertical and horizontal aisles. By knowing the length and width of facilities, (*lm*, *wm)*, the number of vertical (R) and horizontal (S) aisles must be so that Equations (1) and (2) are satisfied.

$$\lfloor (L - lm)/(lm + wa) \rfloor \leq R \leq \lfloor (L + lm)/(lm + wa) \rfloor \qquad (4\text{-}1)$$

$$\lfloor (W - wm)/(wm + wa) \rfloor \leq S \leq \lfloor (W + wm)/(wm + wa) \rfloor \quad (4\text{-}2)$$

Therefore, there is a possibility to select the number of aisles inside a special range. Since at least one facility can be placed in each position, the number of vertical and horizontal aisles must be determined so that the possible number of positions is greater than the number of facilities. This is guaranteed through the following equations.

$$M \geq N \quad (4\text{-}3)$$

$$N = R' \times S' \quad (4\text{-}4)$$

$$R' = \begin{cases} R + 1, & if\ R = \lfloor (L - lm)/(lm + wa) \rfloor \\ R - 1, & if\ R = \lfloor (L + lm)/(lm + wa) \rfloor \\ R, & else \end{cases} \quad (4\text{-}5)$$

$$S' = \begin{cases} S + 1, & if\ S = \lfloor (W - wm)/(wm + wa) \rfloor \\ S - 1, & if\ S = \lfloor (W + wm)/(wm + wa) \rfloor \\ S, & else \end{cases} \quad (4\text{-}6)$$

M is the number of facilities and N is the number of possible positions that are generated after creating aisles. This guarantees that the number of generated positions is at least equal to the number of facilities. We start by placing vertical aisles. If we had used the maximum number of allowable vertical aisles, we start by placing the aisle. Then, the next vertical aisle is placed so that the distance between it and the left-side vertical aisle is equal to the length of a facility. According to the same procedure, other vertical aisles are placed one by one until it is not possible to add a new aisle or facility. If we had used the minimum allowable aisle, then we start by placing the facility. After that aisles and facilities are placed one by one according to the described procedure. After placing the vertical aisles, there may be empty space between the boundaries of the shop floor and the last facility or aisles. These empty spaces can be used to increase the width of the most used aisles. The horizontal aisles are placed just like the way we placed vertical aisles. Next section describes the optimization algorithm to place facilities in positions.

4.5.2. Optimizing the location of facilities

After determining the aisles structure and positions, the facilities must be placed on the shop floor in a manner that no overlap between facilities and aisle occurs. Considering the length and width of the positions and facilities dimension, by placing one facility in each position no overlap will occur. Therefore, we have a set of *M* processing facilities that must be assigned to *N* positions. The aim is to assign the facilities to the positions so that MHC and MFT are minimized. Before characterizing the problem, let us first introduce the new notations:

Indices	
i, j	Index for facilities, i, $j = 1,\ldots,M$
k,l	Index for positions, $k,l = 1,\ldots,N$
tr	Index for transporters, $tr=1,2,\ldots,TR$
a	Index for aisles, $a=1,2,\ldots,R+S$
Parameters	
$F_{i,j}$	Total material flow between facility *i* and *j*
$D_{k,l}$	The distance between positions *k* and *l*
$C_{i,j}$	Transportation cost between facility *i* and *j*
wth_{tr}	The width of transporter tr
wa_a	The width of aisle a
Decision variable	
$M_{tr,tr',a}$	1 i1if transporter tr and tr' go across each other in aisle *a* at the same time 0 otherwise

$X_{j,l}$	1 if the facility *j* is placed in the position *l* 0 otherwise

According to the above parameters and decision variables, the problem is mathematically modeled as follows:

$$min\ Z_1 = \text{MHC} = \sum_{i=1}^{M}\sum_{j=1}^{M} D_{k,l} \times C_{i,j} \times F_{i,j} \times X_{i,k} \times X_{j,l} \tag{4-7}$$

$$min\ Z_2 = MFT = E\left[f(X_{j,l}, \epsilon)\right] \tag{4-8}$$

$$\sum_{l=1}^{N} X_{j,l} = 1 \qquad \forall j \tag{4-9}$$

$$\sum_{j=1}^{M} X_{j,l} \leq 1 \qquad \forall l \tag{4-10}$$

$$M_{tr,tr',a}(wth_{tr} + wth_{tr'}) \leq wa_a \qquad \forall tr, tr', a \tag{4-11}$$

$$X_{j,l}, M_{tr,tr',a} \in \{0,1\} \qquad \forall\ i,k,tr,tr',a \tag{4-12}$$

The first objective function minimizes the MHC. The second objective function minimizes MFT. It can be seen as a measure of the operational performance of the system and almost all simulation studies include MFT as a major performance measure (Bokhorst, 2005). MFT can reflect the impact of the position of facilities and capacitated aisles. For example, when two transporters are going to pass through a special aisle with capacity one, then interference among transporters occurs and one of them must wait for the aisle to get empty. This situation can result in considerable delay and can impact the MFT in manufacturing systems (Chiang et al., 2006). Therefore, the second objective of the mathematical model is to minimize the MFT. Formally, the

binary decision variable $X_{j,l}$ takes value 1 if the facility j is placed in the position l, and 0 otherwise. Constraints set (4-9) guarantee that each facility is assigned to one position. Constraints set (4-10) guarantee that in each position at most one facility is placed. Constraints set (4-11) control that at each time the number of transporters in an aisle is less than the aisle capacity. The constraints set (4-12) control the decision variables.

4.5.3. Multi-objective metaheuristic algorithm

We need to optimize both the MHC and the MFT. As a consequence, we need a multi-objective optimization approach. In this respect, one of the most effective multi-objective evolutionary algorithms called non-dominated sorting genetic algorithm (NSGA-II) is modified and used. NSGA-II is a computationally efficient algorithm implementing the idea of a selection method based on classes of the dominance of all the solutions. The key idea of the NSGA-II is ranking the solutions. The ranking process is based on fast non-dominated sorting algorithm, in which, the solutions are ranked on the basis of an individual's non-domination level. Solutions with equal non-domination level are ranked according to the density of the solutions at the neighborhood of that solution. This criterion, which guarantees diversity along the obtained solutions, is called the crowding distance (CD). The selection of parents for the next generation is based on first the non-domination rank and then the crowding distance. The new solutions are generated by NSGA-II operators such as crossover and mutation. The search process will be continued until the stopping criterion is satisfied.

As mentioned earlier, in NSGA-II the crowding distance metric will guarantee diversity along the non-dominated front (NDF). But it fails to keep lateral diversity. Lateral diversity is essential to have better convergence in the search algorithm as a result of evading too much exploitation than exploration. In order to overcome this shortcoming, we proposed a modified NSGA-II (MNSGA-II) by using a new diversity preservation approach called Dynamic Crowding Distance

(DCD). DCD is able to maintain lateral diversity and to maintain uniform distribution of non-dominated solutions. The concepts of the DCD are explained in the next section.

4.5.3.1. Dynamic crowding distance (DCD)

The horizontal diversity of Pareto front is essential in any multi-objective evolutionary algorithm (MOEA). In normal NSGA-II this task is done by CD as given in Equation (13-4). The removal precedence applies to the individuals with lower values of CD.

$$CD_i = \frac{1}{r}\sum_{k=1}^{r}\left|f_{i+1}^{k} - f_{i-1}^{k}\right| \tag{4-13}$$

where *r* is the number of objectives, f_{i+1}^{k} is the *kth* objective of the *i+1*th individual and f_{i-1}^{k} is the *k*th objective of the *i-1*th individual after sorting the population according to one of the objectives. As illustrated in Figure 4.2, the use of CD criterion may cause lack of uniform diversity in the obtained non-dominated solutions. In Figure 4.2, according to this crowding distance method the individuals C–E must be deleted from NDF, because of their small CD values. Therefore, some parts of this NDF are too crowded and some parts are too sparse. Also, since around point B one side of the rectangle is short then the CD value for B is small, while another side is long. However, the CD of F is large because the length of one side almost equals another side. If one individual must be removed between the individuals B and F because of small CD value, individual B will be taken away and F will be survived in NDF. But, in order to get good horizontal diversity, the individual B should be maintained, because the individual B helps to preserve uniform spread. This is the major shortcoming of CD.

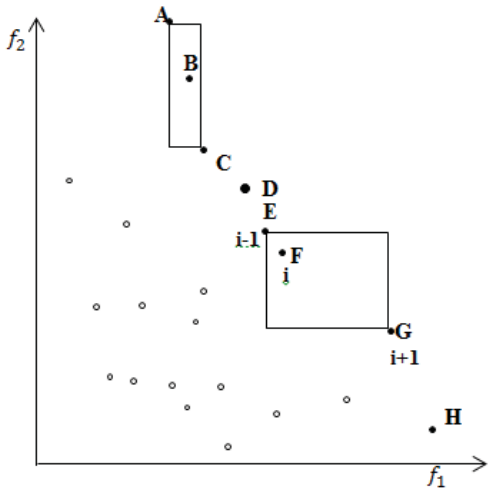

Figure 4.2. Crowding distance of solutions in NDF.

To overcome this weakness, Luo et al. (2008) have been recently suggested the dynamic crowding distance (DCD) method. In this method, every time one individual with the lowest DCD value is eliminated the DCD is recalculated for the remaining individuals. The DCD formula is given in Equation (4-14):

$$DCD_i = \frac{CD_i}{log(1/V_i)} \tag{4-14}$$

In which CD_i is calculated by Equation (4-13) and V_i is given in Equation (4-15).

$$V_i = \frac{1}{r}\sum_{k=1}^{r}(\left|f_{i+1}^k - f_{i-1}^k\right| - CD_i)^2 \tag{4-15}$$

V_i is the variance of CDs of individuals which are neighbors of the *i*th individual. V_i can give information about the different variations of CD in different objectives.

4.5.3.2. A Fast Non-Dominated Sorting Approach

The concept of domination is applied to sort the flows. Based on the non-domination definition, a solution dominates the other solutions if its objective function is not worse than the others and at least, one of its objective functions is better than the other ones. Figure 4.3 shows a graphical representation of the non-dominated sorting for a minimization problem. Individuals, such as x_1, x_4, x_6, and x_7 are assigned the ranks as rank 1 since there is no individual that is superior to them with respect to $f_1(x)$ and $f_2(x)$. The individuals of rank 1 are removed and the individuals with rank 2 are selected in the same way. This procedure is repeated until all the individuals are ranked. The Pareto-optimal front includes the solutions existing in front 1 (rank 1 solutions).

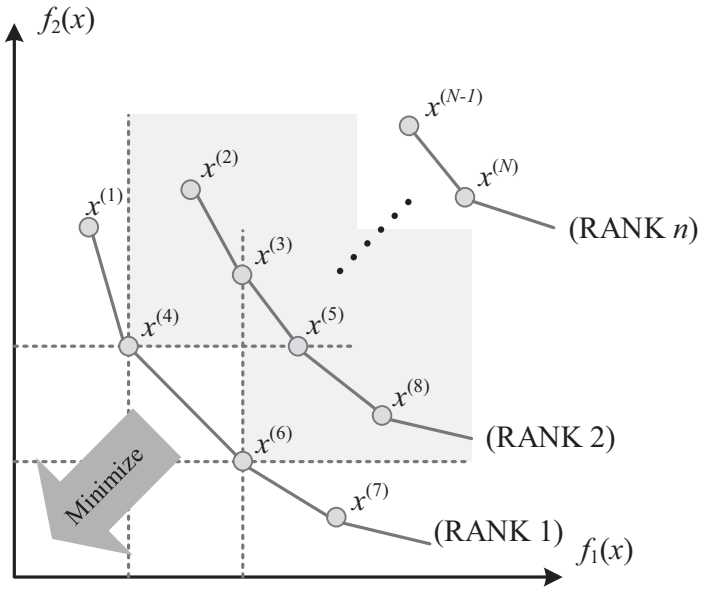

Figure 4.3. Schematic representation of the non-dominated sorting approach for two objectives.

4.5.3.3. Chromosome structure

One of the most important issues in applying any metaheuristic algorithm is to develop an effective solution representation. The solution encoding of the proposed problem is a permutation of $\{1, 2 \dots, N\}$. By scanning from left to right, the first number shows the position wherein facility 1 must be assigned; the second number shows the position wherein facility 2 must be assigned and so on. As explained in Section 4.5.1, the number of facilities is less than the number of positions, $M \leq N$, and hence in order to assign facilities to positions, $N - M$ dummy facilities are defined. If a dummy facility is assigned to a position, that position is empty. For instance, Figure 4.4 shows an example of a chromosome for a problem with 6 facilities and 8 positions. Facilities 7 and 8 are dummy facilities and hence, positions 2 and 6 are empty. In this way, both constraints (4-9) and (4-10) will be satisfied. The constraint related to non-overlapping the facilities is satisfied since the aisle network is determined based on the method described in section 4.5.1, no overlap between facilities and aisles will occur. Constraints (4-9) and (4-10) are satisfied by the way we define the solution in the NSGA-II. To satisfy the constraint (4-11), when a transporter is going to enter an aisle, the simulation model verifies two things: (1) the capacity of that aisles and (2) whether any other transporter is in that aisle. According to these two matters, the simulation model let the transporter go across the aisle or stop the transporter until the aisle gets empty. In this way the constraint (4-11) is satisfied.

Position	1	2	3	4	5	6	7	8
Machine	3	7	5	4	6	8	2	1

Figure 4.4. Chromosome representation

4.5.3.4. Crossover operator

The crossover operator combines two chromosomes to produce two new chromosomes. To apply the proposed crossover operator first a cross point is randomly selected between *1* to *N*. Then, the facility numbers before the cross point of Parent 1 are directly copied in the first offspring. The remaining facility numbers are put into empty positions according to their relative positions in Parent 2 (Figure 4.5). In this way, we avoid duplicating numbers and so constraint sets (4-9) and (4-10) are satisfied.

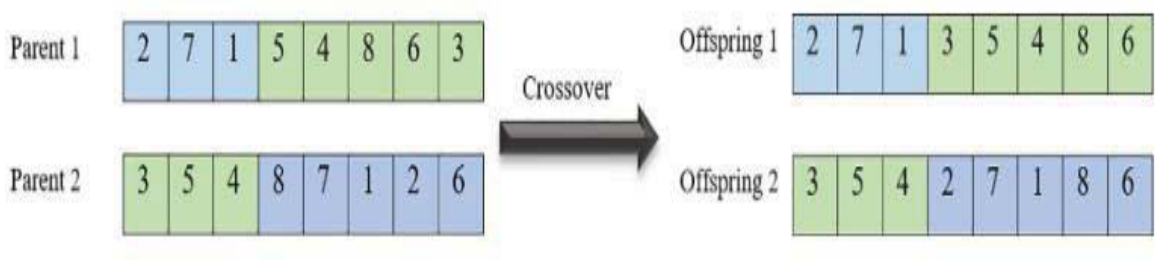

Figure 4.5: An example of a crossover operator

4.5.3.5. Mutation operator

The purpose of the mutation is to prevent the population from being too similar and the algorithm from getting trapped into a local optima. According to (Smullen et al., 2014), it is preferred to apply the mutation only when the similarity solutions exceed a predefined value. In order to find the similarity coefficient (SC) between each pair of chromosomes Equation (4-16) is used

$$SC_{ab} = \frac{\sum_{i=1}^{M}\{\partial(X_{ia}, X_{ib})\}}{\bar{M}} \quad (4\text{-}16)$$

where X_{ia} andX_{ib} are the locations of facility *i'* in the chromosomes '*a'* and '*b'* and $\bar{M}$ *'* is the number of gens. $\partial(\alpha, \beta)$ is the similarity between two especial genes and is expressed as Eq. (4-17).

$$\partial(\alpha, \beta) = \begin{cases} 1 & if\ \alpha = \beta \\ 0 & otherwise \end{cases} \quad (4\text{-}17)$$

The average similarity coefficient of the population is calculated as follows:

$$\overline{SC} = \frac{\sum_{a=1}^{Npop-1}\sum_{b=a+1}^{Npop} SC_{ab}}{\binom{Npop}{2}} \quad (4\text{-}18)$$

where *Npop* is the number of chromosomes in the population. Finally, considering a pre-defined threshold similarity coefficient (φ) and the obtained average similarity coefficient, the mutation operator will be automatically incorporated into the MNSGA-II loop as follows:

$$\begin{cases} \text{if} \overline{SC} > \varphi & \text{apply mutation operator to} \text{MNSGA} - \text{II loop} \\ \text{otherwise} & \text{do not use mutation operator in MNSGA} - \text{II loop} \end{cases}$$

Finally, when the similarity coefficient is greater than the predefined threshold the mutation is incorporated into the NSGA-II loop. To perform the mutation operator, first a chromosome is randomly selected. Then, as shown in Figure 4.6, the genes of the selected chromosome are arranged reversely. It should be noted that because we just change the sequence of genes, the chromosomes remain feasible.

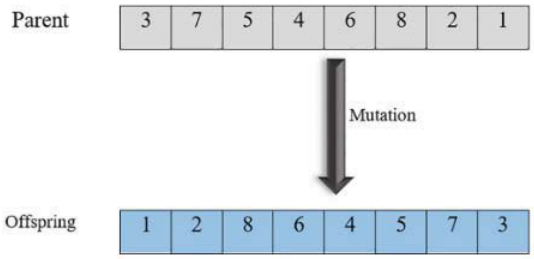

Figure 4.6. An example of a mutation operator

4.5.3.6. Stopping criteria

The stopping criteria are defined as the number of generations. The algorithms continue to generate a new population until the number of generations reaches a predefined value. This value is determined based on the results of some designed experiments.

4.5.4. Simulation model

In this section, the simulation model is described. The simulation model is developed in Simulink. Simulink, developed by MathWorks, is a modeling, simulation and analysis software for dynamic systems. It allows the study of linear and nonlinear systems modeled continuously, discrete or hybrid (MathWorks, 2001). Simulink takes advantage of being fully integrated with Matlab. So, the user has access to all the Matlab features and toolboxes and can create its own scripts algorithm and model that can be used indefinitely. The most important tool in Simulink to develop a simulation model for manufacturing systems is SimEvents. SimEvents (MathWorks, 2005) is designed to simulate Discrete Event Systems and it is fully embedded in Simulink, which is a traditional time-driven simulator. Hence, SimEvents is equipped with functionality that enables an effective co-existence of time-driven and event-driven components in complex hybrid systems. In addition, this design allows SimEvents to take advantage of a rich collection of visualization, data processing, and computation tools in both Simulink and MATLAB. According to (Ait El Cadi et al., 2016), Simulink is almost six times faster than Arena. This simulation model

is used as a fitness function (MFT) calculator and is directly connected to the optimization environment in Matlab to run any of the heuristics and metaheuristics. All the optimization algorithms are tunable. Unlike optimization tools in simulation software that act like a black-box, in Matlab, we could interact with the solvers' parameters like genetic algorithm operators and simulated annealing temperature.

Figure 4.7 shows the main components of the simulation model. There are 12 facilities. Facilities are connected together through input and output switch. Facility 1 is a product generator and is used to enter the parts into the system. Facility 12 is used to exit products from the system. Each facility contains a facility, two queues as temporary buffers to store products and resource releaser and resource acquire. A resource releaser is used to release the transporter when it is delivered to facilities and a resource acquire is used to call a transporter when a product is ready to be sent. In order to calculate the MFT, the time when a job enters and exits the systems is recorded and its deference is called flow time. For each job *i*, the flow time is calculated. Once the simulation model stopped, flow times of all the jobs are averaged and MFT is calculated.

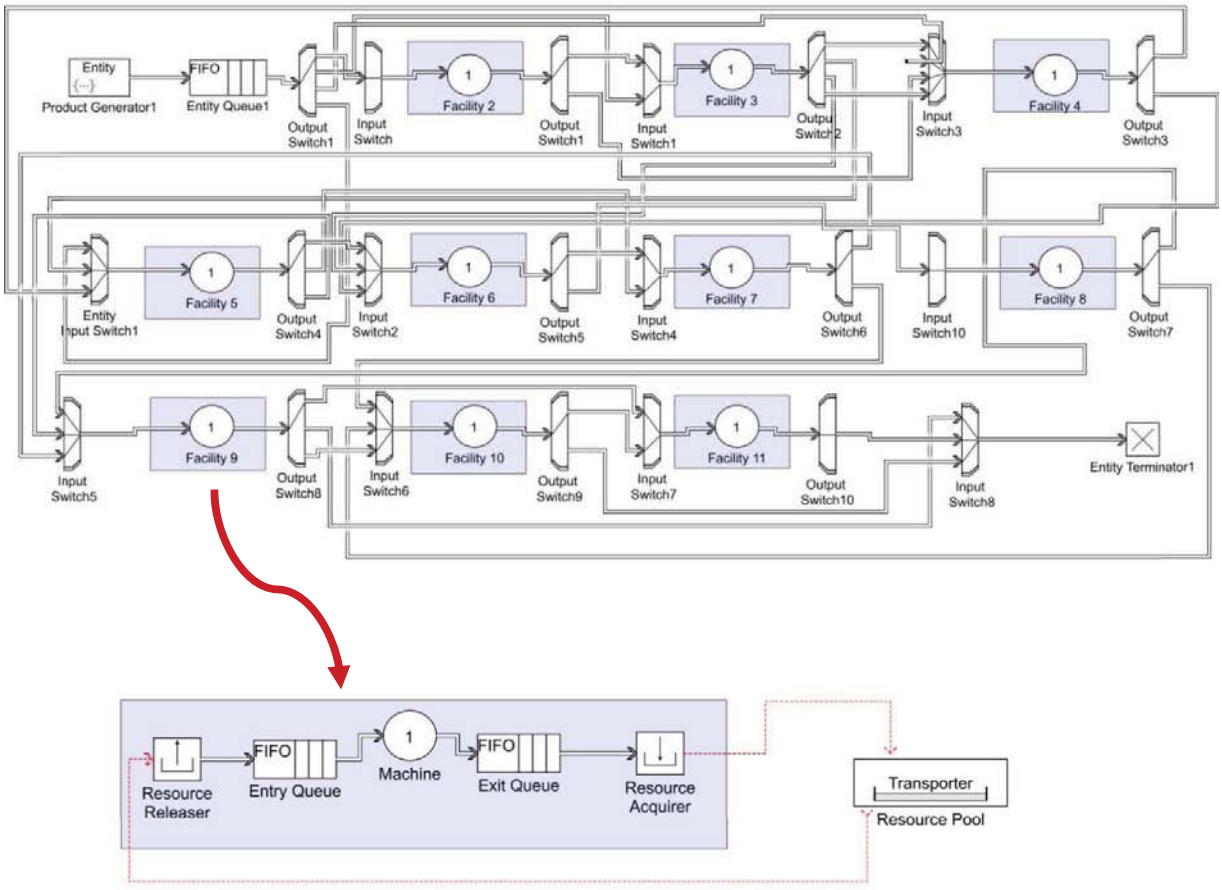

Figure 4.7. An example of the simulation model

4.6. Computational experiments

In this section, the application of the proposed approach is illustrated by an example. The example is an 83m×39m manufacturing system with 12 facilities each with a dimension of 17m×9m. The data is extracted from a case presented by Ho & Liu (2006). Facilities 1 and 12 are virtual facilities to show the system's entry station and exit station, respectively. Table 4.1 shows the probability distribution of demand and process sequence of each product. The details of processing time facilities (machines) and transporters are presented in Table 4.2 and Table 4.3. In

these tables, *N* means normal distribution and *NegExp* means negative exponential distribution. The width of the aisles and transporters are respectively 3 and 2. Therefore, the capacity of the aisle will be equal to 1. According to Equations (4-3)-(4-6), the number of the vertical aisle must be between 3 and 5 and the number of the horizontal aisles must be between 2 and 4. We select 5 vertical and 4 horizontal aisles. Each horizontal aisle *i* is partitioned into five parts (i1….i4) and each vertical aisles *i* is partitioned into three parts (i1…i3) (see Figure 4.8). As a result, 12 possible positions are generated. The facility can be placed inside each position, except positions 1 and 12 which are used as input and output. We consider the capacity of all aisles equal to one. The Greatest Queue-Length (GQL) is selected as a dispatching policy. According to Ho & Liu (2006), GQL is the best dispatching policy for minimizing the time-based indexes. In GQL, a transporter gives priority to the facility that has the greatest number of waiting parts. The number of simulation replications for each layout is set at 30.

Table 4.1. Product routes

Product. No	Demand	Sequence
1	N (25,3)	1→3→5→7→9→11→12
2	N (10,2)	1→2→4→6→8→10→12
3	N (30,4)	1→4→5→7→9→10→12
4	N (23,2)	1→3→4→5→9→11→12
5	N (21,2)	1→2→3→6→8→9→12
6	N (40,4)	1→5→6→7→10→11→12

Table 4.2. The processing time distribution

Facility. No	Process time	Breakdown (s)	Repair (s)
1	N (60,6)	NegExp(2000)	N (150, 10)
2	N (90,9)	NegExp(1800)	N (300, 15)
3	N (120,12)	NegExp(1950)	N (200, 12)
4	N (60,6)	NegExp(1700)	N (100, 5)
5	N (120,12)	NegExp(3100)	N (150, 10)
6	N (120,12)	NegExp(2800)	N (190, 15)
7	N (90,9)	NegExp(2450)	N (250, 18)
8	N (90,9)	NegExp(1900)	N (230, 10)
9	N (120,12)	NegExp(2300)	N (170, 8)
10	N (60,6)	NegExp(2100)	N (150, 10)

Table 4.3. Transporters characteristics

Speed (m/s)	N (1,0.2)	Load time (s)	N (4,1)
Acceleration (m/s^2)	N (0.3,0.02)	Unload time(s)	N (5,1.2)
Deceleration (m/s^2)	N (0.3,0.02)	Turn speed (deg/s)	30

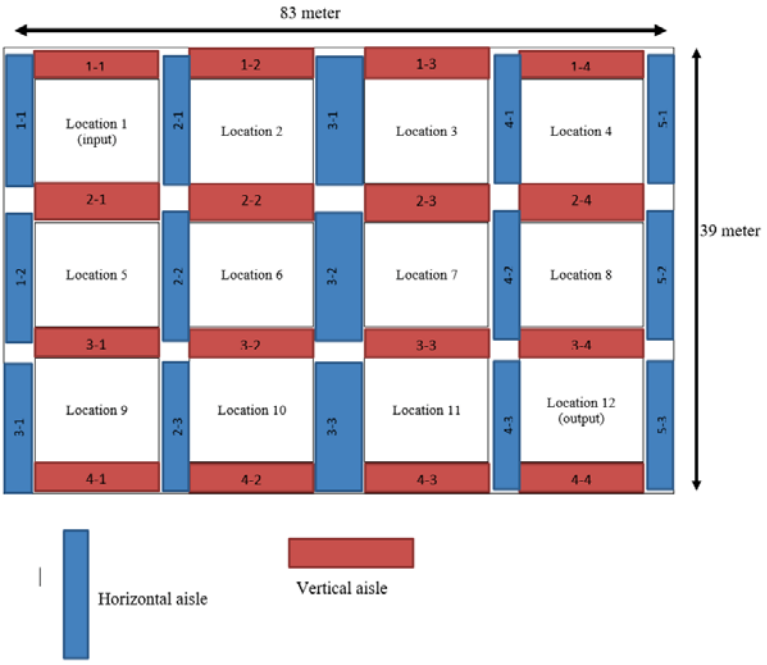

Figure 4.8. Aisles and locations

4.6.1. Tuning the parameters

The metaheuristic algorithms are sensitive to their parameters so that a small change in the algorithm's parameter can affect the quality of the obtained solutions. Therefore, it is necessary to apply a fine tuning procedure for the parameters to find better solutions. In order to tune the parameters of the proposed algorithms, we use the Taguchi method. Taguchi method is a fractional factorial experiment to reduce a large number of experiments in the full Factorial designs. The affecting factors are categorized into two parts, including (1) controllable or signal factors (*S*) and (2) noise factors (*N*). Taguchi proposed a procedure to control *N* for reducing the variation around the target with regard to orthogonal arrays. To this aim, the method seeks to minimize the effect of noise and to determine the optimal level of signal factors. According to the type of the response, the calculation of signal to noise ratio is classified into three types: (I) smaller is better type, (II) nominal is better type and (III) larger is better type. Then, the aim of the method is to maximize the *S/N* ratio. Considering the high importance of handling costs, the parameter tuning is done

based on MHC and MHC is used as the response of each experiment. Since the response of each experiment is MHC, the lower is better type is used. The parameters of MNSGA-II along with their levels are shown in Table 4.4.

Table 4.4. Algorithm parameter ranges along with their levels

Algorithm	Parameter	Description	Level 1	Level 2	Level 3
MNSGA-II	*Npop*	Initial pop size	50	75	100
	P_c	Percent of cross over	0.6	0.7	0.8
	P_m	Percent of mutation	0.05	0.1	0.15
	Niter	Number of generation	100	150	200
	φ	Threshold similarity coefficient	0.1	0.15	0.2

Since a solution with the lowest MHC is desired, the aim is to find maximum *S/N* calculated by Eq. (4-19)

$$\frac{S}{N} = -10log(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}) \quad (4\text{-}19)$$

The designed experiments used for algorithms along with the experimental results are presented in Table 4.5. The *S/N* values are shown in Figure 4.9 that the highest values of which present the best level of the algorithms' factors.

Table 4.5. The L27 orthogonal array and experimental results to tune MNSGA-II

Exp No.	*Npop*	*Pc*	*Pm*	*Niter*	φ	Respond
1	1	1	1	1	1	84216
2	1	1	1	1	2	79312
3	1	1	1	1	3	81067
4	1	2	2	2	1	75982

5	1	2	2	2	2	75672
6	1	2	2	2	3	76803
7	1	3	3	3	1	76363
8	1	3	3	3	2	80534
9	1	3	3	3	3	79818
10	2	1	2	3	1	72063
11	2	1	2	3	2	70166
12	2	1	2	3	3	71677
13	2	2	3	1	1	73512
14	2	2	3	1	2	75087
15	2	2	3	1	3	76353
16	2	3	1	2	1	71831
17	2	3	1	2	2	72321
18	2	3	1	2	3	73361
19	3	1	3	2	1	77929
20	3	1	3	2	2	70934
21	3	1	3	2	3	73349
22	3	2	1	3	1	71936
23	3	2	1	3	2	73120
24	3	2	1	3	3	72327
25	3	3	2	1	1	70125
26	3	3	2	1	2	74699
27	3	3	2	1	3	69308

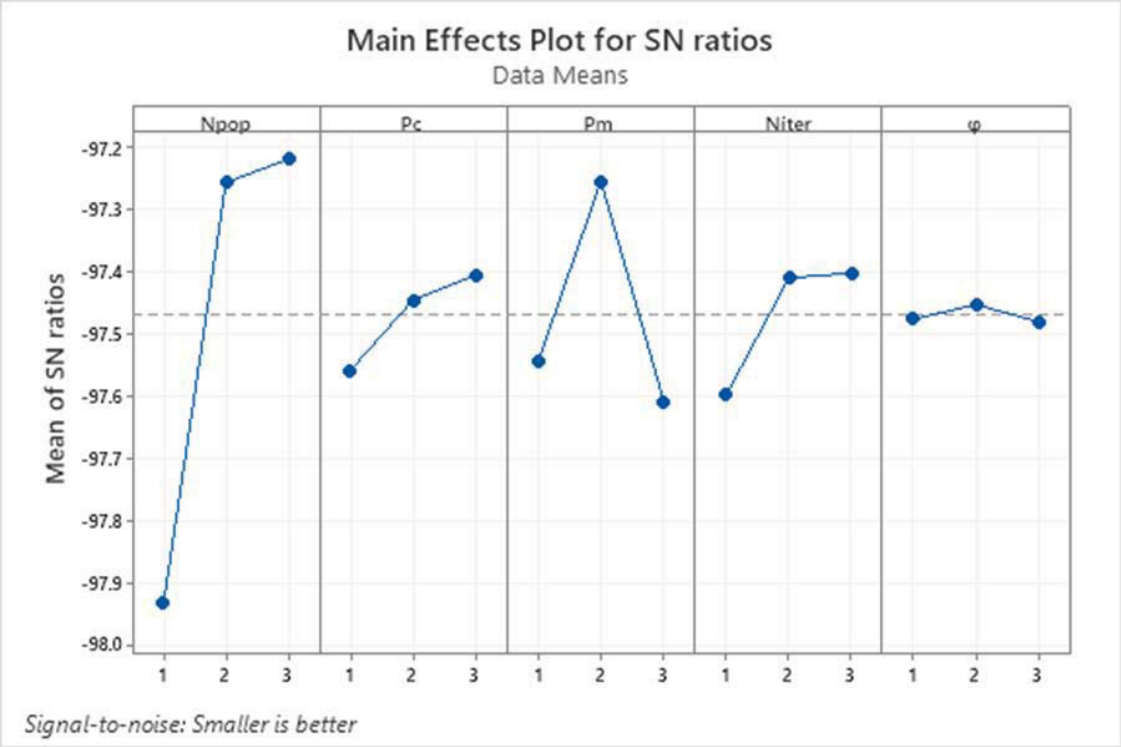

Figure. 4.9. Taguchi ratios for all proposed algorithm

4.6.2. Pareto front

The parameters of MNSGA-II is set based on the results of parameter tuning. During the search process, MNSGA-II uses the simulation to calculate the MFT corresponds to each layout. To take randomness into account we used 30 replications of 10000 with a warm-up time of 1000 (Law, 2014). To verify the simulation model, we first consider that all the parameters as deterministic parameters Then, the value of objective function is calculated by exact formula and compared with the simulation results (Sargent, 2010). Also, some input parameters were changed (sensitivity analysis) and the simulation model showed a logical behavior. This simulation model is used to compute the objective function of each chromosome. Figure 4.9 presents the Pareto front of the MNSGA-II.

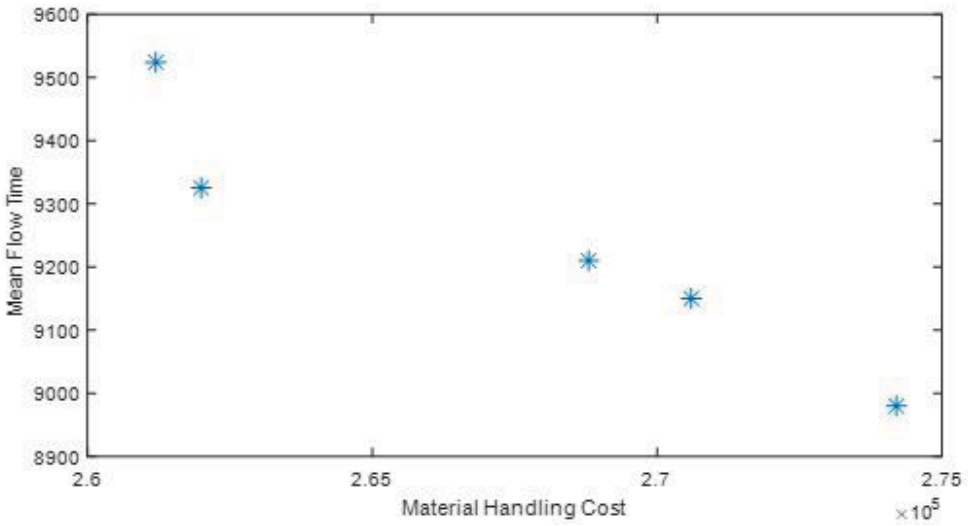

Figure 4.10. Pareto front of the MNSGA-II

After optimizing the problem, the following optimum solutions are found. Figure 4.11 shows the layout of each solution in Patero front along with the value of its objective function. It can be seen that there are only four solutions in Patero front and the diversity of the solutions is low. Accordingly, we can conclude that the two objective functions are not totally contradicting each other. In fact, the solutions with very bad MHC have a very bad MFT and vice versa.

As it can be seen in all the solutions the facilities 9, 10 and 11 are the closest facilities to facility 12 (exit door). This is because these are the only facilities that communicate with facilities 12. Facilities 2, 3, 4 and 5 are always close to facility 1 (entrance door). In all the Pareto solutions, facility 3 was always the closest facility to the entrance door. Facilities 10 and 11 have the farthest distance to facilities 3 and 4. This is because there is no material flow between these facilities. Facilities 6, 5 and 7 were in the middle, facilities 10 and 11 are in the right corner layout and facilities 3, 4 and 2 are in the left corner of the layout. Two facilities of 11 and 12 and 5 and 6 are next to each other in all the solutions.

The first solution is the worst solution in terms of MFT because all the facilities with high material flow are in the middle of the layout and so the traffic increase and MFT will increase. Because the transportation time, load and unload time and facility (machine) process time is stochastic, and facilities and transporters interact with each other, the time that a transporter uses an aisle cannot be estimated and simulation is used to find it.

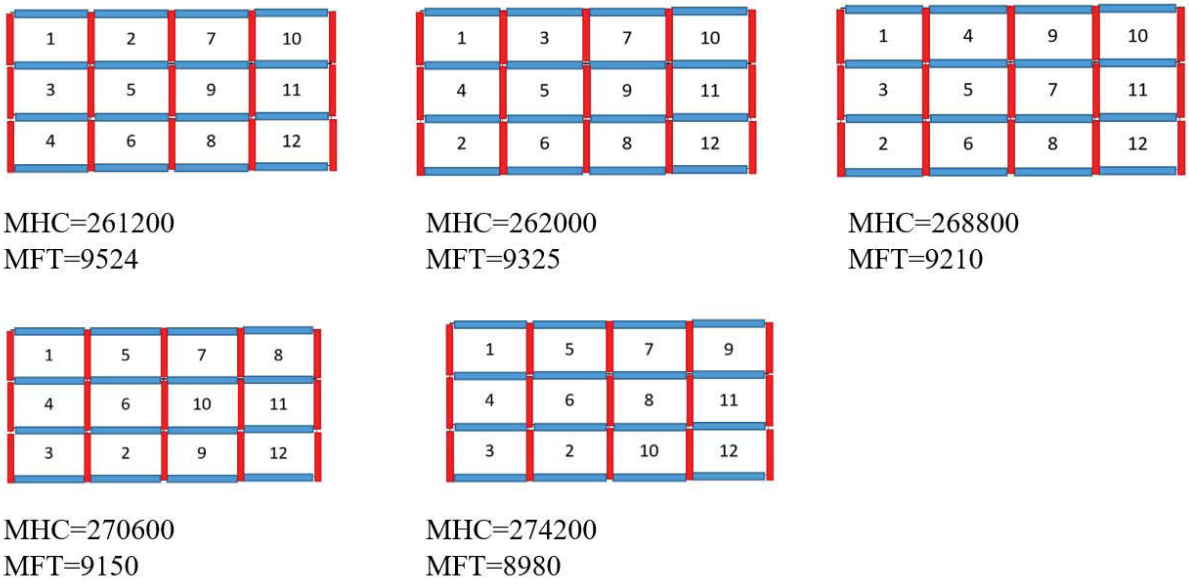

Figure 4.11. Pareto solutions of the MNSGA-II

4.7. Conclusion

This section presented a simulation optimization approach and show its applicability for a FLP. To solve it we first determined the structure of the aisles. Then, a simulation optimization method was used to find the best layout of the facilities. In this way, the simulation model was used to evaluate the layouts. Thanks to simulation, we can take into account such realistic considerations as the limited capacity of aisles, stochastic acceleration and deceleration of transporters, stochastic transportation time, stochastic process time of facilities (machines),

stochastic demand of products. Each layout was evaluated by simulation and the MFT corresponding to each layout was given to MNSGA-II for conducting the optimization process.

Although our approach was tested with a discrete FLP with 12 facilities, it has the ability to solve problems with high number of facilities. Since in the proposed approach the optimization is done in a powerful and totally independent programming language and can unconditionally be connected to the simulation model, it can be used for continuous problems with different forms of aisles structure. Therefore, it can be applied to a broad spectrum of FLPs for a wide variety of manufacturing systems.

Chapter 5: Conclusion and directions for future research

5.1. General conclusion

Facility layout is known as one of the most important issues in manufacturing systems. Many approaches have been developed based on finding the best layout of facilities. However, as explained in Chapter 1, the efficiency of a layout depends heavily on the aisles structure and to improve the performance of a layout it is necessary to optimize the aisles structure in addition to the layout of facilities. Through Chapter 1, it has been shown that obtaining an efficient aisles structure is a very complex issue and is subject to several practical considerations and requirements. In this thesis, we aimed to discuss, analyze and propose approaches regarding the issue of designing aisles structures in FLPs. For this, first, an analysis of the literature was carried out in Chapter 2 and the existing approaches for optimizing aisles in FLPs were studied. Through this analysis, it was found that despite the huge literature of FLPs, there are very few researches related to optimizing aisles structure in FLP. It was seen that some important considerations of aisles have not been addressed and need to be analyzed deeper. For example, the previous research works have not considered the problem of optimizing the location of entrance and exit doors and

how to connect them to the aisles network. Space occupied by the aisles as an important consideration in designing aisles (Friedrich et al., 2018), has been ignored in many research works. Also, the width of the aisles has not been considered as a decision variable in these researches. Choosing the aisles' width not adequately can result in the slow down of the traffic in certain aisles or having unnecessary space in certain other aisles. Furthermore, there are a few research works in which the aisles structure consists of both vertical and horizontal aisles and most researches are limited to design aisles with only one type of vertical or horizontal aisles. In this way, a larger variety of aisles structures can be generated which can lead to a more efficient design for an aisles structure.

Therefore, it was found that considering the requirements of aisles in manufacturing systems, there has not been enough attention to the issue of optimizing aisles structure in manufacturing systems. To do a deeper study on this issue, in Chapter 3, an approach was proposed to deal with optimizing aisles in manufacturing systems. The proposed approach described a way to find the position of facilities and structure of aisles in manufacturing systems, which satisfies such principles as the accessibility of all facilities through aisles, avoiding the design of redundant and irregular shape aisles and having no overlap between aisles and other facilities. Furthermore, the proposed approach considered the traffic in the aisles as a result of passing the transporters. In this regard, the width of the aisles was set according to the aisles' traffic. The position of entrance/exit doors and how to connect them to aisles was another issue investigated in the proposed approach. In this approach, the problem is formulated as a mixed-integer linear programming (MILP) model. The model can simultaneously find the optimum structure of the aisles, position of facilities, width of the aisles and position of entrance/exit doors. In order to solve the model, an improved Branch and Cut algorithm was applied in which the quality of branching was enhanced by adding optimality cuts and selecting an efficient branching strategy. The approach was successfully applied on a set of practical FLPs with 7 to 12 facilities. Even though the objective function of the model was minimizing the total transportation distance, the optimal layout obtained by the proposed approach prepared acceptable layouts in terms of space utilization. Moreover, optimum solutions have been found in a reasonable amount of time. Considering the fact that the maximum

number of facilities in many real manufacturing systems is less than 13 (Tompkins et al., 2010), it can be expected that the proposed approach can be applied in many real manufacturing systems.

The quality and relevance of a layout obtained by our exact approach can be influenced by various dynamic and stochastic factors such as transportation time, facility (machine) and transporters breakdown, stochastic demand for products and stochastic process time. These factors affect the waiting time of facilities for transporters, the waiting time of transporters to load the products from facilities and traffic in the aisles. Therefore, to reach a more realistic layout, these stochastic and dynamic phenomena should have been taken into account. To resolve this problem, in Chapter 4, another approach is proposed which is a multi-objective optimization via simulation approach. Simulation plays a crucial role in this approach because it can represent, quite realistically, the dynamic and complex behavior of facilities and transporters in the system and avoid restrictive assumptions while taking into account random data. The literature review of Chapter 4 showed that even if simulation technique has already been used in FLPs, there is a need for a generic approach that allows the direct connection between simulation and optimization algorithm. The proposed approach can handle this direct connection through implementation with the MATLAB simulator, named Simulink, to implement these realistic considerations and search for the best layout.

The employed multi-objective metaheuristic, named non-dominated sorting genetic algorithm, offered a Pareto front of possible compromise solutions. These solutions can help managers better design the layout while taking into consideration the dynamic and stochastic characteristics of their systems as well as their preferences. This approach was applied to a case study with 12 facilities from the literature. The resulted Pareto front consisted of four solutions which showed the minimization of the material handling costs does not lead to the minimization of mean flow time.

The great advantage of the proposed simulation optimization approach is that it can be applied to a wide variety of FLPs in many manufacturing systems. In addition, the proposed approach is flexible enough to be applied to other operations researches problems such a supply chain, inventory control and reliability, which are known to be subjected to stochastic and dynamic phenomena. The proposed simulation optimization approach has these two advantages since it can directly connect the simulation model to a powerful programming language through it many optimization algorithms can be performed.

5.2. Directions for future works

There are several possible opportunities for future research. In the exact approach, it was not taken into account that between two horizontal aisles more than one vertical aisles can be placed. This leads to the development of new routes for facility accessibility and adds the complexity of routing optimization to the problem. Also, future work can include extending the algorithm to handle non-straight-shaped aisles. Designing aisles structures that support multiple routes to access a facility could be a future research direction. The applicability of these types of aisles structures is highlighted in a situation where an aisle is blocked and an alternative route is required. The simulation optimization approach was applied for a discrete FLP with simple aisles structure. Its applicability to solve more complicated FLPs with more complicated aisles structure is an interesting direction for future research. In simulation optimization approach a non-dominated genetic algorithm was used to optimize the example. It is possible to use different optimization algorithms and evaluate the performance of these algorithms through a set of test problems. Other future research directions are concerned with reducing computing costs by formulating the problem based on stochastic mathematical programming or queueing theory. Furthermore, in simulation optimization approach, the aisles structure was first determined and then the layout of facilities was optimized. The problem of simultaneously determining the aisles structure and facilities layout can also be investigated. Since the proposed simulation optimization approach prepares a flexible environment for programming optimization algorithm and simulation,

analyzing and optimizing other combinatorial optimization problems such as supply chain, scheduling and inventory control using the proposed approach could be interesting for future work.

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Appendix A: Résumé

L'agencement des installations peut avoir des impacts importants sur la sécurité, le coût, le temps et la productivité des systèmes de production. Il y a plusieurs décisions importantes impliquées lors de la conception d'un agencement d'installation. En général, les problèmes d'agencement des installations concernent les décisions liées à déterminer la position des installations telles que les machines, les départements et les postes de travail en atelier d'un système de production pour atteindre les objectifs donnés et en tenant compte de certaines contraintes. Cependant, les installations nécessitent des chemins qui leur permettent de se connecter. Ces chemins, appelés allées, sont utilisés pour le transport des matériaux et des opérateurs entre les installations. Étant donné que le transport des matériaux entre les installations est effectué via un réseau d'allées, la conception d'une bonne structure d'allées peut contribuer à réduire la distance de transport entre les installations, à réduire les coûts de manutention ainsi que le temps de transport et à préparer un transport de matériaux fluide et sûr. Par conséquent, la conception d'une bonne structure d'allée est très importante pour l'efficacité des systèmes de production et devrait être incluse dans le problèmes de position des installations (FLPs). Cette thèse étudie et analyse le problème de la conception des allées dans les problèmes de position des installations et propose une approche qui permet de concevoir la structure des allées et la position des installations de manière intégrée.

Deux nouvelles approches sont développées pour trouver la position optimale des installations et la structure des allées. Dans la première approche, un modèle de programmation linéaire à nombres entiers mixtes est développé pour trouver simultanément la structure optimale des allées, y compris le nombre, la position et la largeur des allées, la position des installations et la position des portes d'entrée / sortie dans un problème de position des installations de zone inégale. Un algorithme de separation et évaluation (Branch and cut), amélioré en ajoutant des coupes d'optimalité et des stratégies de branchement et de nœud efficaces, est utilisé pour résoudre le problème. Les expériences de calcul montrent que l'approche proposée est capable de trouver la

position appropriée des installations et de la structure des allées pour fabriquer des systèmes jusqu'à 12 installations.

Dans la deuxième approche, la simulation est entièrement intégrée à une méthode d'optimisation (un algorithme métaheuristique), permettant aux concepteurs de prendre en compte divers facteurs dynamiques et stochastiques (tels que les temps de transport, les pannes de machines et de transporteurs, la demande de produits et les temps opératoires). Le grand avantage de l'approche d'optimisation basée sur la simulation proposée est qu'elle peut prendre en charge une connexion directe entre la simulation et de nombreux algorithmes d'optimisation et peut gérer les phénomènes stochastiques et dynamiques mentionnés du système. Par conséquent, il peut être appliqué à une grande variété de FLPs dans de nombreux systèmes de production.

Mots clés: Déterminer la position des installations, Structure d'allées, Programmation linéaire en nombres entiers mixtes, Optimisation via simulation

Appendix B: Résumé étendu

L'objectif de cette thèse est de développer des méthodologies qui incorporent les allées dans la conception de l'agencement d'une installation de production afin d'obtenir un agencement plus réaliste. Pour atteindre cet objectif, une étude complète est d'abord réalisée pour identifier les principales exigences et caractéristiques de la structure des allées dans les systèmes de production. Ensuite, un modèle mathématique linéaire mixte est développé pour trouver simultanément la structure des allées et la position des installations. Le modèle proposé permet d'obtenir la meilleure position des machines, la meilleure structure des allées, y compris le nombre, la largeur et la position de chaque allée, et la meilleure position des portes d'entrée et de sortie. Le modèle proposé appartient au groupe des modèles linéaires qui permettent d'atteindre des solutions optimales globales. Nous utilisons un algorithme de branchement et de coupe qui peut fournir une solution optimale globale. Afin d'obtenir une position plus réaliste en ce qui concerne les phénomènes stochastiques du système tels que le temps de transport stochastique, le temps de traitement, la panne, etc, une approche d'optimisation basée sur la simulation est proposée. Son applicabilité est testée à travers un exemple concernant la recherche de la structure optimale des allées et la position des installations dans un FLP discret. L'approche d'optimisation basée sur la simulation proposée a la capacité d'établir une connexion directe entre la simulation et n'importe quel algorithme d'optimisation. Elle peut donc gérer l'optimisation de la structure des allées et de la position des installations pour n'importe quel type de FLP.

1. La question de recherche fondamentale à laquelle répond cette thèse est de savoir comment concevoir une structure d'allées dans un système de production sous les exigences d'un agencement efficace dans un contexte plus réaliste et en évitant les hypothèses restrictives. Pour atteindre l'objectif de recherche et répondre à cette question de recherche, les sous-questions suivantes sont introduites, chacune d'entre elles étant traitée dans l'un des chapitres :

1. Que sont les FLP, les allées et comment les allées affectent la performance de l'agencement des installations ? Quelles sont les exigences et les caractéristiques d'une bonne structure d'allées dans un système de production ? Pour répondre à ces questions, le chapitre 1 présente différents types de FLP et analyse le problème des allées dans l'agencement des systèmes de production.
2. Qu'est-ce qui a été fait dans la littérature concernant l'optimisation de la structure des allées dans les problèmes d'agencement d'installations ? Pour répondre à cette question, dans le chapitre 2, une revue complète de la littérature est effectuée pour étudier les dernières recherches et développements sur l'optimisation des allées dans les FLP.
3. Comment trouver la position optimale des installations et de la structure des allées dans les systèmes de production afin de satisfaire les exigences d'une structure d'allées ? Le chapitre 3 répond à cette question. Tout d'abord, les variables de décision et les contraintes qui représentent le mieux la structure optimale des allées et les paramètres d'agencement sont identifiés. Ensuite, le problème est formulé comme un modèle MILP pour générer une solution optimale basée sur la minimisation de la distance totale de transport. Une technique d'optimisation efficace est appliquée pour résoudre le modèle.
4. Comment les phénomènes dynamiques et stochastiques des systèmes de production peuvent-ils être pris en compte afin d'obtenir une position plus réaliste ? Le chapitre 4 répond à cette question. Dans ce but, on détermine d'abord différents types de phénomènes stochastiques et dynamiques dans les systèmes de production qui peuvent être influencés par l'implantation. Ensuite, pour considérer ces phénomènes, un modèle de simulation est développé. Ce modèle de simulation est connecté à un algorithme métaheuristique multi-objectif pour optimiser le problème en fonction de deux objectifs : minimiser la distance totale de transport et le temps moyen d'écoulement.

Dans le chapitre 1, nous essayons d'expliquer les FLP, comment la structure des allées peut affecter les FLP et la nécessité d'optimiser les allées et les FLP en même temps. Dans le chapitre 2, nous effectuons une revue complète de la littérature publiée dans le domaine de la FLP, en nous concentrant sur les recherches qui ont pris en compte les allées dans leurs FLP. Dans le chapitre

3, nous développons un nouveau modèle d'optimisation et un algorithme d'optimisation exact pour générer la structure optimale des allées et la position des installations afin de minimiser la distance totale de transport. Dans le chapitre 4, nous développons un algorithme métaheuristique multi-objectif et un modèle de simulation. Dans le chapitre 5, les résultats de la recherche sont expliqués et les limites et recommandations pour les travaux de recherche futurs sont décrites.

Parmi les nombreuses questions qui se posent dans le domaine du système de production, la conception de l'agencement des installations est un domaine de recherche intéressant et en cours (Dessens, 2003). L'agencement des installations a un effet significatif sur les performances des systèmes de production. Entre 20 et 50 % des dépenses d'exploitation d'une installation de production sont liées aux coûts de manutention des matériaux (CMH) et une installation correctement conçue peut réduire ces coûts de 10 à 30 % (Tompkins et al., 2010). Cependant, l'impact de l'agencement de l'installation va au-delà des CMH. En plus de réduire les coûts de manutention, il est probable que cela réduise également la taille des lots de manutention. En réduisant la taille des lots de manutention, le stock de travaux en cours (WIP) diminuera également. La diminution de l'encours a une incidence directe sur les coûts (probablement importante) et est également susceptible d'améliorer le délai de livraison et la qualité du produit transporté (puisque le retour d'information dû à la mauvaise qualité est raccourci en même temps que le délai de livraison). Enfin, les entreprises qui sont en mesure de réduire simultanément le délai d'exécution, d'améliorer la qualité et de réduire leurs coûts sont beaucoup plus susceptibles d'avoir des débouchés accrus pour leur produit. Ainsi, l'impact de la planification des installations va bien au-delà de l'impact sur les dépenses de manutention (par exemple, les ratios de productivité concernant le cycle de production, l'espace dans les allées et l'énergie (Sule, 2008).

La recherche de l'agencement des installations a été étudiée par de nombreux chercheurs sous le thème des problèmes d'agencement des installations (FLP). L'agencement des installations nécessaires à la production d'un produit ou à la prestation d'un service dans un espace donné est appelé FLP (Drira et al., 2007). Toute entité physique qui facilite l'exécution d'un travail peut être considérée comme une installation ; une installation peut être une machine, un poste de travail,

une station d'inspection, une station de lavage, un vestiaire, une cellule de production, un entrepôt, un bureau, un salon, une salle de repos, etc. (Heragu, 2018). Puisque l'installation comprend une définition étendue, les FLP apparaissent dans la production, l'entreposage, les hôpitaux et les écoles, les casernes de pompiers, les postes de police, etc. L'agencement des installations est une question stratégique importante et fondamentale dans tout système de production et de services et peut avoir un impact significatif sur la viabilité et la productivité de celui-ci (Singh & Sharma, 2006a). Il existe de nombreux types de FLP, qui seront détaillés dans le chapitre suivant. Une classification de ceux-ci est donnée, par exemple, dans (Drira et al., 2007) et (Hosseini-Nasab et al., 2018). Lors de l'élaboration d'un plan d'installation, les concepteurs doivent tenir compte des contraintes suivantes :

- Certaines paires d'installations doivent être situées sur des sites adjacents pour des raisons de sécurité, quel que soit le volume du flux de matériaux entre elles. Les stations de forgeage et de traitement thermique en sont un exemple. En raison des risques d'incendie, ces deux stations doivent être situées l'une à côté de l'autre, même si relativement peu de pièces passent entre elles.
- Certaines paires d'installations doivent être situées sur des sites non adjacents. Parfois, des raisons technologiques imposent que deux ou plusieurs installations ne puissent pas être proches l'une de l'autre, même si un grand nombre de pièces doivent les visiter pour des opérations successives. Comme le poste de soudage génère des étincelles susceptibles d'enflammer des solvants inflammables dans le poste de peinture, les deux postes doivent être situés dans des sites non adjacents, aussi éloignés que possible, même s'il peut y avoir beaucoup d'interaction entre eux.
- Certaines installations doivent être situées à des endroits spécifiques. Prenons cet exemple concret.

Un fabricant de serpillières et de seaux industriels possède une perceuse à colonne qui est plus haute que le toit du bâtiment. Pour l'installer, un trou a dû être fait dans le toit. Si cette entreprise prévoit un changement d'agencement, elle ne peut pas justifier le changement de position de cette perceuse à colonne.

- Les réglementations gouvernementales locales et les réglementations des compagnies d'assurance contre les risques doivent être respectées. Les codes d'incendie peuvent exiger un certain nombre d'issues de secours. L'Occupational Safety and Health Administration (OSHA) exige des toilettes séparées pour les hommes et les femmes en fonction du nombre d'employés et d'autres facteurs. D'autres réglementations de l'OSHA concernent les entrées et les sorties de l'usine, les normes de santé et de sécurité, les exigences selon lesquelles les processus ou les équipements dangereux doivent être situés de manière à ce que le contact avec les employés soit minimal, etc.

Par conséquent, l'agencement des installations est complexe à résoudre et est considéré comme un problème de recherche opérationnelle. En raison de la variété des considérations trouvées dans les articles, les chercheurs ne sont pas d'accord sur une définition commune et exacte des problèmes d'agencement. Dans cette thèse, les problèmes d'agencement d'installations (Facility Layout Problems - FLP) sont définis comme la recherche de la meilleure position des installations dans un espace donné soumis à certains critères de conception et à des limitations de surface, avec un ou plusieurs objectifs. Les FLP sont connus pour être complexes et sont généralement NP-Hard (Garey & Johnson, 1979). Ils ont été énormément étudiés en tant que domaine de la recherche opérationnelle. Les objectifs les plus courants des recherches dans ce domaine comprennent la réduction des coûts de manutention, l'utilisation efficace et efficiente de l'espace disponible, la fourniture d'un environnement sûr et agréable pour le personnel, la réduction de la congestion pour permettre une circulation fluide des personnes et des matériaux, et la facilitation de la communication et de la supervision (Heragu, 2018).

La plupart des études précédentes sur la FLP dans les systèmes de production se sont concentrées sur la recherche de la meilleure position des installations telles que les machines et les postes de travail dans l'atelier (Friedrich, Klausnitzer & Lasch, 2018). Cependant, les installations nécessitent des chemins pour se connecter les unes aux autres. Ces chemins, appelés allées, sont utilisés pour le transport des matériaux et des personnes entre les installations. Les allées occupent

une partie du sol et peuvent nécessiter beaucoup d'espace dans les installations (Stephens & Meyers, 2013). En outre, étant donné que le transport des matériaux entre les installations s'effectue à travers le réseau d'allées, la conception d'une bonne structure d'allées peut contribuer à l'efficacité de l'agencement en réduisant le MHC, le temps moyen d'écoulement et la quantité d'espace nécessaire, et en assurant un transport fluide. Par conséquent, la conception d'une bonne structure d'allées est très importante pour l'efficacité des systèmes de production, et pour réaliser un bon agencement, il est essentiel de déterminer non seulement la position des installations telles que les machines et les postes de travail, mais aussi la structure d'allées correspondante (Friedrich et al., 2018).

Les allées sont les zones du plancher de l'atelier qui sont utilisées par les opérateurs et les dispositifs de transport. L'espace de l'atelier consacré aux allées ne peut pas être occupé par une installation. Plusieurs considérations doivent être prises en compte lors de la configuration des allées. La principale est de configurer les allées de manière à ce que les points de ramassage/dépose (P/D) de toutes les installations aient accès aux allées et qu'il y ait un chemin à travers les allées entre chaque paire d'installations. Les allées doivent également être reliées aux portes d'entrée/sortie. Les portes d'entrée et de sortie sont les endroits où les pièces, les matières premières et les dispositifs de transport entrent et sortent du système de production. Il n'est généralement pas possible de construire des portes d'entrée et de sortie tout autour du bâtiment pour des raisons techniques ou environnementales (par exemple, s'il y a une rue à côté d'un côté du bâtiment ou si certaines parties du bâtiment sont à proximité d'un autre bâtiment de sorte qu'il n'y a pas assez d'espace pour les opérations de chargement/déchargement). Dans cette situation, dans la zone autorisée pour la construction de portes d'entrée/sortie, les points les plus proches des allées sont considérés comme des points potentiels pour la construction de portes d'entrée/sortie afin de réduire les coûts de transport. Il convient donc de déterminer l'emplacement des portes d'entrée/sortie dans la zone autorisée et de les relier à la structure des allées lors de la conception de l'agencement. La largeur des allées est une autre considération importante lors de la conception de la structure des allées. La largeur d'une allée correspond à la distance latérale entre deux côtés opposés d'une allée. La largeur des allées doit être suffisante pour que le chemin ne soit pas bloqué

lorsqu'un dispositif de transport s'arrête pour effectuer un processus de prise en charge/dépose. En outre, en cas de panne d'une machine et de la nécessité de la déplacer hors du système de production, la largeur de l'allée doit être suffisante pour permettre le transport de la plus grande partie démontée de la machine. Toutefois, un espace trop important pour les allées serait préjudiciable au système. La détermination de la largeur appropriée pour chaque allée est donc une question importante. Les allées dans lesquelles transitent le plus de matériaux doivent être plus larges. Ainsi, la quantité de matériaux qui transitent dans une allée doit être prise en compte pour déterminer la largeur de l'allée. Il convient de noter que l'espace nécessaire aux allées doit être ajouté dans les calculs relatifs à la largeur des allées.

Pour optimiser la structure des allées, il faut prendre en compte les problèmes mentionnés ci-dessus. Toutes ces exigences augmentent la complexité de la conception des allées de sorte que, comme nous le verrons dans le chapitre 2, le problème de l'optimisation de la structure des allées a été moins pris en compte dans la littérature sur les FLP. Par conséquent, dans cette thèse, l'optimisation simultanée de la structure des allées et de la position des installations est étudiée. Une approche exacte basée sur un modèle de programmation linéaire en nombres entiers mixtes (MILP) est proposée pour trouver les meilleures positions des équipements et la meilleure structure des allées dans un FLP à surface inégale (UA-FLP). Même si le modèle proposé est destiné aux FLP UA, il peut être facilement étendu à d'autres types de FLP, décrits dans le chapitre 1.

Le modèle proposé est résolu par un algorithme de Séparation et évaluation (B&C) amélioré et la solution optimale globale est trouvée. La méthode B&C a été utilisée avec succès pour résoudre une variété de problèmes MILP (Karaoglan, Erdogan & Koç, 2018) et elle peut également garantir l'optimalité globale. Même si l'algorithme B&C est une méthode efficace pour résoudre les MILP, certains mécanismes sont appliqués pour améliorer l'algorithme B&C dans la résolution du modèle proposé. Ces mécanismes consistent à (1) ajouter des coupes d'optimalité, (2) définir l'ordre de branchement des variables et (3) choisir les meilleures stratégies de sélection des nœuds. Cette approche est testée avec succès pour un ensemble d'instances comportant jusqu'à 12 installations. Les problèmes avec 11 installations sont résolus de manière optimale et les problèmes avec 12

installations sont résolus avec un écart d'optimalité de 7 à 15 %. L'approche proposée peut donc être appliquée à des systèmes de production réels comprenant jusqu'à 11 installations. La meilleure position obtenue par l'algorithme B&C5 pour le problème 21 est présentée à la figure 3.13.

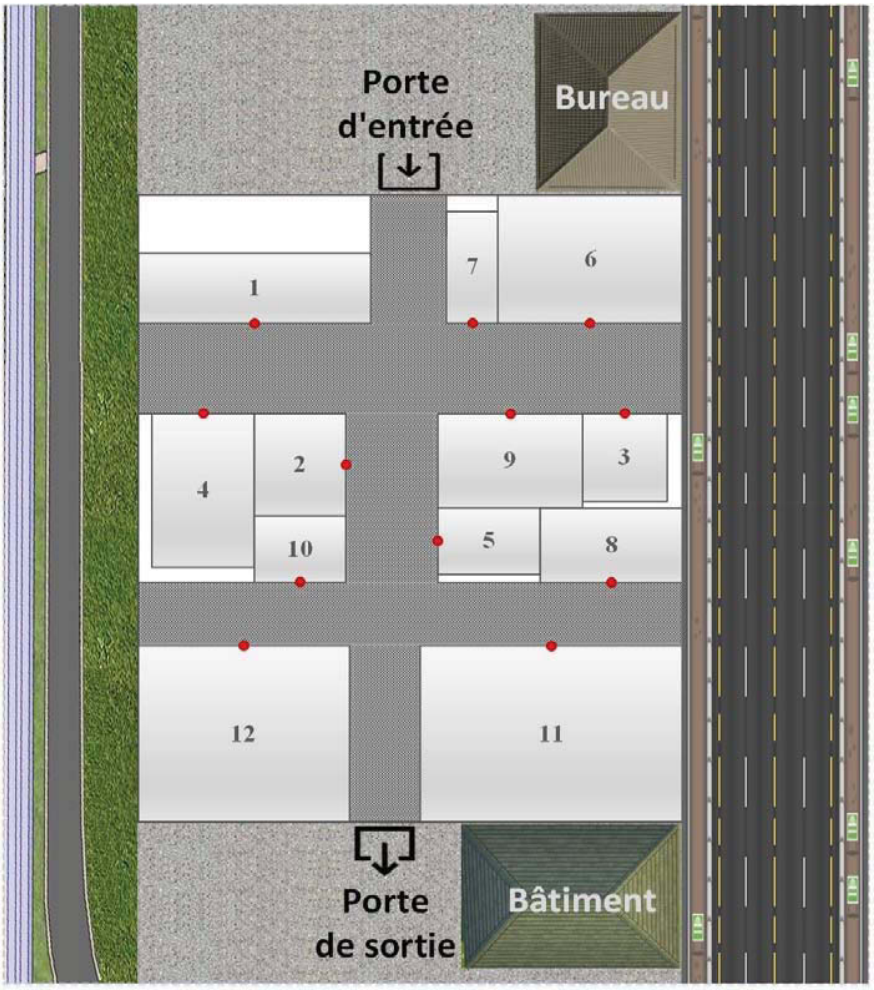

Figure 3.13. La meilleure mise en page obtenue pour l'instance de test 21.

Dans l'approche exacte, la position optimale globale est atteinte. Cependant, il faut mentionner que l'optimalité d'une implantation dans les systèmes de production est influencée par divers facteurs dynamiques et stochastiques tels que le temps de transport, les pannes des machines et des transporteurs, la demande stochastique des produits et le temps stochastique du processus. Par

conséquent, dans la suite de la thèse, l'optimisation du problème de l'agencement et de la structure des allées est étudiée sous les phénomènes dynamiques et stochastiques des systèmes de production afin d'obtenir un agencement plus réaliste. Dans ce but, une approche d'optimisation basée sur la simulation est proposée.

L'optimisation basée sur la simulation est l'une des techniques les plus applicables et les plus populaires pour traiter le stochastique dans la recherche opérationnelle et en particulier dans les FLP. Même si plusieurs chercheurs ont utilisé l'approche d'optimisation basée sur la simulation dans les FLP, ils n'ont pas abordé spécifiquement la structure des allées et leur capacité. D'autre part, nous appliquons une approche différente des articles précédents. Certains de ces articles ont utilisé l'optimisation par simulation en deux étapes distinctes. Dans la première étape, un modèle de simulation est construit et exécuté pour un ensemble de solutions. Ensuite, les résultats sont utilisés pour développer un méta-modèle. Ce méta-modèle permet d'estimer la mesure de performance.

Le principal défaut de l'approche en deux étapes est la précision du méta-modèle. Pour remédier à ce problème, certains articles ont utilisé l'interaction dynamique entre la simulation et l'optimisation pendant l'exécution. De cette façon, pendant le processus d'optimisation, chaque solution est donnée au modèle de simulation, évaluée et les résultats sont renvoyés à l'algorithme d'optimisation. En intégrant la simulation et l'optimisation et en établissant une communication dynamique entre la simulation et l'optimisation, la précision des résultats augmentera. Selon nos connaissances, dans toutes les recherches, la communication dynamique a été faite par l'utilisation de la boîte à outils d'optimisation des paquets de simulation ou de deux logiciels différents et de les connecter par un fichier texte ou Excel. La boîte à outils d'optimisation des progiciels de simulation a été conçue pour rechercher une solution optimale dans des problèmes moins compliqués. En outre, ces boîtes à outils contiennent un nombre très limité d'algorithmes d'optimisation. Malheureusement, l'établissement d'une connexion entre la simulation et

l'optimisation s'est avéré être un grand défi pour ces types d'approches. Lorsqu'une connexion entre les algorithmes de simulation et d'optimisation est exécutée dans deux logiciels différents via un fichier texte ou Excel, le temps de calcul augmente. L'optimisation basée sur la simulation proposée dans cette thèse a utilisé une connexion directe entre la simulation et l'optimisation pour augmenter l'efficacité de calcul.

Nous utilisons le progiciel intégré Matlab/Simulink. Dans Matlab, nous avons accès à une grande variété d'algorithmes d'optimisation heuristiques et métaheuristiques que l'on peut régler, manipuler et améliorer en fonction de ses besoins. Simulink est un outil intégré à Matlab. De cette façon, les parties simulation et optimisation peuvent être directement connectées. L'approche proposée d'optimisation basée sur la simulation peut supporter une connexion directe pour traiter les phénomènes stochastiques et dynamiques du système. La procédure de l'approche d'optimisation basée sur la simulation proposée est illustrée à la figure 4.1.

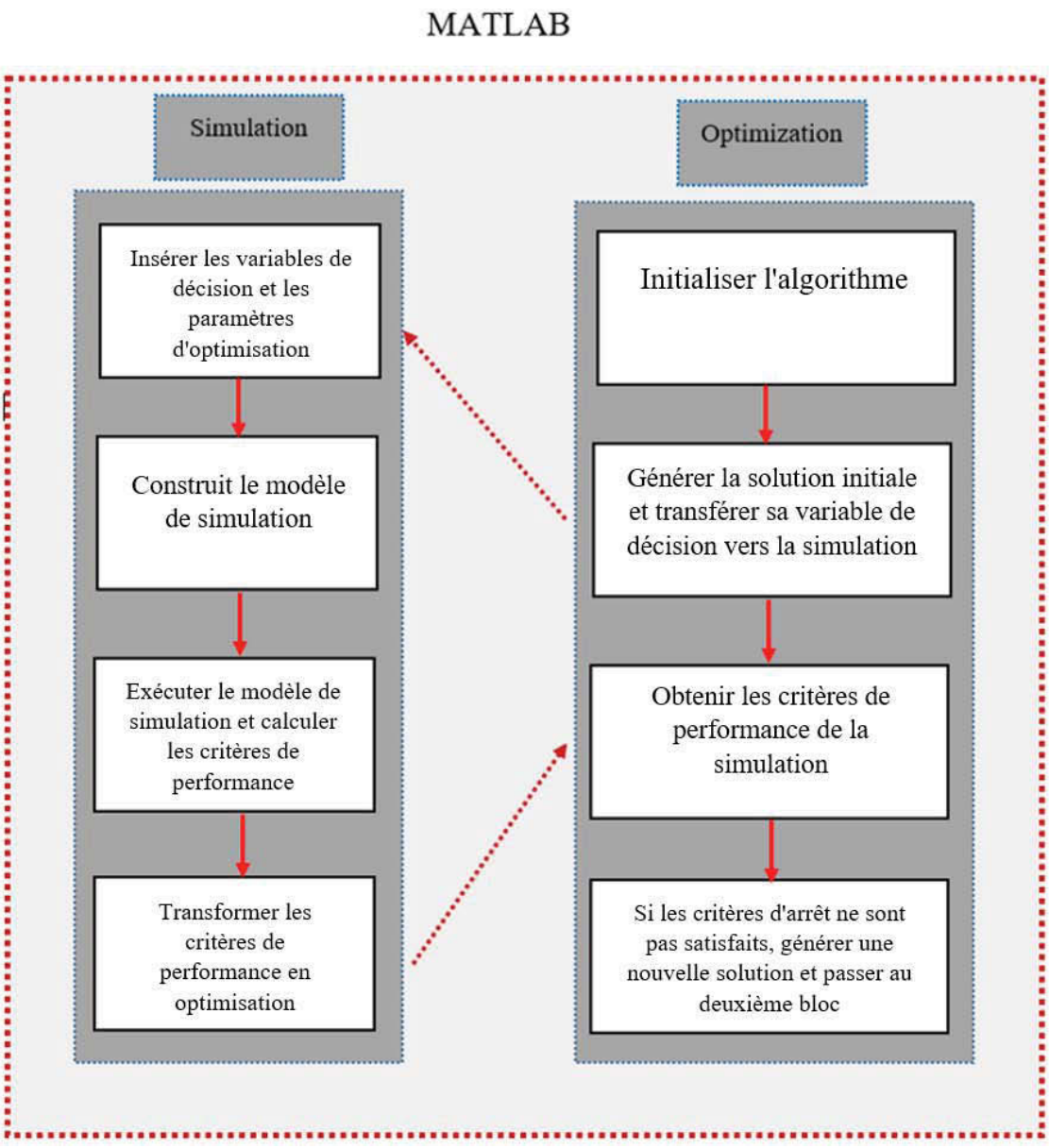

Figure 4.1. Approche d'optimisation basée sur la simulation

Pour montrer comment l'approche de simulation proposée peut être appliquée pour optimiser le problème de l'agencement des installations et de la structure des allées, un exemple d'application est décrit dans la section 4.5, dans lequel l'agencement des installations et la structure des allées

dans un système de production sont déterminés. Chaque installation est considérée comme une machine de traitement de dimension lm× wm et la taille du plancher de l'atelier est L×W. Le système comporte des transporteurs qui se déplacent dans les allées et transportent les matériaux entre les installations. Les temps de traitement des installations (machines) et les temps de transport sont stochastiques. Pour appliquer l'approche d'optimisation basée sur la simulation proposée, la structure des allées est conçue dans un premier temps. Nous utilisons une version simple de la structure des allées qui est utilisée pour concevoir les allées par le biais d'une heuristique. Une série de positions est créée et les installations doivent être allouées à ces positions. Cela implique que le problème se transforme en un problème discret d'allocation des installations aux positions. Cependant, étant donné que dans l'approche proposée, l'optimisation est effectuée dans un langage de programmation puissant et totalement indépendant et qu'elle peut être connectée inconditionnellement au modèle de simulation, elle peut être utilisée pour un problème continu avec n'importe quelle forme de structure d'allées. Comme la largeur des allées ne peut pas être infinie, on attribue à chaque allée une capacité qui indique le nombre de transporteurs qui peuvent passer dans une allée en même temps.

Le réseau d'allées doit être tel qu'il y ait suffisamment d'espace pour que les machines puissent être affectées à l'intérieur des positions. Pour cela, il faut d'abord déterminer le nombre maximum d'allées verticales et horizontales. En connaissant la longueur et la largeur des machines et de l'atelier, on calcule le nombre d'allées verticales (R) et horizontales (S). Ensuite, les allées sont placées une par une et la structure des allées est créée. Après la conception des allées, un algorithme métaheuristique multi-objectif est utilisé pour trouver l'emplacement optimal des installations. À cet égard, l'un des algorithmes évolutionnaires multi-objectifs les plus efficaces, appelé algorithme génétique de tri non dominé (NSGA-II), est modifié et utilisé. Le NSGA-II est un algorithme efficace en termes de calcul qui met en œuvre l'idée d'une méthode de sélection basée sur les classes de dominance de toutes les solutions. L'idée clé de la NSGA-II est de classer les solutions. Le processus de classement est basé sur un algorithme de tri rapide non dominé, dans lequel les solutions sont classées sur la base du niveau de non-domination d'un individu. Les solutions ayant un niveau de non-domination égal sont classées en fonction de la densité des

solutions dans le voisinage de cette solution. Ce critère, qui garantit la diversité des solutions obtenues, est appelé distance de crowdingue (CD). La sélection des parents pour la génération suivante est basée d'abord sur le rang de non-domination et ensuite sur la distance d'encombrement. Les nouvelles solutions sont générées par des opérateurs NSGA-II tels que le croisement et la mutation. Le processus de recherche se poursuit jusqu'à ce que le critère d'arrêt soit satisfait.

Deux objectifs de minimisation du coût de la manutention (MHC) et du temps de passage moyen (MFT) sont utilisés comme critères de performance. Le modèle de simulation est utilisé pour calculer le MFT. Le modèle de simulation est développé dans Simulink. Simulink, développé par MathWorks, est un logiciel de modélisation, de simulation et d'analyse des systèmes dynamiques. Il permet l'étude de systèmes linéaires et non linéaires modélisés de façon continue, discrète ou hybride (MathWorks, 2001). Simulink a l'avantage d'être totalement intégré à Matlab. Ainsi, l'utilisateur a accès à toutes les fonctionnalités et boîtes à outils de Matlab et peut créer ses propres algorithmes et modèles de scripts qui peuvent être utilisés indéfiniment. L'outil le plus important de Simulink pour développer un modèle de simulation pour les systèmes de production est SimEvents. SimEvents (MathWorks, 2005) est conçu pour simuler des systèmes à événements discrets et est entièrement intégré à Simulink, qui est un simulateur traditionnel piloté par le temps. Par conséquent, SimEvents est doté d'une fonctionnalité qui permet une coexistence efficace des composants temporels et événementiels dans les systèmes hybrides complexes. En outre, cette conception permet à SimEvents de tirer parti d'une riche collection d'outils de visualisation, de traitement des données et de calcul dans Simulink et MATLAB. Selon (Ait El Cadi et al., 2016), Simulink est presque six fois plus rapide qu'Arena. Ce modèle de simulation est utilisé comme un calculateur de fonction de fitness (MFT) et est directement connecté à l'environnement d'optimisation dans Matlab pour exécuter l'une des heuristiques et métaheuristiques.

L'application de l'approche proposée est illustrée par un exemple. L'exemple est un système de production de 83m×39m avec 12 installations, chacune ayant une dimension de 17m×9m. Après avoir optimisé le problème, les solutions optimales suivantes sont trouvées. La figure 4.11 montre la position de chaque solution dans le front de Patero ainsi que la valeur de sa fonction objective.

On peut voir qu'il n'y a que quatre solutions dans le front de Patero et que la diversité des solutions est faible. Par conséquent, nous pouvons conclure que les deux fonctions objectives ne sont pas totalement contradictoires. En effet, les solutions avec un très mauvais MHC ont un très mauvais MFT et vice versa.

Bien que notre approche ait été testée avec un FLP discret avec 12 installations, elle a la capacité de résoudre des problèmes avec un nombre élevé d'installations. Puisque dans l'approche proposée l'optimisation est faite dans un langage de programmation puissant et totalement indépendant et qu'elle peut être inconditionnellement connectée au modèle de simulation, elle peut être utilisée pour des problèmes continus avec différentes formes de structure d'allées. Par conséquent, elle peut être appliquée à un large spectre de FLP pour une grande variété de systèmes de production.

L'agencement des installations est connu comme l'un des problèmes les plus importants des systèmes de production. De nombreuses approches ont été développées pour trouver la meilleure position des installations. Cependant, comme expliqué dans le chapitre 1, l'efficacité d'un agencement dépend fortement de la structure des allées et pour améliorer les performances d'un agencement, il est nécessaire d'optimiser la structure des allées en plus de l'agencement des installations. A travers le chapitre 1, il a été montré que l'obtention d'une structure d'allées efficace est une question très complexe et est soumise à plusieurs considérations et exigences pratiques. Dans cette thèse, nous avons cherché à discuter, analyser et proposer des approches concernant la question de la conception de la structure des allées dans les FLP. Pour cela, tout d'abord, une analyse de la littérature a été réalisée dans le chapitre 2 et les approches existantes pour l'optimisation des allées dans les FLP ont été étudiées. Cette analyse a permis de constater que, malgré l'abondante littérature sur les PLF, il existe très peu de recherches sur l'optimisation de la structure des allées dans les PLF. Il a été constaté que certains aspects importants des allées n'ont pas été abordés et doivent être analysés plus en profondeur. Par exemple, les travaux de recherche précédents n'ont pas considéré le problème de l'optimisation de l'emplacement des portes d'entrée et de sortie et la façon de les connecter au réseau d'allées. L'espace occupé par les allées, qui est une considération importante dans la conception des allées (Friedrich et al., 2018), a été ignoré

dans de nombreux travaux de recherche. De même, la largeur des allées n'a pas été considérée comme une variable de décision dans ces recherches. Un choix inadéquat de la largeur des allées peut entraîner un ralentissement du trafic dans certaines allées ou un espace inutile dans d'autres allées. En outre, il existe quelques travaux de recherche dans lesquels la structure des allées se compose à la fois d'allées verticales et horizontales et la plupart des recherches se limitent à la conception d'allées avec un seul type d'allées verticales ou horizontales. De cette façon, une plus grande variété de structures d'allées peut être générée, ce qui peut conduire à une conception plus efficace d'une structure d'allées.

Par conséquent, il a été constaté que, compte tenu des exigences des allées dans les systèmes de production, on ne s'est pas suffisamment intéressé à la question de l'optimisation de la structure des allées dans les systèmes de production. Pour approfondir cette question, le chapitre 3 propose une approche de l'optimisation des allées dans les systèmes de production. L'approche proposée décrit un moyen de trouver la position des installations et la structure des allées dans les systèmes de production, qui satisfait à des principes tels que l'accessibilité de toutes les installations par les allées, en évitant la conception d'allées redondantes et de forme irrégulière et en n'ayant aucun chevauchement entre les allées et d'autres installations. En outre, l'approche proposée tient compte de la circulation dans les allées à la suite du passage des transporteurs. À cet égard, la largeur des allées a été fixée en fonction du trafic dans les allées. La position des portes d'entrée/sortie et la manière de les relier aux allées est une autre question étudiée dans l'approche proposée. Dans cette approche, le problème est formulé comme un modèle de programmation linéaire en nombres entiers mixtes (MILP). Ce modèle permet de trouver simultanément la structure optimale des allées, la position des installations, la largeur des allées et la position des portes d'entrée/sortie. Afin de résoudre le modèle, un algorithme de branchement et de coupe amélioré a été appliqué, dans lequel la qualité du branchement a été améliorée en ajoutant des coupes d'optimalité et en sélectionnant une stratégie de branchement efficace. L'approche a été appliquée avec succès sur un ensemble de FLP pratiques avec 7 à 12 installations. Même si la fonction objective du modèle était de minimiser la distance totale de transport, la position optimale obtenue par l'approche proposée a préparé des positions acceptables en termes d'utilisation de l'espace. De plus, les

solutions optimales ont été trouvées en un temps raisonnable. Compte tenu du fait que le nombre maximal d'installations dans de nombreux systèmes de production réels est inférieur à 13 (Tompkins et al., 2010), on peut s'attendre à ce que l'approche proposée puisse être appliquée dans de nombreux systèmes de production réels.

La qualité et la pertinence d'une position obtenue par notre approche exacte peuvent être influencées par divers facteurs dynamiques et stochastiques tels que le temps de transport, les pannes des installations (machines) et des transporteurs, la demande stochastique de produits et le temps stochastique du processus. Ces facteurs affectent le temps d'attente des installations pour les transporteurs, le temps d'attente des transporteurs pour charger les produits des installations et le trafic dans les allées. Par conséquent, pour obtenir un agencement plus réaliste, il aurait fallu tenir compte de ces phénomènes stochastiques et dynamiques. Pour résoudre ce problème, le chapitre 4 propose une autre approche, à savoir une approche d'optimisation multi-objectifs par simulation. La simulation joue un rôle crucial dans cette approche car elle peut représenter, de manière tout à fait réaliste, le comportement dynamique et complexe des installations et des transporteurs dans le système et éviter les hypothèses restrictives tout en prenant en compte les données aléatoires. La revue de la littérature du chapitre 4 a montré que même si la technique de simulation a déjà été utilisée dans les PFL, il existe un besoin pour une approche générique qui permette la connexion directe entre la simulation et l'algorithme d'optimisation. L'approche proposée peut gérer cette connexion directe grâce à l'implémentation du simulateur MATLAB, appelé Simulink, pour mettre en œuvre ces considérations réalistes et rechercher la meilleure position.

La métaheuristique multi-objectifs employée, nommée algorithme génétique de tri non-dominé, a offert un front de Pareto de solutions de compromis possibles. Ces solutions peuvent aider les gestionnaires à mieux concevoir l'agencement tout en tenant compte des caractéristiques dynamiques et stochastiques de leurs systèmes ainsi que de leurs préférences. Cette approche a été appliquée à une étude de cas portant sur 12 installations issues de la littérature. Le front de Pareto obtenu se compose de quatre solutions qui montrent que la minimisation des coûts de manutention ne conduit pas à la minimisation du temps moyen d'écoulement.

Le grand avantage de l'approche d'optimisation basée sur la simulation proposée est qu'elle peut être appliquée à une grande variété de FLP dans de nombreux systèmes de production. En outre, l'approche proposée est suffisamment flexible pour être appliquée à d'autres problèmes de recherche opérationnelle tels que la chaîne d'approvisionnement, le contrôle des stocks et la fiabilité, qui sont connus pour être soumis à des phénomènes stochastiques et dynamiques. L'approche d'optimisation basée sur la simulation proposée présente ces deux avantages car elle permet de connecter directement le modèle de simulation à un langage de programmation puissant grâce auquel de nombreux algorithmes d'optimisation peuvent être exécutés.

Il existe plusieurs possibilités de recherches futures. Dans l'approche exacte, il n'a pas été tenu compte du fait qu'entre deux allées horizontales, plus d'une allée verticale peut être placée. Cela conduit au développement de nouveaux itinéraires pour l'accessibilité des installations et ajoute la complexité de l'optimisation du routage au problème. En outre, les travaux futurs peuvent inclure l'extension de l'algorithme pour traiter les allées non droites. La conception de structures d'allées qui prennent en charge plusieurs itinéraires pour accéder à une installation pourrait être une direction de recherche future. L'applicabilité de ces types de structures d'allées est mise en évidence dans une situation où une allée est bloquée et où un autre itinéraire est nécessaire. L'approche d'optimisation basée sur la simulation a été appliquée à un FLP discret avec une structure d'allées simple. Son applicabilité à la résolution de FLP plus complexes avec une structure d'allées plus compliquée est une direction intéressante pour les recherches futures. Dans l'approche d'optimisation basée sur la simulation, un algorithme génétique non dominé a été utilisé pour optimiser l'exemple. Il est possible d'utiliser différents algorithmes d'optimisation et d'évaluer les performances de ces algorithmes grâce à un ensemble de problèmes de test. D'autres directions de recherche futures concernent la réduction des coûts de calcul en formulant le problème sur la base de la programmation mathématique stochastique ou de la théorie des files d'attente. En outre, dans l'approche d'optimisation basée sur la simulation, la structure des allées a d'abord été déterminée, puis la position des installations a été optimisée. Le problème de la détermination simultanée de la structure des allées et de la position des installations peut également être étudié. Puisque l'approche d'optimisation basée sur la simulation proposée prépare un environnement flexible pour la

programmation de l'algorithme d'optimisation et la simulation, l'analyse et l'optimisation d'autres problèmes d'optimisation combinatoire tels que la chaîne d'approvisionnement, l'ordonnancement et le contrôle des stocks à l'aide de l'approche proposée pourraient être intéressantes pour les travaux futurs.