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Combining metaheuristic search and simulation to deal with capacitated aisles in facility layout

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ABSTRACT

The layout of machines in a manufacturing system has a significant impact on production time and cost. The aim of a good layout is generally determining the machines' position on the shop floor to minimize transportation time and cost. However, not only machines' positions but also aisle affect transportation cost and time. The aisles are paths that transporters go through them to move the materials between machines. The capacity of the aisles is limited to a specific number of transporters and this may cause transporters to wait before being allowed to pass an aisle. Therefore, when optimizing the layout of machines, the aisles structure and their capacity must be considered. This article presents a hybrid approach for layout design in manufacturing systems taking into account capacitated aisles structure. The proposed approach combines a metaheuristic algorithm and simulation. First, the aisle structure is defined and then, the layout of the machines is determined. Each layout is evaluated through a simulation model. In this way, it is possible to avoid unrealistic assumptions and consider realistic conditions such as stochastic demand, random process time and random transportation time. Finally, a numerical example is included to illustrate the proposed approach.

KEYWORDS: *Facility Layout Problem, Manufacturing Systems, Capacitated Aisles, Simulation*

1. Introduction

Determining the best position of facilities in a system is known as Facility Layout Problem (FLP). FLPs are difficult combinatorial optimization problems in operational research. One of the most studied areas of FLPs is manufacturing systems. The layout of the facilities plays a very important role in the productivity and efficiency of these systems [1]. Tompkins et al. [2] estimated that between 20%-50% of the total costs in manufacturing systems are related to material handling and a good layout can at least reduce those costs up to 30%. The research questions are concerned with the placement of facilities on the surface of the workshop to minimize production objective(s), under several types of constraints [3].

The design of a manufacturing layout is more efficient by considering the reflection of transportation details such as aisles structure and transporter movement path for material handling [4]. However, only the layout of machines has been usually studied in published articles and the design of aisles has been less investigated. In manufacturing systems aisles are paths used by transporters to transport the materials

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between machines. The aisle structure is very important in determining the machine layout and it affects the distance between machines.

Another important issue in the layout of a manufacturing system is considering the width of aisles. The width of an aisle determines the capacity of the aisle which is the number of transporters that can pass an aisle at the same time. Actually, the width of the aisles cannot be infinite and there is a limitation of the number of transporters that can pass an aisle at the same time. 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 transportation time in manufacturing systems [5]. Since minimizing transportation time is one of the most important objectives of machine layout, paying attention to the capacity of aisles is essential to find the best layout.

Considering capacitated aisles in layout design is the main motivation of this research. To this aim, the dynamic and stochastic behavior of the manufacturing system such as the stochastic demand of products, stochastic transportation time and stochastic process time must be considered. Due to the complexity of the problem, we propose a hybrid approach based on simulation and optimization. In the proposed approach first, the structure of the aisles is determined. Then, a metaheuristic algorithm is combined with a simulation model to find the best position of machines. In this way, each solution in the metaheuristic algorithm is given to the simulation model to be evaluated. A stochastic simulation is used to evaluate the performance of a layout. This allows the calculation of the real performance of a manufacturing system by holding in high regard what happens in reality especially those that are related to the material handling process. In the simulation model, the realistic considerations of material handling such as the transporters are only allowed to move through the aisles, the capacity of aisles is limited, the traveling time is stochastic, there is a time required to load and unload the products in each machine which is stochastic, acceleration, deceleration and turn speed is considered when the transporters come across an intersection is taken into account. The remainder of the article is structured as follows. In Section 2 we analyze the related literature and highlight our contribution regarding the works published in this area. In Section 3 the general principals are presented. Then, the suggested approach is explained in Section 4. Section 5 discusses the experimental results to illustrate the applicability of the approach. Finally, our conclusion and future research directions are provided in Section 6.

2. Related research

In this section, articles concerning aisles structure and facility layout in manufacturing systems are reviewed. These articles both the aisles structure and the position of machines. Peters and Yang [6] proposed an approach to solve an FLP considering the aisles in a semiconductor manufacturing industry. The aisles structure was limited to be around the floor or one central aisle. Benson and Foote [7] defined a set of aisle structures with both vertical and horizontal aisles. Then a genetic algorithm was applied to select the best aisle structure and locating the input and output points of each department. Gomez et al. [8] designed a **Genetic Algorithm (GA)** which can be used in plant layout and is able to incorporate aisles design. The aisles structure consisted of a set of vertical aisles. Chang et al. [9] addressed an optimal multiple-floor layout with aisles. The departments allocated to each floor were grouped by the K-means clustering algorithm. Then, a hybrid GA was applied to find the layout of departments and aisles structure on each floor. Zhou et al. [10] considered some fixed spaces as aisles for moving the transportation

devices and optimize FLP with two objectives functions of minimization of the material handling cost and maximization adjacent requirement between resources. They formulated the problem as a bi-criteria nonlinear **Mixed-Integer Programming** (MIP) model and used a multi-objective GA to solve it. Wang and Chang [11] presented an FLP where workstations are assigned to several parallel bays. In their investigated problem, a central vertical aisle was used to move the materials between bay. In order to handle the material inside each bay, there exists a set of horizontal aisles connected to the central vertical aisle. They proposed a two-stage MIP model to solve the problem. In the first stage, each workstation was allocated to a bay and in the second stage, the exact position of workstations inside their relevant bay was determined. Klausnitzer and Lasch [12] proposed a MIP approach to simultaneously optimize the aisle structure and the layout of facilities. They assumed that the aisles have a predefined width and can be placed around the facilities and next to floor space borders. Allahyari and Azab [13] proposed a mathematical model for FLP which considered operation sequences, parts' demand and aisles 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 aisle 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. They used a heuristic algorithm to find feasible initial solution and then a multi-start search simulated annealing algorithm was used to search the optimum solution. Gülşen et al. [14] presented a double row FLP with multiple replicates of different classes of machines. The machines were placed on either side of a central aisle. The central aisle was straight with a fixed width. the problem was formulated as a nonlinear MIP model and solve by a hierarchical optimization approach was developed.

Based on this review, it can be noted that the literature is relatively limited in terms of methods addressing the layout design considering aisles. Among these few articles, some issues concerning aisles like the capacity of the aisles have been less paid attention and need to be analyzed deeper. This has been pointed out as one literature gap in Friedrich et al. [15]. Aisles capacity is a key factor to determine the number of transporters that can go through an aisle at the same time. Furthermore, most of the articles in this area have not addressed the stochastic characteristics of manufacturing systems such as the stochastic demand of products and stochastic transportation time. In the next sections, the main principles of aisle and aisles capacity are first described. Then, the proposed approach in this article to deal with the mentioned considerations in the layout of manufacturing systems is presented.

3. General principles

3.1. Layout and aisle network

In manufacturing systems, the products require to be processed on different machines and this causes the flow of materials between machines. Different types of transporters, such as industrial trucks, conveyors, hoists, and cranes are used to handle the materials between machines. In certain manufacturing systems, producing small batches of a variety of products, industrial trucks such as forklifts, hand lifts and side loaders are often used for transportation. In these manufacturing systems, the transporters are only allowed to move on specified paths, named aisles. By crossing the aisles, a network is generated. The transporters are only allowed to move through this network. Designing the aisles network is important to determine the machine layout [4]. The machines and aisles must be placed on the shop floor so that (1) all

the machines have access to the aisles network, (2) no overlap between machines and aisles occurs and (3) a path between each pair of machines via the aisle network is available. When the transportation system receives the movement request, a transporter is dispatched to the origin machine and handles the material to the destination machine. Sometimes the received requests are more than the capacity of transporters and we need to prioritize the requests. This leads to bring up phenomena such as dispatching policy and queuing (e. g., parts waiting for the availability of a transporter).

3.2. Aisle capacity

Each aisle is characterized by its width, length and location. The width of each aisle a , wa_a , induces a capacity related to the transporters. When a transporter tr is going to pass aisle a , obviously its width, wth_{tr} , must be less than the width of the aisle, $wa \geq wth_{tr}$. When two transporters tr and tr' are passing aisle a in opposite direction, they definitely will go across each other. Therefore, the width of the aisle must be larger than their total width, $wa \geq wth_{tr} + wth_{tr'}$. Otherwise, transporters would collide with each other. In general, it can be said that the width of an aisle must be larger than the total width of transporters that go across each other in that aisle.

4. Proposed approach

4.1. Determining the aisle network

The shop floor of the manufacturing system has a rectangular shape with length L and width W . The machines are equal and have rectangular shapes with predetermined orientation. There are vertical and horizontal aisles. The width of the aisles is equal to wa . The aisles divide the shop floor into sections, called position. 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 a consideration we avoid creating triangular or odd-shaped positions. Therefore, each possible position of machine will have a rectangular shape. Machines are assigned to possible positions. The aisle network must be so that there is enough space for machines 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 machines, (lm, wm) , the number of vertical (R) and horizontal (S) aisles must be so that Equations (1) and (2) are satisfied.

$$\lfloor (L - lm)/(lm + wa) \rfloor \leq R \leq \lfloor (L + lm)/(lm + wa) \rfloor \quad (1)$$

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

Therefore, there is a choice in determining the number of aisles. Since at last one machine 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 machines. This is guaranteed through the following equations.

$$M \leq N \quad (3)$$

$$N = R' \times S' \quad (4)$$

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

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

M is the number of machines and N is the number of possible positions generated by aisles. This guarantees that the number of generated positions is at least equal to the number of machines.

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 machine. According to the same procedure, other vertical aisles are placed one by one until it is not possible to add a new aisle or machine. If we had used the minimum allowable aisle, then we start by placing the machine. After that aisles and machines 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 machine 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. An example of an aisle structure for a manufacturing system with $N = M = 12$ is given in Fig. 1. The aisle structure shown in this figure consists of two horizontal aisles and three vertical aisles. Also, the real distance to go from machine Grind to machine Drill can be seen.

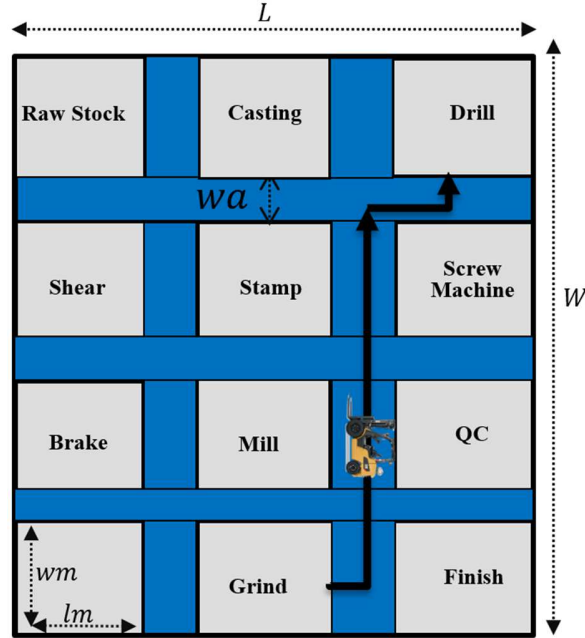


Fig. 1. An example of aisle structure.

4.2. Assignment of machines to possible positions

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

Indices

j, i Index for machines, $j = 1, \dots, M$

l Index for positions, $l = 1, \dots, N$

tr Index for transporters, $tr = 1, 2, \dots, TR$

a Index for aisles, $a = 1, 2, \dots, R + S$

Parameters

wth_{tr} The width of transporter tr

wa_a The width of aisle a

f_{ji} Material flow between machines j and i

Dependent decision variable

$$M_{tr, tr', a} = \begin{cases} 1 & \text{if transporter } tr \text{ and } tr' \text{ go across each other in aisle } a \\ 0 & \text{otherwise} \end{cases}$$

d_{ji} Distance between machine j and i

Independent decision variable

$$X_{j,l} = \begin{cases} 1 & \text{if the machine } j \text{ is placed in the position } l \\ 0 & \text{otherwise} \end{cases}$$

$$\min E (MFT) = E [f (X_{j,l}, d_{ji}, f_{ji}, \epsilon)] \quad (7)$$

$$\sum_{l=1}^N X_{j,l} = 1 \quad \forall j \quad (8)$$

$$\sum_{j=1}^M X_{j,l} \leq 1 \quad \forall l \quad (9)$$

$$M_{tr, tr', a} (wth_{tr} + wth_{tr'}) \leq wa_a \quad \forall tr, tr', a \quad (10)$$

$$X_{j,l}, M_{tr, tr', a} \in \{0, 1\} \quad \forall tr, tr', a, j, l \quad (11)$$

MFT is selected as a performance measure. 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 [16]. MFT can reflect the impact of the position of machines and capacitated aisles. Therefore, the objective of the mathematical model is to minimize the MFT. Formally, the binary decision variable $X_{j,l}$ takes value 1 if the machine j is placed in the position l , and 0 otherwise. Constraints set (8) guarantee that each machine is assigned to one position. Constraints set (9) guarantee that in each position at most one machine is placed. Constraints set (10) control that at each time the number of transporters in an aisle is less than the aisle capacity. The constraints set (11) control the decision variables.

A major difficulty to solve the model comes from calculating the objective function. The stochastic aspects of the manufacturing system and capacitated aisles make it difficult to calculate the value of MFT. To deal with these difficulties, we propose a simulation optimization approach to search the best assignment of machines for possible positions.

4.3. Simulation optimization

Simulation optimization is one of the most applicable and popular techniques to handle the stochastic in operational research and particularly FLPs [17–21]. Even if several researchers have used simulation optimization approach in FLPs they have not specifically addressed aisles structure and their capacity. On the other hand, we apply a different approach from prior articles. In some of these articles have used simulation optimization in two separate steps. In the first step, a simulation model is built and run for a set of solutions. Then, the results are used to develop a meta-model. This meta-model will estimate the performance measure. The main shortcoming of two steps approach is the accuracy of the meta-model. To cope with this shortcoming some articles have used dynamic interaction between simulation and optimization during execution. In this way, during the optimization process, each solution is given to the simulation model, evaluated and the results are resent to optimization algorithm. By integrating simulation and optimization and make a dynamic communication between simulation and optimization the accuracy of the results will increase. According to our knowledge, in all the researches the dynamic communication has been done through the use of optimization toolbox of simulation packages or two different software and connect them through a text or excel file. The optimization toolbox of simulation packages has been designed to search optimum solution in less complicated problems. Also, there are a very limited optimization algorithm in these toolboxes. Make a connection between simulation and optimization algorithms that are executed in two different software through a text or excel file leads to an increase the computational time. The proposed simulation optimization in this article has used a direct connection between simulation and optimization to increase computational efficiency. We utilize the integrated package Matlab/Simulink. In Matlab, we have access to a wide variety of heuristics and metaheuristics optimization algorithms that one could tune, manipulate and enhance according to its needs. The GA is used as an optimization algorithm and Simulink is used to develop the simulation model. Simulink is a tool embedded inside the Matlab. In this way, the simulation and optimization parts can be directly connected. As a metaheuristic algorithm, we apply a GA. The GA iteratively searches to find the best layout while each layout is given to Simulink to be evaluated. This continues until the stopping criterion is satisfied.

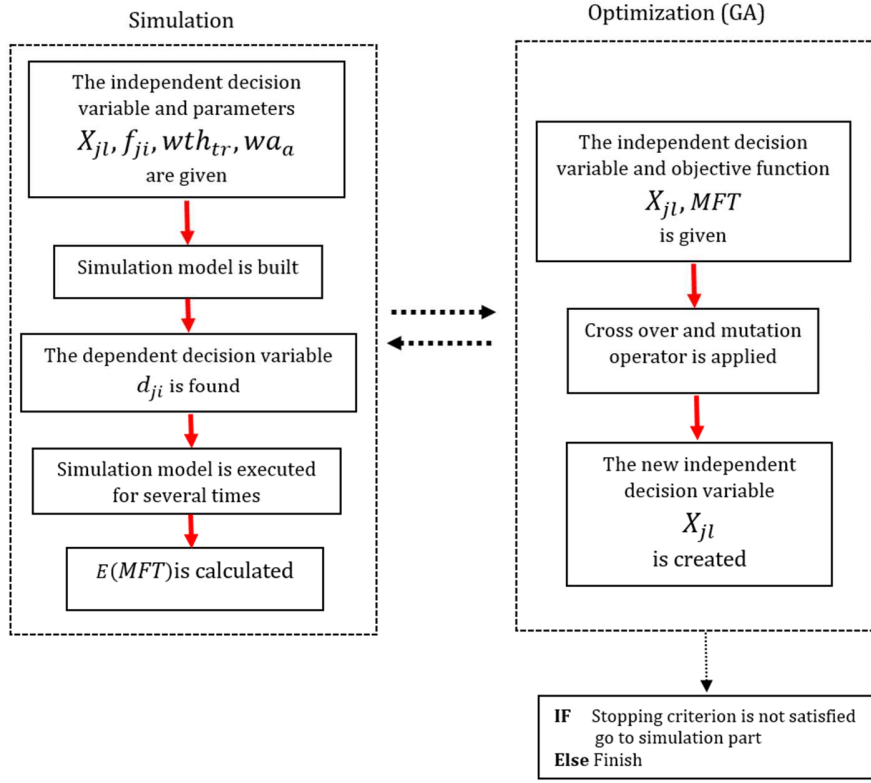


Fig. 2. Simulation optimization approach.

4.3.1. The simulation model

Simulink is a modeling, simulation and analysis software for dynamic systems. It allows the study of linear and nonlinear systems modeled continuously, discrete or hybrids. The system under study in this article is a discrete system. the dedicated module for discrete event systems in Simulink is called SimEvents. SimEvents, embedded in Simulink, is a simulation engine and has a wide verity of components for analyzing event-driven system models and optimizing performance characteristics such as throughput, MFT and packet loss [22]. In order to build the simulation model, first the structure of the aisles is created based on the method described in section 4.1. Then, given the value of the decision variable $X_{j,l}$, machines are placed in positions. By this method, it is guaranteed that no overlap between machines and aisles will occur. When a transporter is going to enter an aisle, the simulation model verifies two things. (1) The capacity of that aisles and (2) if any other transporter is in that aisle or not. According to these two matters, the simulation model let the transporter to go across the aisle or stop the transporter until the aisle gets empty. In this way the constraint (10) is satisfied. Constraints (8) and (9) are satisfied by the way we define the solution in the GA. Therefore, the simulation model calculates the MFT of a feasible solution.

4.3.2. Optimization algorithm

Genetic Algorithms (GAs) have been successfully used for layout design [23–27]. The GA starts with a set of chromosomes. In order to produce new chromosomes, two operators crossover and mutation are used in GA. Then, based on the fitness function values, some of the chromosomes with better values of the fitness function are saved. In this way, better chromosomes can participate to generate new chromosomes in the next generations. The algorithm continues this procedure until some termination criteria is satisfied.

4.3.2.1. Fitness function

Our fitness function is the MFT that should be minimized (Equation 7). The MFT of jobs is defined by Equation (12).

$$MFT = \frac{\sum_{i=1}^I f_i}{I} \quad (12)$$

Where f_i is the flow time of job i and I is the number of jobs.

4.3.2.2. Chromosome structure

One of the most important issues in applying any meta-heuristic 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 the machine 1 must be assigned; the second number shows the position wherein the machine 2 must be assigned and so on. As explained in section 4.1 the number of machines is less than the number of positions, $M \leq N$, and hence in order to assign machines to positions, $(N - M)$ dummy machines are defined. If a dummy machine is assigned to a position, that position is empty. For instance, Fig. 3 shows an example of a chromosome for a problem with 6 machines and 8 positions. Machines 7 and 8 are dummy machines and hence, positions 2 and 6 are empty. In this way, both constraint set (8) and (9) will be satisfied.

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

Fig. 3. An example of chromosome representation.

4.3.2.3. 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 machine numbers before the cross point of Parent 1 are directly copied in the offspring. The remaining machine numbers are put into empty positions according to their relative positions in Parent 2 (Fig 4). In this way, we avoid duplicating numbers and so constraint sets (8) and (9) are satisfied.

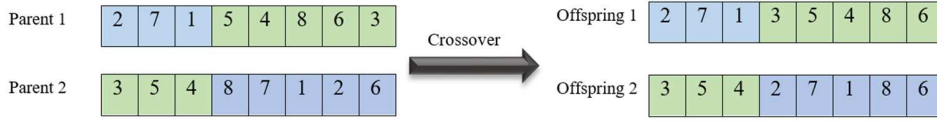


Fig. 4. An example of a crossover operator.

4.3.2.4. Mutation operator

The purpose of the mutation is to prevent the population from being too similar and getting trapped into local optima. According to [28], it is interesting 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 Equations (13) and (14) are used.

$$SC_{ab} = \frac{\sum_{j=1}^M \partial(X_{ja}, X_{jb})}{M} \quad (13)$$

$$\partial(X_{ja}, X_{jb}) = \begin{cases} 1 & \text{if } X_{ja} = X_{jb} \\ 0 & \text{otherwise} \end{cases} \quad (14)$$

In which SC_{ab} are the positions of the machine in the chromosomes a and b is the number of machines. $\partial(X_{ja}, X_{jb})$ is the similarity between two especial genes. Then, the average similarity coefficient of the population is calculated by Equation (15).

$$\overline{SC} = \frac{\sum_{a=1}^{N_p-1} \sum_{b=a+1}^{N_p} SC_{ab}}{\binom{N_p}{2}} \quad (15)$$

In which N_p is the number of chromosomes in the population. Finally, when the similarity coefficient is greater than the predefined threshold the mutation is incorporated into the GA loop. To perform the mutation operator first a chromosome is randomly selected. Then, as shown in Fig 5, the genes of the selected chromosome are arranged reversely. We note that because we just changed the sequence of genes, the chromosomes remain feasible.

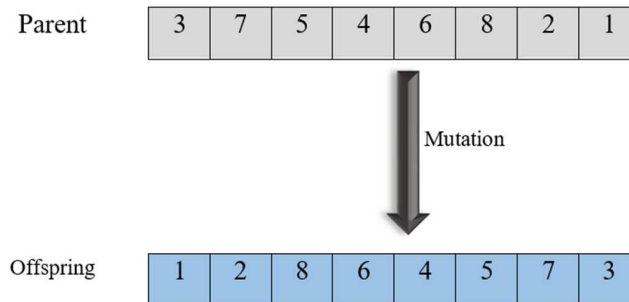


Fig. 5. An example of a mutation operator.

4.3.2.5. Stopping criterion.

The algorithm generates new populations until the total number of iterations reached to a predefined number.

5. Application example

In this section, the application of the proposed approach is illustrated by an example. The example is a 83m×39m manufacturing system with 12 machines. The data is extracted from a case presented in Ho and Liu [29]. Machines 1 and 12 are virtual machines to show the system's entry station and exit station, respectively. The stochastic process time of each machine is presented in Table 1. In this table, N means normal distribution. Table 2 shows the stochastic demand and process sequence of each product. 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 the Equations (1) and (2) the number of vertical aisle must be between 3 and 5 and the number of horizontal aisle must be between 2 and 4. We select 5 vertical and 4 horizontal aisles. As a result, 12 possible positions are generated. The machine 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 [29], GQL is the best dispatching policy for minimizing the time-based indexes. In GQL, a transporter gives priority to the machine that has the greatest number of waiting parts. The number of simulation replications for each layout is set at 30.

Table 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 2
The processing time distribution

Machines	Process time	Machines	Process time
2	N(1, 0.1)	7	N(2, 0.2)
3	N(1.5, 0.15)	8	N(1.5, 0.15)
4	N(2, 0.2)	9	N(1.5, 0.15)
5	N(1, 0.1)	10	N(2, 0.2)
6	N(2, 0.2)	11	N(1, 0.1)

The GA searches for the best layout and uses the simulation to calculate the MFT corresponds to each layout. to this aim, first, all of the parameters of the GA are tuned via response surface method. The optimum value for the parameters including the size of the population, crossover percent, mutation percent, similarity coefficient and the number of replication are respectively set to 30, 0.6, 0.05, 0.9 and 30. Based on these values the GA is run and the problem is optimized. Fig. 6 presents the convergence diagram of the GA. The mean curve shows the average values objective function of chromosomes in each generation and best is the objective function of the best chromosome. The MFT for the best obtained layout is 5982s.

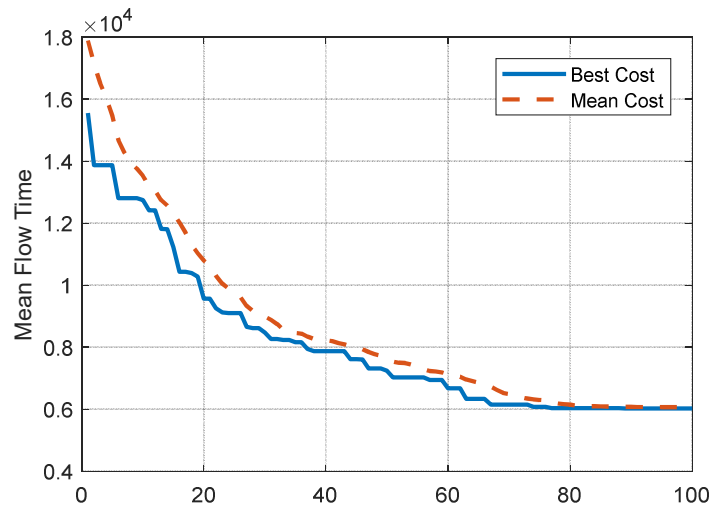


Fig. 6. The convergence diagram of GA.

6. Conclusion

This article studied the issue of aisles structure and being capacitated of aisles in the layout of facilities in manufacturing systems. The structure of the aisles and their capacity, as an inseparable part of the layout, affect system performance. Throughout this study, the importance of aisles and considering the limited capacity for the aisles were examined and an approach was proposed to deal with. The proposed approach first determined the structure of the aisles. Then, a simulation optimization method was used to find the best layout of the machines. In this way, the simulation model, directly connected to the optimization algorithm, was used to evaluate the layouts. Thanks to simulation, the proposed approach can take into account the realistic considerations such as stochastic transportation time and stochastic demand of products and so it can be applied for a wide variety of manufacturing systems. The applicability of the proposed approach was tested by an example. In this example, we determine the aisles structure and position of machines in a manufacturing system with twelve machines. **The next step of this research is to**

conduct more experiments to evaluate the performance of the proposed algorithm compared to other search optimization algorithms such as Tabu Search, Simulated Annealing and so on. Other future research directions are concerned with reducing computing costs by formulating the problem based on stochastic mathematical programming or queueing theory. The problem of simultaneously determining the aisles structure and machine layout can also be investigated.

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