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OPTIMIZATION OF THE DESIGN OF THE FLEXIBLE MANUFACTURING SYSTEM

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Hassan MROUE, 2016

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OPTIMISATION DE LA CONCEPTION DU SYSTÈME MANUFACTURIER FLEXIBLE

Hassan MROUE

Résumé

La conception des systèmes manufacturiers flexibles est étudiée dans cette thèse. Dans le contexte de la compétition industrielle, les systèmes de fabrication doivent être flexibles pour pouvoir fabriquer, sur la même ligne ou plateforme, plusieurs types de produits avec des quantités variables dans le temps. En plus, la modification de la conception de la ligne de fabrication dans certains secteurs est en train de devenir de plus en plus importante à cause du changement constant du marché en termes de types et de volumes des produits à fabriquer. La performance et la fiabilité d'un système de fabrication ont un impact important sur le coût opérationnel du système donc sur le profit et la compétitivité d'une entreprise. Face à ce contexte / dilemme, les industriels ont besoin d'outils pratiques et performants pour répondre rapidement aux besoins des clients. Dans le contexte de la globalisation, les entreprises doivent être compétitives pour rester sur le marché. La performance du système de fabrication est l'un des éléments essentiels permettant aux entreprises de réduire les coûts et d'être compétitives.

En effet, un système manufacturier flexible est une combinaison d'un atelier et des cellules manufacturières. Chaque cellule contient toutes les ressources requises pour traiter des pièces qui ont des caractéristiques de fabrication semblables. Ces ressources s'agissent des machines, travailleurs, outils, équipements, etc. Les cellules peuvent être conçues de plusieurs façons. Afin de diminuer les coûts et les durées de la fabrication ainsi que d'éviter les conflits, il est très important d'acheminer les pièces d'une façon optimale et d'optimiser par la suite la formation des cellules.

Cette étude vise à améliorer la conception des systèmes manufacturiers flexibles tout en prenant le côté économique en considération à travers le développement de trois nouveaux algorithmes. Le premier a comme but d'optimiser la formation des cellules manufacturières et fractionnelles tout en introduisant une nouvelle trousse à outils théorique. Cette trousse accélère énormément la découverte de la solution finale parmi un nombre énorme des solutions candidates. Le deuxième algorithme concentre sur l'optimisation de l'acheminement des pièces à travers un modèle heuristique qui minimise à la fois les coûts et les durées de la fabrication. Le dernier algorithme introduit une méthodologie qui maximise les profits des entreprises à travers l'investissement sur des nouvelles machines ou bien la mise à jour des machines existantes dans le contexte de la fabrication flexible. L'importance industrielle de ce travail provient du fait qu'une entreprise peut utiliser les trois algorithmes d'une façon interdépendante afin d'optimiser son système.

Mots-clés : Système manufacturier flexible; cellule manufacturière; cellule fractionnelle; acheminement des pièces; maximisation des profits; sélection des machines

OPTIMIZATION OF THE DESIGN OF THE FLEXIBLE MANUFACTURING SYSTEM

Hassan MROUE

Summary

The design of flexible manufacturing systems is studied in this thesis. In the context of the industrial competition, the manufacturing system must be flexible in order to be able to produce, on the same line or platform, several types of products with varying amounts over time. In addition, the change of the design of the production line in some areas is becoming increasingly important due to the constant changes in the market in terms of the types and volumes of products to manufacture. The performance and reliability of a production system have a significant impact on the operational costs of the system and therefore, on the profits and the competitiveness of the enterprise. According to this context / dilemma, the manufacturers need practical and efficient tools to effectively design their flexible manufacturing systems in order to become able to respond quickly to their customers' needs.

Indeed, a flexible manufacturing system is a combination of a job shop and manufacturing cells. Each cell contains all the resources required to treat the parts that have similar production characteristics. These resources consist of machines, labor, tools, equipment, etc. The cells may be designed in many ways. In order to reduce the cost and the duration of the fabrication and to avoid the conflicts, it is very important to optimally route the manufacturing parts and to optimize thereafter the formation of the cells.

Hence, this study aims to improve the design of flexible manufacturing systems while taking into account the economic aspect through the development of three new algorithms. The first work aims to optimize the formation of the manufacturing and fractional cells, while introducing a new theoretical toolkit. This kit greatly accelerates the discovery of the final solution from a large number of candidate solutions. The second one focuses on the optimization of the part routing through a heuristic model that minimizes the costs and the durations of the production. The last algorithm presents a new method that maximizes the profits of the manufacturing enterprises through the investment on new machines or through the upgrade of the existing ones in the context of the flexible fabrication. The industrial importance of this work comes from the fact that an enterprise can use all of the three algorithms in an interdependent manner in order to optimize its system.

Keywords: Flexible manufacturing system; Manufacturing cell; Fractional cell; Part routing; Profit maximization; Machine selection

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABREVIATIONS

CMS	Cellular Manufacturing System
FMS	Flexible Manufacturing System
GT	Group Technology
NP-HARD	Non-deterministic Polynomial-time HARD
SA	Simulated Annealing

LIST OF SYMBOLS AND UNITS OF MEASUREMENTS

SPECIFIC FOR CHAPTER 2

A	Incidence matrix
a_{mn}	Workload of the part number n when being processed on the machine number m
e	Grouping efficiency
e_1	Measure of the cell density
e_2	Measure of the intercellular material flow
K	Number of manufacturing cells
k	Index of the manufacturing cells
M	Total number of machines
m	The index of the machines
M^*	Latest configuration of the incidence matrix
M_k	Number of machines which are assigned to the manufacturing cell number k
N	Total number of parts
n	The index of the parts
n_1	Number of nonzero entries existing in the manufacturing cells
n_2	Number of the exceptional elements
N_f	Nonzero entry neighboring factor
N_k	Number of parts which are assigned to the manufacturing cell number k
N_M	Neighborhood factor of the incidence matrix
N_M^*	Latest neighborhood factor of the whole matrix

SPECIFIC FOR CHAPTER 3

C	Maximum allowable cost for treating all of the manufacturing parts
c_{2nm}	Weighed cost
C_{ai}	Additional processing cost in the iteration number i
C_{fi}	Final operational cost in the iteration number i

c_{nm}	The required cost for processing the part number n on the machine number m
C_{ti}	Total cost in the iteration number i
D	Maximum acceptable duration for treating all of the manufacturing parts
d_{2nm}	Weighed duration
D_{ai}	Additional processing duration in the iteration number i
D_{fi}	Final operational time in the iteration number i
d_{nm}	The required duration for processing the part number n on the machine number m
D_{ti}	Total duration in the iteration number i
i	Iteration number
M_N	Weighed matrix
O	Total number of required operations
o_n	Number of operations required on the part number n
v_{nm}	Total weighed value for each operation
x_1	The weight of the processing cost with respect to the duration
x_2	The weight of the processing duration with respect to the cost

SPECIFIC FOR CHAPTER 4

c	Total cost of processing a part on a machine
C_m	Costs of buying new machines or upgrading the existing ones
crt_{nm}	Resulting run-time to cost conversion value
dc_{nm}	Direct costs of processing the part number n on the machine m
Fp	Final net profits
M_c	Manufacturing costs
mrt_{nm}	Maximum allowable run-time for each operation
n_e	Number of exceptional elements
nn_e	Number of non-exceptional elements
O	Total number of required operations

P	Net profits
R	Estimated revenues
rt_{nm}	Required run time for processing the part n on the machine m
t	Number of types of products
tc_{nm}	Total cost that is defined as the sum of the direct costs and the resulting run-time to cost conversion values
x_1	Average index of conversion into costs of the run-time
x_2	Indicator for the required machines’ processing speeds

INTRODUCTION

A manufacturing system is composed of labor, machines and equipment as well as a flow of information. Such a system is called flexible when it has a certain degree of ability to respond to changes. In fact, a flexible manufacturing system is a combination of a job shop and manufacturing cells (Chryssolouris, 2006). Each cell contains all the resources required to treat parts that have similar production characteristics (Marghalany *et al.,* 2004). These resources may consist of machinery, labor, tools, equipment, etc. (Luggen, 1991). The manufacturing cells may be designed in many ways. In order to reduce the cost and the duration of the production, the first step consists of optimally routing the parts and of optimizing thereafter the formation of the cells. This step constitutes a serious problematic since there is an undetermined number of possibilities for routing the parts and designing the cells. In other words, there is no a precise mathematical formula that can solve such a problem which is classified as non-deterministic polynomial-time hard (NP-hard). The term NP-hard means that for any technical optimization, increasing the size of the problem will cause an exponential increase in the computational time (Ben Mosbah and Dao, 2013). That is why; there is a need to develop algorithms which are able to give optimal or near-optimal solutions. The economic aspect constitutes as well a vital factor for the enterprises which use such systems. Hence, the present work focused on three subjects. The first one is how to optimally design the manufacturing cells, the second one is how to find the optimal routing of the manufacturing parts, and the third concentrates on the maximization of the profits for the enterprises which are looking to buy new machines in order to establish a new FMS or to upgrade an existing one.

Organization of the thesis

This manuscript-based thesis is divided into four chapters.

The first chapter defines the design of the flexible manufacturing system. In addition, it describes the manufacturing cell and mentions some advantages and disadvantages of the FMS with respect to a non-flexible system. Furthermore, it presents a review of the related subjects from the literature. Finally, it lists some industrial benefits which result from applying the algorithms presented in the last three chapters.

The second chapter presents a journal article. It introduces a new algorithm which aims to search for the optimal manufacturing and fractional cell formation procedure within a flexible manufacturing system. In addition, the article includes a new set of logical operations in order to greatly accelerate the procedure of finding final solutions among a huge number of possibilities.

The third chapter provides a new algorithm which describes how to route the manufacturing parts within a flexible manufacturing system. The algorithm takes into consideration both the manufacturing durations and costs in order to find optimal solutions. In addition, it establishes a direct relation between the routing of the parts on one hand and the design of the cells on the other hand in order to make sure that the routing is not necessarily optimal by itself, but it leads to an optimal cell design. The algorithm constitutes as well an advisor for the enterprises which are fully busy with processing customers' commands whether to accept or to refuse a new fabrication demand.

The last chapter describes a new algorithm for maximizing the manufacturing profits through a machine selection procedure within a flexible manufacturing system. The algorithm links the routing of the parts and the formation of the cells to the machine selection and it is mainly useful for the profit maximization of the enterprises which are looking to buy new machines in order to establish a new FMS or to upgrade an existing one. In addition, the whole procedure tends to eliminate the exceptional elements within the system. The article combines together the engineering and the economic aspects in order to end up with final results.

It is important to note that the logical order of the last three chapters can also be considered the inverse of their sequential order in the thesis. Namely, the reader can begin by the last chapter followed by the third and lastly by the second.

Finally, the thesis ends up with a conclusion as well as some recommendations.

CHAPTER 1

REVIEW OF THE LITERATURE

1.1 Introduction

A manufacturing system is known as flexible when it has a certain degree of ability to respond to changes. According to (Das, 1996), there are five kinds of flexibilities. The first one is the machine flexibility which means that the machine is able to shift from one task to another without major difficulties. The second is the routing flexibility which refers to the possibility of having various routes for the fabrication of a certain product within the system. The third one is the process flexibility which is related to the diversity of the products that the system can produce without the need of important setups. The fourth is the product flexibility which is a measure for the easiness to add new products or to remove existing ones from the production line of the system. The last one is the volume flexibility which refers to the possibility of changing economically the production rate of the system. The degrees of these flexibilities depend on the layout of the system, the specifications of the machines, the products' processing requirements, etc. The generic layout of the system together with its components are discussed in this chapter and the consideration is mainly accorded to the subjects treated in the next three chapters of this thesis.

1.2 Flexible Manufacturing System (FMS) design

There are lots of types of flexible manufacturing systems around the world. In other words, a FMS can be designed in different ways depending on the production types. A generic layout of the system is shown in Figure 1.

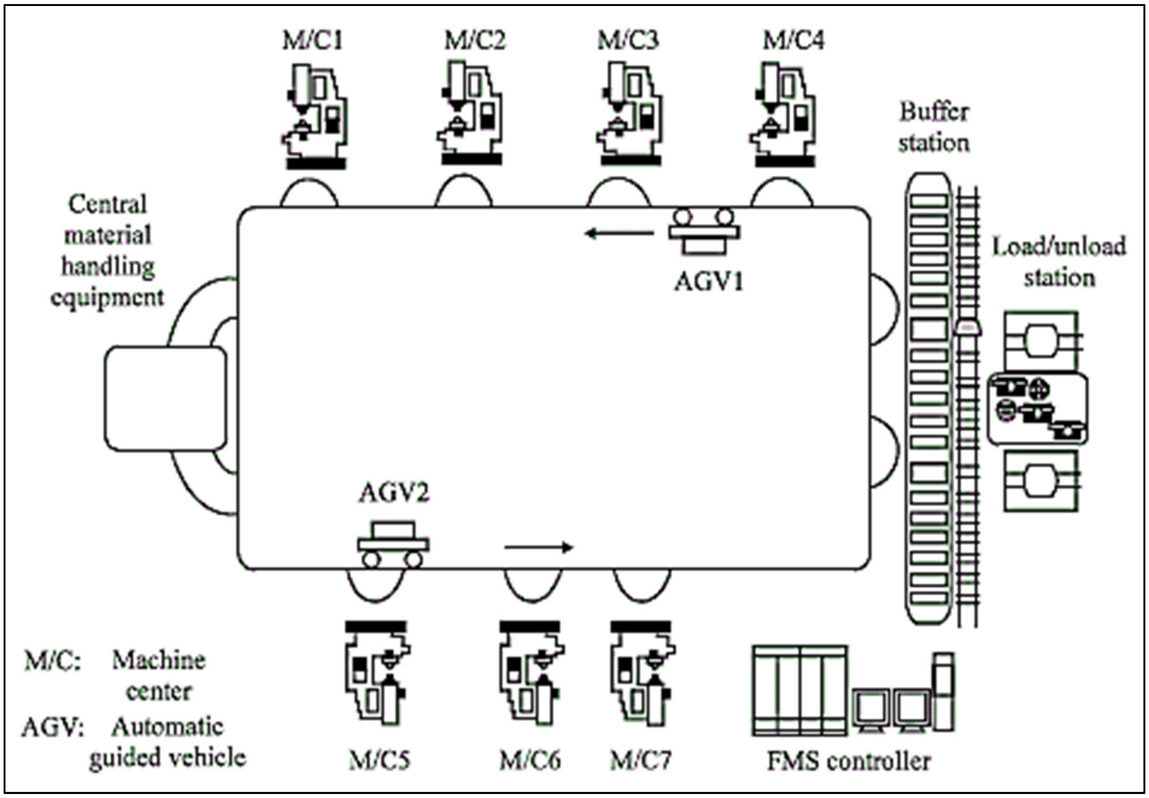

Figure 1 Generic layout of the FMS (Buzacott and Yao, 1986)

Yang *et al.* (2005) presented four main layouts for a flexible manufacturing system. These layouts are the spine, the circular, the ladder, and finally the open-field as shown in Figure 2.

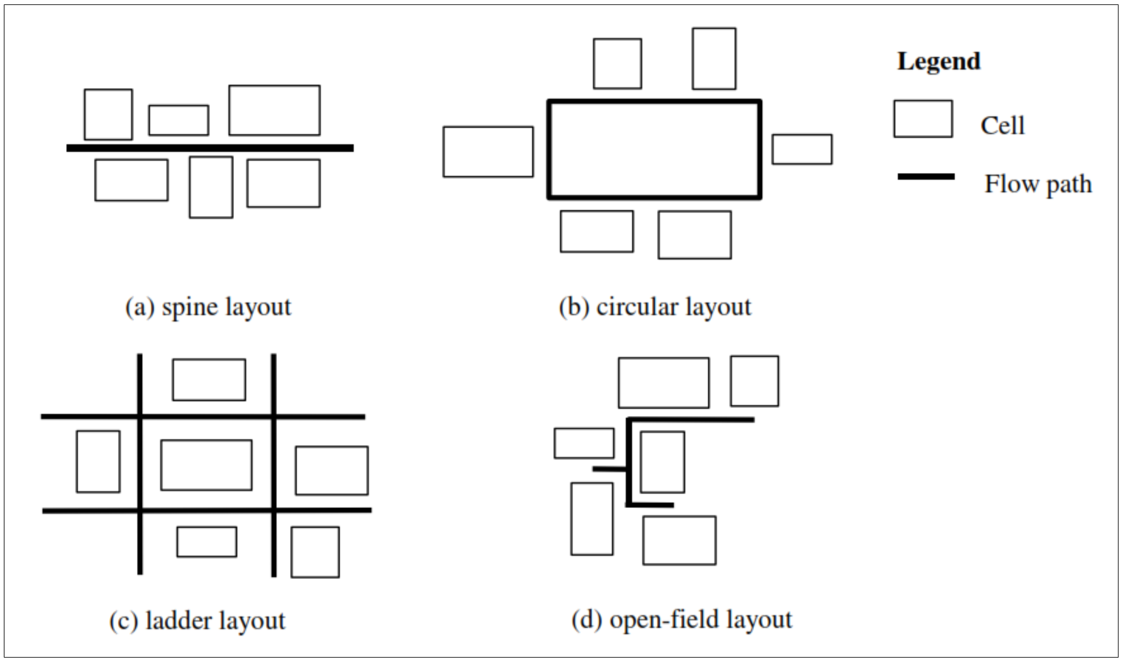

Figure 2 Layout types in a FMS (Yang *et al.*, 2005)

Thus, a flexible manufacturing system consists mainly of a flow path surrounded by a set of cells. The system includes machine centers as well as buffer stations. "The buffer storage in a manufacturing system serves to decouple the unbalance of processing time and the variability of breakdowns among different machines, and allows for flexible operations under fluctuated production requirements" (Lee and Ho, 2002). In addition, the load/unload stations of the system play a role in queuing the work pieces whereas the transportation of the manufacturing parts occurs through automatic guided vehicles (Cubberly and Bakerjian, 1996). Finally, the FMS involves other components such as a central material handling equipment, electronic controllers (Buzacott and Yao, 1986), etc. On the other hand, a linked-cell assembly can be found in the majority of the flexible manufacturing systems. The manufacturing and the assembly cells are interconnected through the Kanban links (Black and Hunter, 2003). Figure 3 shows a configuration of a system containing both manufacturing and assembly cells.

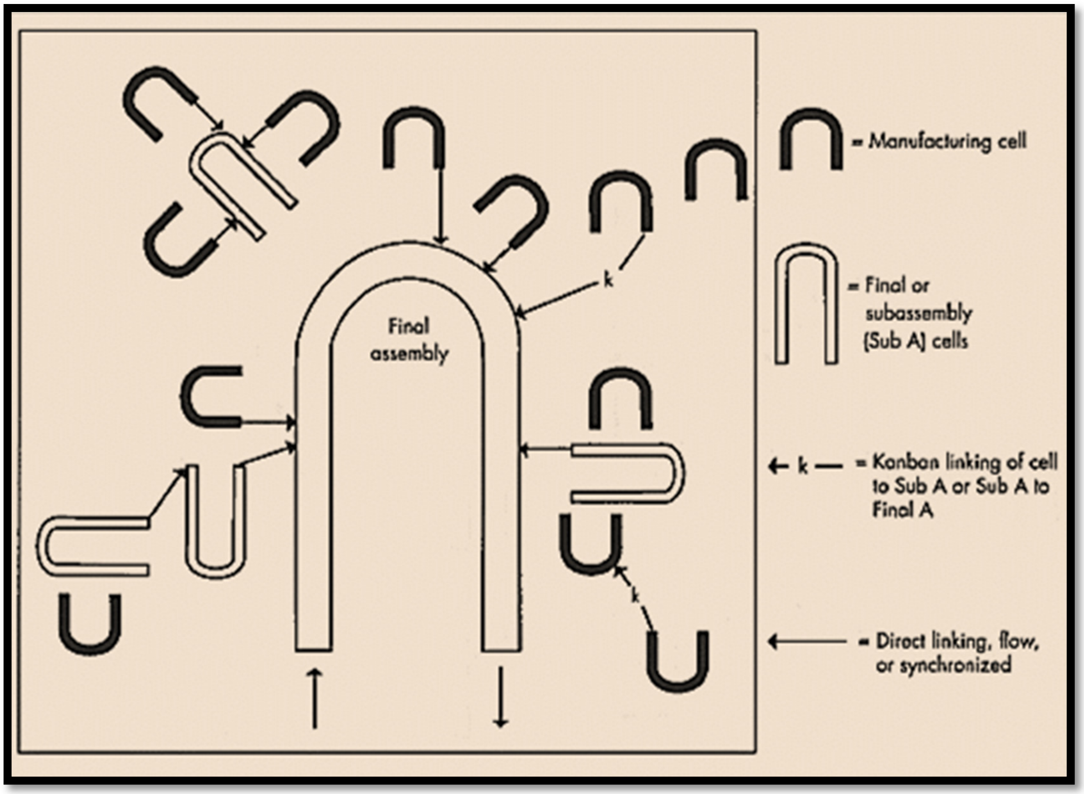

Figure 3 Linked manufacturing and assembly cells (Black and Hunter, 2003)

The Kanban links play the role of controllers by pulling only the required quantity of the parts and subassembly to the final assembly (Black and Hunter, 2003). Each manufacturing cell contains all the resources which are required in order to fabricate a certain type of parts. A general layout of the cell is shown in Figure 4.

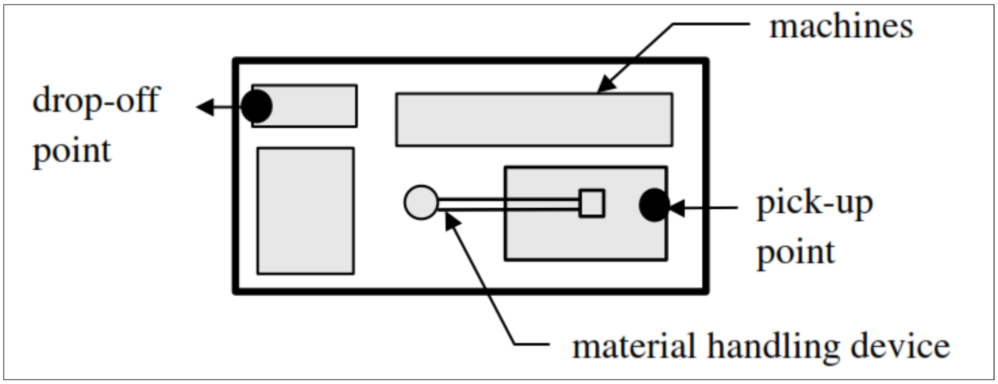

Figure 4 Manufacturing cell layout. (Yang *et al.,* 2005)

There are various types of manufacturing cells such as the virtual cell, dynamic cell etc. For instance, a virtual cell is composed of machines which are located in different departments in order to fabricate a part family. In other words, the machines are not adjacent to each other as they are in a regular manufacturing cell (Nomden et al., 2006). In a dynamic cellular environment, the machines and equipment can be moved whenever the mix of parts to fabricate gets changed. Namely, the system can be reconfigured when necessary (Chen, 1998). The layout of the system and of the contained cells depend on many factors such as the shop floor dimensions, the number and the nature of the machines to be installed, the parts and the products to be fabricated, etc. The design of the manufacturing cells and the routing of the parts occur according to a manufacturing philosophy that aims to ameliorate the productivity and which is known as group technology. This philosophy consists of grouping into families the parts that have resembling production requirements and grouping the machines that have different processing characteristics into production cells (Edwards, 1971). The importance of such a philosophy comes from the fact that the absence of an efficient way of routing the parts and designing the cells may lead to some disorders into the system which may cause major problems such as production conflicts, waste of time, increase in the level of inventories, etc. (Luggen, 1991). In fact, the configuration of the FMS can be presented through what is so called incidence matrix like the one presented in Table 1-1.

Table 1-1 An incidence matrix

Machine / Part	Part 1	Part 2	Part 3	Part 4
Machine 1	1	0	1	1
Machine 2	1	0	0	0
Machine 3	0	1	0	1

The matrix contains only two characters such as ones and zeros. The non-zero entry (i.e. the one digit) in the incidence matrix means an operation. If we take as for example the non-zero entry in the first row and third column, it means that the part number three has to be processed by the machine number one; whereas, a zero entry means the opposite. The entries in the incidence matrix have been obtained after routing the parts. The routing will be discussed in details in the third chapter. It is to note that the configuration of the matrix and consequently the system can be changed by swapping either any two rows or any two columns. In other words, two different machines can interchange their locations within the system as well as any two different parts. Surely, a row and a column cannot be swapped since a machine cannot replace a part and vice-versa. The main goal of the swapping procedure is to obtain an optimal configuration of the system in order to design efficiently the manufacturing cells. If we swap, as for example, the parts number two and three, we get the matrix shown in Table 1-2.

Table 1-2 A new configuration for the incidence matrix

Machine / Part	Part 1	Part 3	Part 2	Part 4
Machine 1	1	1	0	1
Machine 2	1	0	0	0
Machine 3	0	0	1	1

By this way, two manufacturing cells highlighted in light blue can be formed within the system as shown in Table 1-3.

Table 1-3 Manufacturing cells

Machine / Part	Part 1	Part 3	Part 2	Part 4
Machine 1	1	1	0	1
Machine 2	1	0	0	0
Machine 3	0	0	1	1

Indeed, the cells have to contain all the machines and the parts of the system and each machine or part cannot be contained in more than one cell. The zero entry located in the second column and second row in Table 1-3 is called a void element because it means that the part number three will get into the first cell but it will not be processed by the machine number two. The non-zero entry located in the first row and fourth column in Table 1-3 is not contained in any cell and hence, it is called an exceptional element. This nomenclature comes from the fact that the part number four, which belongs to the second cell, needs to be processed by the first machine which belongs to the first cell. Both the void and the exceptional elements are undesirable since they will cause additional processing costs (Luggen, 1991) as will be explained in more details in a later paragraph. A perfect cell configuration means that all the non-zero entries are included within the cells which do not contain any zero entry on one hand; and that there are no non-zero entries outside the cells. By this way, the terms of the concept of group technology will be fulfilled perfectly. In addition to the routing of the parts and the formation of the cells, the design has to take into consideration the minimization of the costs of fabrication. Since the scope of study of the design of these systems is very wide, the current research does not focus on all the aspects but only on the ones which were described in the paragraph entitled "organization of the thesis" in the introduction of the thesis. In addition, the scheduling of the FMS, the production planning, the electric and electronic components, etc. are not addressed as well.

1.3 Advantages and disadvantages of using FMS

There are lots of advantages for using a flexible manufacturing system with respect to a non-flexible one such as the reduction of the setup time and production time, the diversity of the production types, the amelioration of the quality of the products, etc. On the other hand, these systems suffer as well from some disadvantages since they have sophisticated designs, they are relatively expensive etc. (Luggen, 1991).

1.4 Problematics

When establishing a new flexible manufacturing system or upgrading an existing one, an enterprise has to take into account the machines to select for this purpose. Such a selection is directly related to the nature of the products to manufacture as well as to the production volumes and costs. In addition, the configuration of the system has to be studied together with the estimated revenues and expenses in order to know whether the system is profitable or not. On the other hand, the manufacturing enterprises which are manufacturing high volume customers' demands need a decisional tool to help them decide whether they are able to accept a new fabrication request and whether such an acceptation is profitable. This is because the implementation of the new command may require a partial reconfiguration of the system. As can be obviously seen, all of these subjects directly influence and are directly influenced by the design of the system. In fact, the design of the FMS is a critical step since a random machine-part cell arrangement may cause production conflicts as well as higher costs and processing durations. On the other hand, the number of machines and parts which may be found in a FMS is not fix and consequently, we have an unlimited number of different sizes of the system (hence of the incidence matrix). Furthermore, the number of non-zero and that of zero entries within the incidence matrix are not constant and their distributions are various since each matrix represents a different system. In other words, we are dealing with an infinite number of possibilities and there is no a precise mathematical formula which can provide optimal solutions for all of these possibilities. In addition, the limitations of the processors' speeds of the computers constitute a major obstacle for finding all the possible configurations within a single incidence matrix. For instance, a matrix consisting of only twenty rows and forty columns contains a huge number of possible configurations which is equivalent to factorial (20) multiplied by factorial (40). This is because every swapping of any two rows or any two columns results in a new configuration. A recent computer with high computational capabilities may need billions of years in order to provide all the configurations for such a matrix. On the other hand, any methodology that will be developed in order to optimize the design of these systems has also to take the processing costs into consideration in order to avoid the wastes.

1.5 Hypotheses and objectives

In order to become able to optimize the design of the manufacturing system, new methodologies/algorithms have to be developed while taking into account that:

- The processing needs for each work piece are known (i.e. we know if a certain part needs grinding and/or boring and/or welding etc.)
- A machine and/or a part can be assigned to a single flexible manufacturing cell
- The processing duration and cost for each of the parts on each of the machines can be determined

The new algorithms aim to:

- Provide optimal configurations that lead to an efficient design for the flexible manufacturing and fractional cells and to the elimination of the exceptional elements as much as possible
- Optimally route the parts while taking into consideration the economic aspects of the system
- Decrease the wastes and consequently increase the profits through a machine selection procedure for the enterprises which aim to implant a new FMS or to upgrade an existing one. What is mainly meant by the upgrade of an existing one is the replacement the actual machines by new ones due to the increase of the customers' demands

1.6 Review of the literature

The design of the flexible manufacturing systems has been addressed by some authors such as (Spano *et al.,* 1993) who focused on the design of the facilities, the material handling system, the control system as well as on the scheduling. Lau and Mak (2004) presented the design of the FMS through a framework with an associated graphical development environment. There are some authors who already addressed the manufacturing and fractional cell formation in the literature. For instance, Mak *et al.* (2000) proposed an adaptive genetic algorithm in order to solve the cell formation problem. Liang and Zolfaghari (1999) provided a new neural network approach to solve the comprehensive grouping problem. Solimanpur *et al.* (2010) approached this problem through an ant colony optimization (ACO) method whereas, Lei and Wu (2006) applied a tabu search method for the same purpose, etc. Concerning the problematic of the formation of the additional fractional cell, the authors who addressed it are very few; Venkumar and Noorul Haq (2006) applied a modified ART1 neural networks algorithm in order to treat it whereas Murthy and Srinivasan (1995) used a simulated annealing approach for the same purpose. The relative importance of the work presented in the second chapter comes from three facts. The first one is that it presents a new algorithm instead of applying an existing methodology. The second advantage is that it contains a new theoretical toolkit for quickly finding the final solution. Finally, it succeeded to give better results when compared to a well-known approach (simulated annealing) through the same numerical example. Concerning the routing of the manufacturing parts, a genetic algorithm approach can be used to determine the best processing plan for each of them. This solution allows the factory to select the appropriate machines for every operation according to the determined plan. In addition, it leads to finding the solution that minimizes the total average flow times for all parts (Geyik and Dosdogru, 2013). Another approach based on a heuristic algorithm was proposed. The purpose is to solve the machine loading problem of a random type flexible manufacturing system by determining the part type sequence and the operation machine allocation that guarantees the optimal solution to the problem (Tiwari and Vidyarthi, 2000). A third approach was presented as an artificial intelligence. Indeed, it is an integrated concept for the automatic design of flexible manufacturing system which uses simulation and multi-criteria decision-making techniques. Through this approach, intelligent tools (such as expert systems, fuzzy systems and neural networks) were developed for supporting the flexible manufacturing system design process (Chan *et al.*, 2000). All of these works did not provide a direct feedback that influences the first step (part routing) according to the results obtained in the last step (manufacturing cells) as in the case of the algorithm presented in the third chapter. The importance of such a feedback is that it ensures that the routing of the parts is not necessarily optimal by itself, but it is able to lead at the end to an optimal formation of the cells. Regarding the maximization of the profits, the selection of the machines, and the treatment of the exceptional elements in the context of the flexible fabrication, there are some authors who addressed them as well. For instance, Shishir Bhat (2008) used a heuristic algorithm in order to maximize the profits by optimizing the manufacturing system design. Almutawa *et al.* (2005) developed a methodology that searches for the optimal number of machines to purchase for each stage in a multistage manufacturing system. Myint and Tabucanon (1994) presented a framework that can be used for the pre-investment period in a flexible manufacturing system in order to help managers evaluate various possibilities for a certain number of configurations each of which consists of different machine types and degrees of flexibility. Wang *et al.* (2000) used a fuzzy approach in order to select the machines for each manufacturing cell. Regarding the treatment of exceptional elements, Xiangyong *et al.* (2010) noted that one possible way is to duplicate some machines in a flexible manufacturing system, another way consists of transferring the operations on the exceptional elements to one of the cells as mentioned in (Pachayappan and Panneerselvam, 2015). A third possibility is to subcontract these elements to another manufacturer as described in (Mansouri *et al.*, 2003). The main difference/advantage between these works and the research presented in the last chapter is that it links multiple concepts (profit maximization, routing of the parts, manufacturing cell formation, elimination of the exceptional elements) in a single algorithm in order to end up with a final solution.

1.7 Conclusion

A flexible manufacturing system has certain degree of ability to respond to changes. It is composed mainly of manufacturing cells, material handling equipment, buffer stations and a transport system. Since the domain of the design of such a system is a very wide subject, the next chapters concentrate only on three main features which are the design of the cells, the routing of the parts and the maximization of the profits through a selection procedure of the machines. In addition, some algorithmic methodologies will be implemented due to the limitations of the available computational capabilities. The durations as well as the costs of the fabrication constitute main aspects which will be considered in the last two chapters in order to increase the manufacturing profits and decrease the wastes.

CHAPTER 2

MANUFACTURING AND FRACTIONAL CELL FORMATION USING A NEW BINARY DIGIT GROUPING ALGORITHM WITH A PWAVROID SOLUTION EXPLORER TOOLKIT

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2.1 Abstract

A new algorithm is presented in order to search for the optimal solution of the manufacturing and fractional cell formation problem. In addition, this paper introduces a new toolkit, which is used to search for the various candidate solutions in a periodic and a waving (diversified) manner. The toolkit consists of 15 tools that play a major role in speeding up the obtainment of the final solution as well as in increasing its efficiency. The application of the binary digit grouping algorithm leads to the creation of manufacturing cells according to the concept of group technology. The nonzero entries, which remain outside the manufacturing cells, are called exceptional elements. When a lot of such elements are obtained, an additional cell called fractional (or remainder) cell may be formed; the aim of which is to reduce their number. This algorithm was tested by using illustrative examples taken from the literature and succeeded to give better or at least similar results when compared to those of other well-known algorithms.

Keywords: Binary digit grouping algorithm, pwavroid toolkit solution explorer, cell formation, manufacturing cell, fractional cell, exceptional elements.

2.2 Introduction

This paper presents the binary digit grouping algorithm, which is a completely new algorithm in the literature. It treats the formation of manufacturing cells problematic according to the concept of group technology. In addition, a toolkit which involves new candidate solutions' searching tools is introduced. These tools are used in order to search for the candidate solutions in a periodic and a waving (diversified) manner; wherefore, the toolkit is entitled Pwavroid. After testing it through numerical examples, the binary digit grouping algorithm succeeded to demonstrate its capabilities to form not only manufacturing cells, but also an additional fractional cell when applicable. The Pwavroid toolkit plays a major role in reducing the time needed for reaching the final solution. Indeed, the cellular manufacturing system (CMS) results from applying the concept of group technology (GT) (Asokan *et al.*, 2001). This concept is an industrial philosophy which aims to group the machines having common production capabilities into manufacturing cells, as well as the parts having common geometric shapes or processing requirements into part families in order to benefit from these similarities (Xiaodan *et al.,* 2007). The manufacturing cell formation problematic is considered as a non-deterministic polynomial-time hard (NP-hard) problem and it was classified for a long time as being the most challenging one because the processing time required to solve it increases exponentially with the size of the problem (Ben Mosbah and Dao., 2013). On the other hand, the inter-cell movement occurs when a part is treated by the relevant machine outside the manufacturing cells. In such cases, the concerned elements will be called exceptional elements. In the problems where we find that a lot of exceptional elements, a fractional cell (also called remainder cell) may be formed. The remainder cell must contain all of the machines of the system as well as the greatest possible number of exceptional elements. By this way, the elements which are included not only in the manufacturing cells, but also in the remainder cell will be no longer exceptional (Murthy and Srinivasan, 1995). Numerous researchers worked on this problem and provided methodologies which succeeded to give optimal or near-optimal solutions. Mak *et al.* (2000) proposed an adaptive genetic algorithm in order to solve the cell formation problem. Liang and Zolfaghari (1999) provided a new neural network approach to solve the comprehensive grouping problem. Solimanpur *et al.* (2010) approached this problem through an ant colony optimization (ACO) method whereas; Lei and Wu (2006) applied a tabu search method for the same purpose, etc. Concerning the problematic of the formation of the additional fractional cell, the authors who addressed it are very few; Venkumar and Noorul Haq (2006) applied a modified ART1 neural networks algorithm in order to treat it whereas Murthy and Srinivasan (1995) used a simulated annealing approach for the same purpose.

2.3 The binary digit grouping algorithm

The first step of forming manufacturing cells consists of using a matrix which is called incidence matrix. The size of an incidence matrix is $M \times N$ where M represents the machines and N the parts. The matrix can be presented in the following form: A = [a_{mn}] where a_{mn} is the workload (production volume multiplied by the unit processing time) of the part number n when being processed on the machine number m (Mak *et al.,* 2000). Let us take as an example the 5×5 incidence matrix which is shown in Table 2-1.

Table 2-1 A 5 x 5 incidence matrix

m \ n	1	2	3	4	5
1	1	0	1	0	0
2	0	0	0	1	0
3	0	0	1	0	0
4	0	0	0	1	1
5	0	1	0	0	0

A nonzero entry (i.e. a 1 digit) means that the relevant part will be processed by the concerned machine. If we take the nonzero entry in the upper left corner as an example, it means that the part number 1 will be processed by the machine number 1; whereas, a zero entry means the inverse. We can divide the elements of the incidence matrix into 3 categories:

- Elements in the corner of the matrix (the 4 elements highlighted in pink in table 1.1).
- Elements in the borders (but not the corners) of the matrix (highlighted in bright green).
- Finally, elements in the heart of the matrix (highlighted in yellow).

Thereafter, we calculate the nonzero entry neighboring factor (N_f) for each non-zero entry. If we take as an example the element located in the 4th row and 4th column and we isolate it with its surrounding elements as shown in Table 2-2.

Table 2-2 A nonzero entry with its surrounding elements

m \ n	1	2	3	4	5
1	1	0	1	0	0
2	0	0	0	1	0
3	0	0	1	0	0
4	0	0	0	1	1
5	0	1	0	0	0
			1	0	0
			0	1	1
			0	0	0

Its neighboring factor (N_f) is the sum of the values resulting from the following operations:

- If the surrounding element is located in the same row or in the same column, it will be multiplied by a factor of 2.
- Otherwise, it will be multiplied by 1.
- After completing the first 2 steps for all the surrounding elements, the results will be summed up all together.

Accordingly, we begin the calculations by considering at first the element located in the upper left corner of the elements surrounding the isolated non-zero entry, and we proceed in the counterclockwise direction in order to get the results shown in equation 1.1.

$$Nf = (1\,x\,1) + (2\,x\,0) + (1\,x\,0) + (2\,x\,0) + (1\,x\,0) + (2\,x\,1) + (1\,x\,0) + (2\,x\,0) = 3 \tag{1.1}$$

After calculating the individual neighboring factor (N_f) of all the nonzero entries of the incidence matrix, we sum up them all together in order to get the nonzero entries neighborhood factor of the whole matrix (N_M). As a next step, we swap randomly 2 or more rows and/or columns by using a new solution explorer toolkit (which will be explained later) in order to get a new configuration of the incidence matrix called M^*. Thereafter, the algorithm re-calculates everything from the beginning for the new configuration in order to get the new value of (N_M) called (N_M^*). If (N_M^*) is greater than (N_M), the new matrix will be considered as the new solution for the problem; otherwise, the previous configuration will be kept. The computational process continues in this manner until testing all, or at least a great number, of the possible configurations. In the latter case, the user ends manually the simulation after noticing that the value of (N_M) remains constant for a long time. As a last step, the matrix with the greatest value of (N_M^*) will be selected as the final solution. The binary digit grouping algorithm can be illustrated in Figure 5.

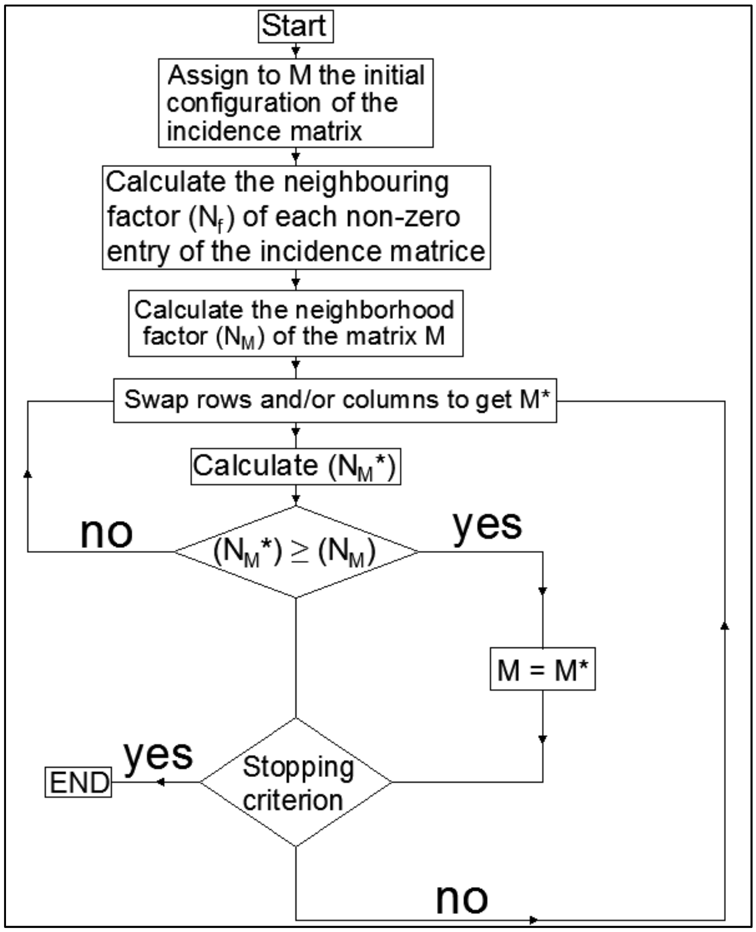

Figure 5 The binary digit grouping algorithm

As can be easily deduced, the binary digit grouping algorithm aims to group the nonzero entries as close to each other as possible within the incidence matrix. The main goal is to come up with manufacturing cells which have to include the greatest possible numbers of nonzero entries. The effectiveness of the resulting solution can be evaluated through some formulas which were used for evaluating other algorithms such as the genetic algorithm proposed by Mak *et al.* (2000).

If we let:

- K be the number of manufacturing cells which will be formed within the incidence matrix
- n_1 represents the number of nonzero entries existing in the manufacturing cells

- M_k and N_k where k = (1,2,…,K) be consecutively the numbers of machines and parts which are assigned to the manufacturing cell number k; we can get the equation 1.2.

$$e_1 = \frac{n_1}{\sum_{k=1}^{K} M_k N_k} \tag{1.2}$$

Where (e_1) is a measure of the cell density. On the other hand, if we let (n_2) be the number of the exceptional elements (which are the nonzero entries that are not located within the manufacturing cells), we get the equation 1.3.

$$e_2 = 1 - \frac{n_1}{n_1 + n_2} \tag{1.3}$$

Where (e_2) is a measure of the intercellular material flow as it increases with the increase in the number of exceptional elements and vice-versa. Finally, the grouping efficiency (e) can be calculated as shown in equation 1.4.

$$e = e1 - e2 \tag{1.4}$$

The numerical value of (e) always belongs to the interval [-1, 1].

2.4 The New Pwavroid Solution Explorer Toolkit

A toolkit which is used for exploring candidate solutions is introduced in this paper. It contains 15 searching tools the majority of which are completely new (only the first 2 are taken from the literature). They behave in a diversified and periodic manner. These tools consist of interchanging 2 or more rows and/or columns.

The algorithm uses only one of them per iteration and after applying the 15^{th} tool, it returns back to use the first one and so on. The main advantages of this toolkit are:

- It helps explore very quickly and efficiently the candidate solutions of the incidence matrix.
- It reduces greatly the time needed for finding the final solution. In a later section, a scatter chart is presented in order to shed the light on the importance of this toolkit.
- It can be bundled with any other algorithm that uses the swapping procedure in order to search for candidate solutions within the incidence matrix in the domain of flexible manufacturing systems.

The tools are explained as follows:

1- Swapping randomly 2 rows.
2- Swapping randomly 2 columns.
3- A combination of the first 2 tools (swapping randomly 2 rows and 2 columns).
4- If we have m rows, the 4^{th} tool consists of swapping 2 rows per iteration in the following manner: at first, the 1^{st} and the 2^{nd} rows; thereafter, the 1^{st} and the 3^{rd} ones, and so forth until reaching the m^{th} row. Afterward, the swapping procedure re-begins again but now with the 2^{nd} row on one hand and the remaining rows on the other hand.
5- The same procedure of the 4^{th} searching tool but, by using the columns instead of the rows.
6- A combination of the 4^{th} and 5^{th} tools.
7- Selecting randomly any 2 rows and swapping them inversely; thereafter, increasing the number of the selected rows by 1 and so forth. If we take as an example the selection of 4 rows such as the rows number 3, 4, 7 and 13; they will be inversely swapped in order to become arranged successively as follows: 13, 7, 4 and 3.
8- The same procedure of the 7^{th} searching tool but, by using the columns instead of the rows.
9- A combination of the 7^{th} and 8^{th} tools.

10- Selecting 2 distinct sets of an increasing number of rows (i.e. 2 sets of 1 row each; thereafter, 2 sets of 2 rows … 2 sets of the floor of (m/2) rows) and swapping them. This tool is the most advanced as it involves a number of possibilities. It is important to note that these 2 sets cannot have any row in common and that they will be swapped in a direct manner. If we take as an example any incidence matrix containing 9 rows and a selection of 2 sets each of which consists of 3 rows:
    a. If the first set contains the rows 3, 4 and 5 and the second one consists of the rows number 6, 7 and 8; the 2 sets will be swapped in order to replace each other in a direct manner.
    b. If the first set contains the rows 3, 4 and 5 and the second set begins with the row number 2, then the other 2 rows must be 6 and 7 which means that the second set must surpass the first one and continue with the row location which is indexed directly after the last one in the first set.
    c. If the first set contains the rows 5, 6 and 7 and the second set begins with the row number 8, the other 2 rows must be 9 and 1 because the highest possible row number cannot exceed m (where m is equal to 9 in this example) and consequently; the third row of the second set will be assigned back to the first row index (which is equal to 1).
    d. By following the combination of the logical rules adopted in b. and c., if the first set consists of the rows 6, 7 and 8 and the second set begins with the row number 5, then the other 2 rows must be 9 and 1.
11- The same procedure of the 10th searching tool but, by using the columns instead of the rows.
12- A combination of the 10th and 11th tools.
13- Generating randomly a new configuration of all of the rows.
14- Generating randomly a new configuration of all of the columns.
15- A combination of the 13th and 14th tools.

2.5 Cell Formation

After applying the algorithm, a final configuration of the incidence matrix will be obtained in which, the nonzero entries are expected to get as close to each other as possible. The next step consists of creating only manufacturing cells by keeping in mind three rules:

- The greatest possible number of nonzero entries must be contained in the formed cells.
- Every machine and every part must be involved in a cell.
- A machine or a part cannot be assigned to more than one cell.

In the cases where we obtain many exceptional elements in the final matrix configuration, a re-distribution of the cells may take place according to what follows:

- Creating manufacturing cells, each of which contains a certain number of machines and parts.
- Not all of the machines but all of the parts must be assigned to the manufacturing cells.
- A machine and/or a part cannot be assigned to more than one manufacturing cell.
- Creating one additional fractional cell that contains all of the parts in addition to only the machines which are not assigned to the manufacturing cells.

The nonzero entries, which are included in the manufacturing cells or in the fractional cell, are not considered as exceptional elements. That is why; the addition of the fractional cell may play a major role in reducing the number of these elements. The following section provides a better understanding of this process through two illustrative examples.

2.6 Illustrative Examples

We are going in what follows to test this algorithm through two illustrative examples taken from the literature. The first one leads to the formation of only manufacturing cells; whereas, the second one shows the formation of manufacturing cells as well as an additional fractional cell. Let us consider the following incidence matrix which is taken from (Srinlvasan *et al.,* 1990) and which is shown in Table 2-3.

Table 2-3 The incidence matrix for the first illustrative example

m \ n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	1	1	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
3	0	1	1	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
4	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	0	1
6	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	1	0	0	1	0	1	1	0	0	0	1	0	0	1	0
8	0	0	0	0	0	1	0	0	1	0	1	1	0	0	0	1	0	0	1	0
9	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	0	1
10	0	0	0	0	0	1	0	0	1	0	1	1	0	0	0	1	0	0	1	0

After running the MATLAB code of the binary digit grouping algorithm, the solution provided by the Table 2-4 was obtained in a few seconds.

Table 2-4 The cell design for the first illustrative example

m\n	2	5	3	10	8	11	6	16	9	12	19	17	15	13	14	20	18	1	7	4
2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1

In this example, 4 manufacturing cells were created; the number of nonzero entries existing in the manufacturing cells (n_1) is equal to 49, the number of exceptional elements (n_2) is equal to 0 which means that there is no intercellular material flow. The calculations led to a value equal to 1 for the cell density measure (e_1) and to a value of 0 for the intercellular material flow (e_2). The value of the grouping efficiency is $e = e_1 - e_2 = 1$. There is no need for a fractional cell in this example since there are no resulting exceptional elements.

Let us now consider the second illustrative example which is represented by the incidence matrix in Table 2-5 and which is taken from (Chandrasekharan and Rajagopalan, 1989).

Table 2-5 The incidence matrix for the second illustrative example

m\n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
1																																				1						1
2		1								1																				1				1					1		1			1			1		
3							1										1																	1		1		1								
4					1				1					1					1			1			1						1															
5					1				1		1						1		1		1				1			1			1						1				1								1			1	
6	1		1					1		1		1					1		1		1				1			1					1										1		1		1				1			1		1			1		1	
7	1													1													1																			
8	1		1		1						1		1			1		1				1					1		1		1			1		1				1		1				1							1		1				1			1	
9		1			1							1									1											1					1						1		1			1			1		
10	1												1		1													1		1						1									1					
11			1							1												1					1				1				1														
12											1												1			1				1				1														
13			1																						1																				
14		1					1												1																			1									
15					1										1						1			1													1									1			1	
16		1						1				1									1															1						1		1					1		

After applying the binary digit grouping algorithm; the solution in the Table 2-6, which includes only manufacturing cells, was obtained with a value of (N_m) equal to 650 and with 29 exceptional elements.

Table 2-6 The design of the manufacturing cells for the second illustrative example

m\n	16	29	5	14	21	41	33	43	19	23	9	15	8	12	1	13	25	26	31	39	7	34	36	35	17	6	40	28	38	2	37	32	42	10	18	4	22	30	27	24	3	20	11
7															1		1		1																											
10														1		1		1		1		1		1		1																								
3																					1		1		1		1		1																			
14																								1		1		1				1														
2																											1		1		1		1		1		1		1		1										
9																											1		1		1		1		1		1		1		1		1		1								
16																					1								1		1		1		1		1		1		1									
6				1				1		1		1		1				1		1		1		1					1		1		1				1		1		1				1		1		1		1											
8					1		1			1		1		1		1		1		1		1		1					1										1		1		1		1									1		1		1		1		1
5	1		1		1		1		1		1		1		1		1		1		1		1		1																															
4		1		1		1		1					1		1		1																																	
15			1		1		1		1		1		1		1																																			
1								1																							1													
13																																								1		1			
11											1																											1		1		1		1		1		
12																																					1		1		1		1				1

As a result, many exceptional elements were gotten (which is not good). In such cases, the problem may be solved by constructing one additional fractional (remainder) cell. The reformation of the cells gives the solution in Table 2-7 with zero exceptional elements.

Table 2-7 The design of the manufacturing cells in addition to one fractional cell for the second illustrative example

m\n	16	29	5	14	21	41	33	43	19	23	9	15	8	12	1	13	25	26	31	39	7	34	36	35	17	6	40	28	38	2	37	32	42	10	18	4	22	30	27	24	3	20	11
7															1	1	1																										
10														1	1	1	1	1	1	1																							
3																					1	1	1	1	1																		
14																								1	1	1				1													
2																											1	1	1	1	1	1	1	1									
9																											1	1	1	1	1	1	1	1	1	1							
16																					1								1	1	1	1	1	1	1								
6				1			1	1	1	1			1	1	1	1				1	1	1			1	1	1			1	1	1	1										
8					1	1		1	1	1	1	1	1	1	1				1									1	1	1	1								1	1	1	1	1
5	1	1	1	1	1	1	1	1	1	1	1	1	1																														
4		1	1	1	1				1	1	1																																
15			1	1	1	1	1	1	1																																		
1								1																							1												
13																																								1	1		
11											1																											1	1	1	1	1	
12																																					1	1	1	1			1

This solution demonstrates that the problem of the existence of exceptional elements may be completely solved by introducing a remainder cell. In addition, it demonstrates that the binary digit grouping algorithm may be able to solve not only the manufacturing cell formation problems, but also to form a fractional (remainder) cell as well. Table 2-8 shows a comparison between the results coming from the application of the binary digit grouping algorithm and those obtained after applying the simulated annealing (SA) approach in (Srinlvasan *et al.,* 1990.).

Table 2-8 Comparison between the results coming from the application of the binary digit grouping algorithm and those coming from the application of the simulated annealing approach for the second illustrative example

	Binary digit grouping algorithm	**Simulated annealing (SA)**
Number of exceptional elements	0	2
Number of machines in the remainder cell	4	6

2.7 The advantages resulting from the application of the Pwavroid toolkit

In what follows, we are going to apply the binary digit grouping algorithm in order to solve the cell formation problem of the first data set, which consists of a 24 x 40 incidence matrix taken from (Chandrasekharan and Rajagopalan, 1989). At first, we are going to use the first 2 tools which are the only ones taken from the literature. Thereafter, we are going to use the whole toolkit. The MATLAB code, which is dedicated for the simulation of this algorithm, was set to output one solution every almost one second. The results obtained can be illustrated through the scatter plot in Figure 6.

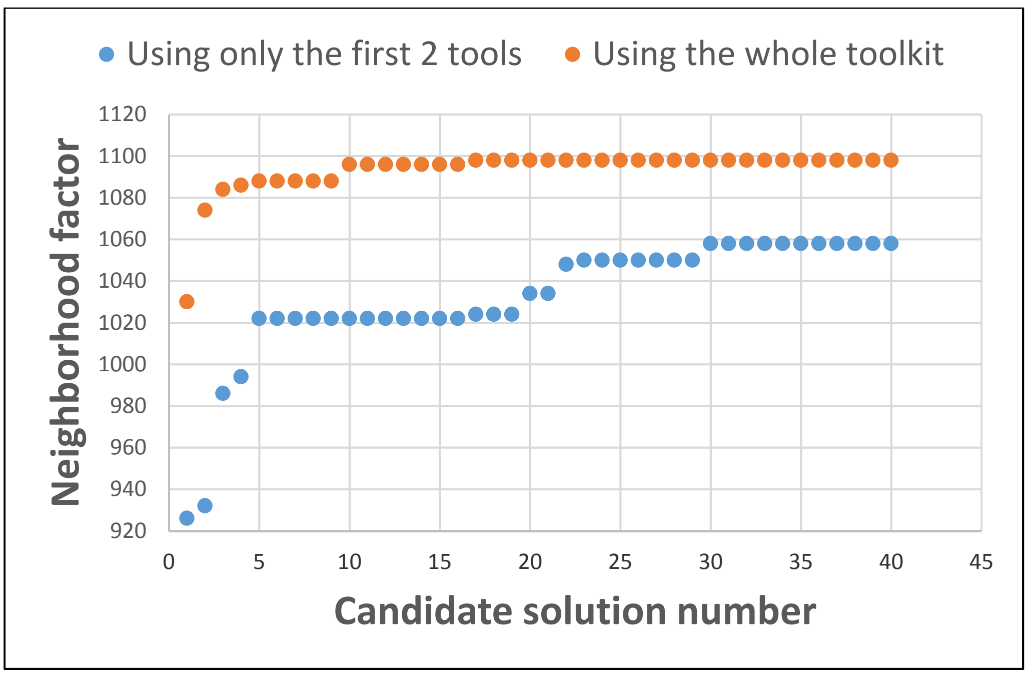

Figure 6 The results coming from the usage of only the first 2 tools versus those coming from the usage of the whole toolkit

Consequently, the benefits of using the whole toolkit with respect to the use of only the first 2 tools are summarized in Table 2-9.

Table 2-9 Benefits of using the new Pwavroid solution explorer toolkit

Criterion	**Using only the first 2 tools**	**Using the whole toolkit**
Final solution	A steady state solution (considered as the final solution) was reached at the iteration number 30	A steady state solution was reached at the iteration number 17 (much more quickly)
Neighborhood factor	The neighborhood factor was always smaller for the successive candidate solutions	The neighborhood factor was always greater
Convergence towards the final solution	Slower	Quicker

2.8 Conclusion

A new algorithm entitled the binary digit grouping algorithm together with the new Pwavroid solution explorer toolkit were presented and explained in order to solve the manufacturing and fractional cell formation problems within the flexible manufacturing systems. The simple and intelligent steps makes them particularly powerful in creating and conserving the improving matrix configurations which a quick convergence towards the final solution for both small and big size problems. The advantages of using this algorithm together with the toolkit have been demonstrated through 2 illustrative examples.

CHAPTER 3

A TIME-COST HEURISTIC ALGORITHM FOR ROUTING THE PARTS IN A FLEXIBLE MANUFACTURING SYSTEM

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3.1 Abstract

A new algorithm is presented in this paper in order to route the parts in a flexible manufacturing system. The algorithm takes into consideration for the first time in the literature both the time and cost in order to accomplish the routing procedure. It helps the factories that are already fully busy with processing customers' commands take a fast decision whether to accept or refuse a new fabrication demand. The reason is that the admittance of the new demand means that the factory has to reorganize its ongoing woks. This may lead to some lags on the existing commands and may cause in turn some harm to the reputation of the factory as well as possible penalties. After each part-routing procedure, another relevant algorithm can be used to form manufacturing cells. This paper presents also for the first time the possibility to re-route the parts according to the feedback coming from the resulting industrial cells. It was tested through two numerical examples and proved its capability to give the favourable final results.

Keywords: Flexible manufacturing system, part routing, cost, time, fabrication, customer demand.

3.2 Introduction

A flexible manufacturing system is a one which has a high capability to adapt to the changes (Gupta and Goyal, 1992). The manufacturing flexibility at the system's level can be a crucial factor in the process of strategic change (Lloréns *et al.*, 2005). For instance, it becomes critical for a narrow fabrication time interval. This happens in some cases such as the one when a factory receives a new fabrication request while it is fully occupied treating other customers' demands. It needs to use an efficient algorithm in order to decide whether to accept or refuse the new demand. Doing so may cause delays or rescheduling of other projects in order to implement the new one. As a result, these delays may result in damages on the reputation of the factory as well as some financial penalties. In addition to the manufacturing costs, the required configuration changes within the factory's flexible manufacturing system will cause additional charges. In order to ensure that the acceptation of the new demand will not cause side problems, the factory has to specify upper limitations for the duration and the cost of treating the new command. In order to treat these kinds of problematics, an intelligent part routing system that leads to an optimal manufacturing cell formation is needed.

Many authors addressed the part routing issue within the context of flexible fabrication. For example a genetic algorithm approach can be used to determine the best processing plan for each part. This solution allows the factory to select the appropriate machines for each operation according to the determined plan. In addition, it leads to finding the solution that minimizes the total average flow times for all parts (Geyik and Dosdogru, 2013). Another approach based on a heuristic algorithm was proposed. The purpose is to solve the machine loading problem of a random type flexible manufacturing system by determining the part type sequence and the operation machine allocation that guarantees the optimal solution to the problem (Tiwari and Vidyarthi, 2000). A third approach, was presented as an artificial intelligence. Indeed, it's an integrated concept for the automatic design of flexible manufacturing system which uses simulation and multi-criteria decision-making techniques. Through this approach, intelligent tools (such as expert systems, fuzzy systems and neural networks) were developed for supporting the flexible manufacturing system design process (Chan *et al.*, 2000). All of these solutions didn't provide a direct feedback that influences the first step (part routing) according to the results obtained in the last step (manufacturing cells).

This paper presents a new methodology that finds an optimal solution for the balanced reduction of both, production time and cost. It consists of a new algorithm which inputs the number of operations required onto each part of a fabrication command as well as the relevant costs and durations. Thereafter, it searches for the optimal parts routing which is able to respect the maximum allowable overall cost and time for the fabrication of the new demand. Afterwards, it uses another algorithm for designing the manufacturing cells. The resulting exceptional elements, if there are any, will cause in turn the increase of the values of both the cost and the time. The new algorithm will then provide a re-routing of the parts only if the maximum allowable cost or duration has been surpassed. The procedure continues in this manner until the algorithm tells whether the situation is or not realizable and the best found solution will be considered as the final one.

3.3 The new algorithm

The first step consists of constructing a matrix which contains the information about the processing cost and time for each part. Let o_n be the number of operations required on the part number n, c_{nm} and d_{nm} are consecutively the cost and the duration required for processing the part number n on the machine number m. The factory specifies C as the maximum allowable cost for treating all of the parts and D as the maximum acceptable duration. The total processing cost and duration must be re-calculated after designing the manufacturing cells because some exceptional elements may result and increase them. Unlike some other algorithms that treat the groups of elements such as the genetic algorithm presented in (Geyik and Dosdogru, 2013); the efficiency of this one is that it applies mathematical and logical operations on the elements separately. For a better understanding, we are going to describe the algorithm step by step in parallel with the application of a numerical example.

A factory receives a fabrication request of 5 parts. It needs 4 different machines in order to complete the request. Each machine can treat all the parts but the first, second and third machines have to be assigned 3 operations, whereas 2 operations are given to the machine number 5. Besides the direct fabrication costs such as those of direct materials, other ones such as those related to the labor in addition to some manufacturing overhead depend on the duration of the fabrication. For instance when the run time gets bigger, the factory needs to work for longer durations or to hire more employees which in turn increases the labors' as well as other relevant costs. That is why; the fabrication run time can be expressed in terms of dollars. In this case, each part costs the amount of money which is equivalent to the sum of the direct costs on one hand, and all the other costs that depend on the run time on the other hand. The matrix illustrated in Table 3-1 specifies the fabrication cost and duration of each part on each of the 4 machines.

Table 3-1 Fabrication costs and durations of the first numerical example

m/n	1	2	3	4	5
1	(c11,d11) = (2,5)	(c12,d12) = (5,3)	(c13,d13) = (5,3)	(c14,d14) = (9,8)	(c15,d15) = (6,8)
2	(c21,d21) = (5,9)	(c22,d22) = (6,4)	(c23,d23) = (4,2)	(c24,d24) = (8,2)	(c25,d25) = (4,7)
3	(c31,d31) = (4,9)	(c32,d32) = (4,6)	(c33,d33) = (7,4)	(c34,d34) = (7,2)	(c35,d35) = (4,6)
4	(c41,d41) = (6,8)	(c42,d42) = (2,3)	(c43,d43) = (7,9)	(c44,d44) = (2,2)	(c45,d45) = (8,2)

The parts number 1, 2, 3 and 4 require 2 operations whereas 3 operations are needed for the part number 5. After making a case study, the factory decides that the maximum allowable cost for accepting this command is 50 and the maximum duration is 55.

1. Let O be the total number of required operations i.e. $O = \sum_{i=1}^{i=n} O_i$

In this example, O = 11

2. Let x_1 be the weight of the processing cost with respect to the duration. Where $0 <= x_1 <= 1$

This factor determines the relation between the 2 parameters. For example if $x_1 = 0.5$, this means that the factory has to route the parts in a manner to get equal values of the fabrication costs and the conversion to the terms of dollars of the run-time. This equality can be achieved as for example by hiring more employees in order to accelerate the fabrication procedure if the final results show that there is a need to speed up the fabrication in order to make the run-tie to cost conversion equal to the direct costs.

In the numeric example, let us begin with $x_1 = 0.65$

3. Let x_2 be the weight of the processing duration with respect to the cost where $x_1 + x_2 = 1$

Thus, $x_2 = 0.35$

4. $c_{2nm} = x_1 \times c_{nm}$ is the weighed cost
5. $d_{2nm} = x_2 \times d_{nm}$ is the weighed duration

After applying the steps 3 and 4 on the numerical example, we obtain the matrix shown in

Table 3-2.

Table 3-2 Weighed costs and durations in the first numerical example

m/n	1	2	3	4	5
1	(1.3,1.75)	(3.25,1.05)	(3.25,1.05)	(5.85,2.8)	(3.9,2.8)
2	(3.25,3.15)	(3.9,1.4)	(2.6,0.7)	(5.2,0.7)	(2.6,2.45)
3	(2.6,3.15)	(2.6,2.1)	(4.55,1.4)	(4.55,0.7)	(2.6,2.1)
4	(3.9,2.8)	(1.3,1.05)	(4.55,3.15)	(1.3,0.7)	(5.2,0.7)

6. Assign a single value v_{nm} for each operation where $v_{nm} = c_{2nm} + d_{2nm}$

7. Build a new matrix M_N which contains the v_{nm} values as shown in Table 3-3.

Table 3-3 The total cost for each element in the first numerical example

m/n	1	2	3	4	5
1	3.05	4.3	4.3	8.65	6.7
2	6.4	5.3	3.3	5.9	5.05
3	5.75	4.7	5.95	5.25	4.7
4	6.7	2.35	7.7	2	5.9

8. Select the lowest O values of v_{nm} (colored in cyan in Table 3-4)

Table 3-4 The lowest selected values in the first numerical example

m/n	1	2	3	4	5
1	3.05	4.3	4.3	8.65	6.7
2	6.4	5.3	3.3	5.9	5.05
3	5.75	4.7	5.95	5.25	4.7
4	6.7	2.35	7.7	2	5.9

9. Begin with the first column, if the number of selected operations is not greater than the required number, do nothing and go to the next column

10. If the number of selected operations is greater than the required number, do the following:

    a. Make a one by one subtraction between each selected element and all of the unselected elements in the same row

In this example, the subtraction procedure gives the results which are coloured in green in Table 3-5.

Table 3-5 Resulting values for the subtraction operations

m/n	1	2	3	4	5
1	3.05	4.3	4.3	-4.35	-2.4
2	-1.1	5.3	3.3	-0.6	5.05
3	-1.05	4.7	-1.25	5.25	4.7
4	-4.35	2.35	-5.35	2	-3.55

    b. Begin with the greatest resulting value from the previous step, check the number of selections in the relevant column:
        i. If it is greater than or equal to the required number, do nothing
        ii. Otherwise, swap the selection between the new and the selected element
        iii. Repeat the steps b.i, and b.ii with the next element until decreasing the number of the selected operations in the column to the required number which is o_n

Thus, the new selection is shown in Table 3-6.

Table 3-6 The new selection in the first numerical example

m/n	1	2	3	4	5
1	3.05	4.3	4.3	8.65	6.7
2	6.4	5.3	3.3	5.9	5.05
3	5.75	4.7	5.95	5.25	4.7
4	6.7	2.35	7.7	2	5.9

11. Repeat the steps 9 and 10 until completing the treatment of all the columns

12. Revert the matrix to its original form and include the elements in the form of ones and zeros in order to obtain the incidence matrix shown in Table 3-7.

Table 3-7 The incidence matrix of the first iteration

m/n	1	2	3	4	5
1	1	0	1	0	1
2	0	1	1	0	1
3	1	0	0	1	1
4	0	1	0	1	0

13. At this stage, the routing of the parts is completed; we make the sum of the costs as well as of the durations of the selected operations in order to obtain the total resulting cost C_{ti} and Duration D_{ti} where i is the iteration number.

The calculations give $C_{t1} = 49$ and $D_{t1} = 51$

14. Use another relevant algorithm such as the binary digit grouping algorithm proposed by Mroue and Dao (2014) in order to form the manufacturing cells

We obtain the 2 cells which are shown in Table 3-8.

Table 3-8 The manufacturing cells of the first iteration

m/n	4	2	1	3	5
1	0	0	1	1	1
2	0	1	0	1	1
3	1	0	1	0	1
4	1	1	0	0	0

15. If there are resulting exceptional elements, we calculate the sum of the additional processing cost C_{ai} and time D_{ai}. Let us assume that the 2 exceptional elements located at (3,4) and at (2,2) cause successively additional costs of 2 and 1 as well additional durations of 2 and 2. Thus, $C_{a1} = 4$ and $D_{a1} = 3$

16. Let C_{fi} and D_{fi} and be successively the final operational cost and time for the iteration number i where $C_{fi} = C_{ti} + C_{ai}$ and $D_{fi} = D_{ti} + D_{ai}$. So $Cf_1 = 49 + 4 = 53$ and $D_{f1} = 51 + 3 = 54$
    a. If $C_{fi} <= C$ and $D_{fi} <= D$; stop and consider the resulting solution as the final one
    b. If $C_{fi} <= C$ and $D_{fi} > D$; increase x_1 by a small value Δx_1 and decrease x_2 by the same amount and go to step 4 in order to begin the next iteration
    c. If $C_{fi} > C$ and $D_{fi} <= D$; decrease x_1 by a small value Δx_1 and increase x_2 by the same amount and go to step 4 in order to begin the next iteration

d. Else, stop and announce that no solution can be found

17. In our example, $C_{f1} = 53 > C = 50$ and $D_{f1} = 54 < 55$; that is why, we decrease x_1 by 0.05 and we increase x_2 by the same value. We repeat the steps 4 to 12 for the second iteration and we obtain a new routing for the elements as shown in Table 3-9.

Table 3-9 The incidence matrix of the second iteration

m/n	1	2	3	4	5
1	1	0	1	0	1
2	1	0	1	0	1
3	0	1	0	1	1
4	0	1	0	1	0

We make the relevant calculations for the second iteration in order to obtain $C_{t2} = 45$ and $D_{t2} = 53$. Thereafter, we repeat the step 14 in order to form the manufacturing cells that are shown in Table 3-10.

Table 3-10 The manufacturing cells of the second iteration

m/n	1	3	5	4	2
1	1	1	1	0	0
2	1	1	1	0	0
3	0	0	1	1	1
4	0	0	0	1	1

A single exceptional element was obtained at (3,5). It causes an additional cost of 1, and an additional processing time of 2. $C_{f2} = 45 + 1 = 46 < C = 50$ and $D_{f2} = 53 + 2 = 55$ which is equal to D. That is why, this solution is acceptable, there is no need for additional iterations and the factory admits accordingly the new command. The algorithm is illustrated in Figure 7.

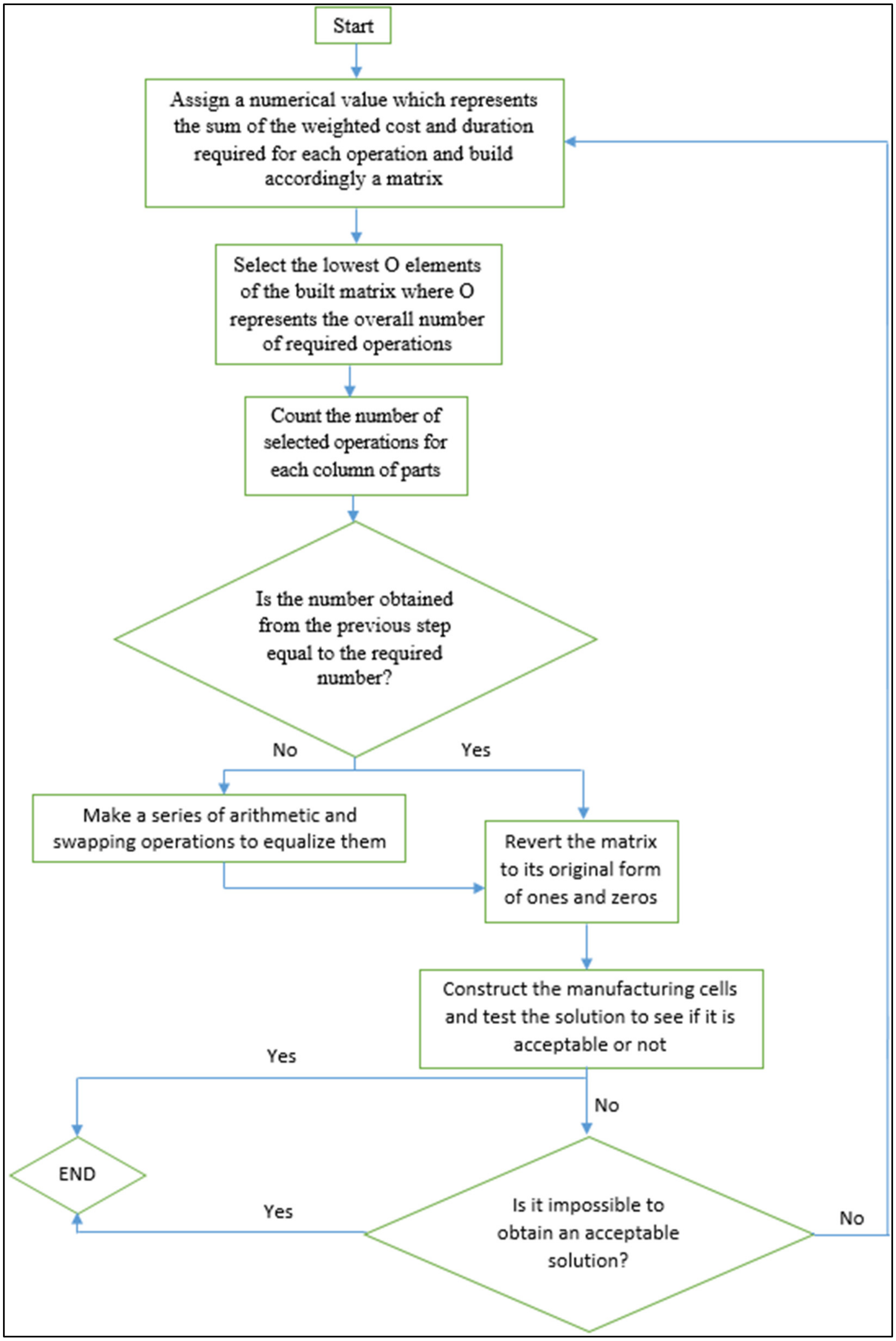

Figure 7 The Algorithm

3.4 The innovation and the industrial importance provided by the new algorithm

The importance of the approach introduced in this paper comes from the fact that it is:

- The only algorithm in the literature which reduces in a balanced manner both the production cost and duration.

- Other methodologies that are based on heuristic solutions such as the one presented in (Shmilovici and Maimon, 1992), as well as the model designed by Lamar and Lee (1999) focused only on the production costs while neglecting the time factor. We can also find others which focused on the production duration such as the fuzzy rule presented by (Mahdavi *et al.,* 2009) and the heuristic based on multi-stage programming approach that is proposed by (Mahesh *et al.,* 2006). However, the inclusion of the two parameters makes this algorithm more useful, efficient, and reliable

- The only algorithm in the literature which introduces a re-routing procedure that links the last step (the formation of the manufacturing cells) to the first step (the routing of parts). In other words, if the routing of parts is efficient by itself but it doesn't lead to an acceptable formation of manufacturing cells, the algorithm re-routes the parts again and again in order to guarantee an acceptable cell design at the end

- The only algorithm in the literature that takes into consideration the additional costs and durations resulting from the appearance of exceptional elements after the formation of manufacturing cells. Thereafter it re-routes the parts if needed in order to decrease these additional costs and durations. In other words, it tries to reduce the number of exceptional elements. Then, the algorithm helps the factories reduce the overall production charge and time and provides a smoother part flow and facilitates the production scheduling.

3.5 A second numerical example

The example illustrated in Table 3-11 and Table 3-12 is a 15 × 30 matrix which shows the processing cost and duration for each operation. For a better illustration, we are going to divide the matrix into two parts. The first one shows all of the rows as well as the columns 1 to 15; whereas, the second shows the rows again but with only the remaining columns.

Table 3-11 Fabrication costs and durations of the second numerical example (columns 1 to 15)

m/n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	(14,25)	(27,30)	(29,34)	(12,17)	(25,28)	(15,23)	(15,18)	(28,33)	(24,35)	(17,21)	(23,31)	(18,17)	(21,21)	(28,31)	(24,30)
2	(26,29)	(17,18)	(28,30)	(30,27)	(15,25)	(13,11)	(26,33)	(24,32)	(18,19)	(27,28)	(30,28)	(23,30)	(22,29)	(21,15)	(24,35)
3	(13,18)	(27,33)	(13,19)	(16,24)	(29,28)	(12,26)	(19,19)	(22,27)	(14,12)	(17,16)	(22,29)	(20,21)	(15,20)	(24,33)	(22,35)
4	(28,29)	(17,12)	(27,27)	(28,34)	(19,12)	(19,21)	(24,27)	(25,32)	(14,20)	(23,31)	(20,23)	(27,27)	(24,27)	(13,24)	(22,27)
5	(29,33)	(23,33)	(28,33)	(22,28)	(29,32)	(27,31)	(11,13)	(13,20)	(25,33)	(25,35)	(29,32)	(29,32)	(24,31)	(24,32)	(15,22)
6	(11,18)	(28,30)	(14,25)	(30,34)	(25,30)	(18,15)	(18,22)	(22,34)	(20,26)	(19,17)	(22,30)	(19,23)	(18,23)	(25,33)	(23,33)
7	(25,32)	(20,16)	(30,33)	(23,32)	(16,14)	(22,29)	(29,29)	(28,31)	(19,23)	(27,27)	(18,21)	(28,31)	(26,31)	(30,34)	(24,32)
8	(13,25)	(22,30)	(13,23)	(14,15)	(27,31)	(21,14)	(16,18)	(27,30)	(24,28)	(20,11)	(29,28)	(19,18)	(15,22)	(28,35)	(25,34)
9	(30,27)	(16,17)	(30,30)	(24,33)	(16,13)	(23,32)	(21,24)	(29,29)	(19,17)	(22,34)	(19,24)	(20,23)	(26,33)	(29,28_	(27,35)
10	(29,35)	(12,10)	(24,31)	(29,27)	(23,32)	(23,30)	(24,31)	(12,26)	(20,24)	(23,33)	(28,28)	(27,34)	(30,30)	(26,30)	(21,11)
11	(19,16)	(23,29)	(11,15)	(18,23)	(23,31)	(19,12)	(15,14)	(22,35)	(22,33)	(21,17)	(28,28)	(12,20)	(21,17)	(25,30)	(23,35)
12	(22,34)	(24,29)	(27,31)	(29,28)	(10,16)	(26,31)	(25,33)	(19,22)	(27,28)	(22,31)	(26,30)	(26,32)	(27,32)	(27,31)	(11,23)
13	(29,33)	(17,26)	(25,28)	(28,31)	(18,16)	(23,28)	(26,33)	(29,30)	(15,18)	(23,29)	(21,15)	(25,31)	(30,30)	(28,32)	(25,27)
14	(17,25)	(18,22)	(16,20)	(19,19)	(19,19)	(11,21)	(21,25)	(28,30)	(13,11)	(11,18)	(28,29)	(15,22)	(16,11)	(30,28)	(28,35)
15	(29,32)	(28,34)	(28,30)	(28,33)	(30,31)	(24,34)	(26,29)	(16,24)	(23,28)	(28,31)	(26,27)	(13,12)	(26,29)	(28,29)	(29,33)

Table 3-12 Fabrication costs and durations of the second numerical example (columns 16 to 30)

m/n	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	(10,15)	(15,11)	(27,33)	(11,20)	(13,19)	(23,30)	(24,29)	(17,17)	(27,32)	(25,27)	(25,32)	(18,14)	(25,27)	(25,29)	(21,12)
2	(17,12)	(30,31)	(17,26)	(19,24)	(27,32)	(12,11)	(25,35)	(26,32)	(25,35)	(15,18)	(23,30)	(25,31)	(20,14)	(18,20)	(29,33)
3	(17,26)	(17,12)	(27,30)	(20,15)	(14,13)	(27,29)	(26,28)	(16,12)	(29,32)	(25,30)	(24,29)	(13,11)	(24,35)	(29,33)	(28,28)
4	(17,13)	(26,31)	(29,32)	(25,35)	(30,27)	(19,11)	(27,28)	(30,32)	(29,33)	(13,16)	(10,12)	(29,27)	(17,14)	(11,12)	(23,32)
5	(28,35)	(25,29)	(27,33)	(23,31)	(22,32)	(24,30)	(28,33)	(24,28)	(20,12)	(29,31)	(15,17)	(25,33)	(23,28)	(28,35)	(29,33)
6	(11,10)	(18,14)	(22,27)	(11,19)	(12,18)	(24,30)	(22,31)	(21,18)	(28,35)	(27,29)	(24,31)	(16,21)	(23,31)	(29,27)	(11,26)
7	(16,25)	(27,31)	(21,16)	(14,12)	(24,30)	(13,19)	(24,28)	(25,27)	(25,34)	(19,16)	(21,26)	(26,34)	(12,11)	(17,15)	(28,30)
8	(18,25)	(19,26)	(30,30)	(11,19)	(13,14)	(24,33)	(30,29)	(11,18)	(22,35)	(28,33)	(25,27)	(16,16)	(25,30)	(30,31)	(15,14)
9	(18,19)	(25,29)	(14,12)	(27,30)	(25,28)	(17,17)	(25,33)	(24,33)	(23,33)	(17,16)	(13,11)	(24,33)	(15,26)	(19,22)	(24,27)
10	(27,35)	(25,35)	(30,31)	(23,34)	(23,29)	(30,27)	(11,17)	(29,32)	(30,33)	(22,31)	(19,17)	(24,34)	(28,30)	(22,31)	(28,30)
11	(24,31)	(17,12)	(27,33)	(13,14)	(15,11)	(24,33)	(22,32)	(18,12)	(30,33)	(24,34)	(26,32)	(12,18)	(28,34)	(27,29)	(16,13)
12	(26,29)	(30,33)	(24,33)	(25,30)	(27,33)	(22,29)	(29,35)	(23,27)	(13,15)	(22,29)	(21,12)	(25,33)	(23,35)	(30,32)	(23,35)
13	(17,13)	(24,33)	(16,15)	(17,16)	(30,27)	(17,25)	(26,29)	(25,28)	(26,32)	(18,18)	(21,24)	(22,33)	(13,17)	(20,21)	(27,29)
14	(29,27)	(14,11)	(25,28)	(15,14)	(20,15)	(28,28)	(27,27)	(16,24)	(24,29)	(22,27)	(25,32)	(29,30)	(22,35)	(22,27)	(18,16)
15	(25,30)	(25,33)	(25,34)	(20,23)	(23,31)	(30,33)	(13,11)	(24,30)	(16,19)	(27,32)	(14,13)	(27,27)	(28,30)	(24,35)	(23,35)

Table 3-13 and Table 3-14 show the number of operations required on each part.

Table 3-13 Number of operations required on each part (columns 1 to 15)

Part number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Number of operations	6	5	6	6	5	6	6	4	5	6	5	6	6	5	4

Table 3-14 Number of operations required on each part (columns 16 to 30)

Part number	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Number of operations	5	6	5	6	6	5	4	6	4	5	4	6	5	5	6

So, the total number of operations required is calculated in equation 3.1.

$$O = \sum_{n=1}^{30} o_n = 159 \tag{3.1}$$

After completing a case study, the factory decides that the maximum allowable cost is C = 3000 and the maximum allowable duration is D = 3500. We begin by assigning a value to x_1 which is equal to 0.65 and 0.35 for x_2. After calculating the weighed relative cost and processing time for each operation, we add them in order to obtain the v_{nm} values. Accordingly, the matrix M_N for the first iteration is illustrated in Table 3-15 and Table 3-16.

Table 3-15 The total cost for each element in the second numerical example (columns 1 to 15)

m/n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	17.85	28.05	30.75	13.75	26.05	17.8	16.05	29.75	27.85	18.4	25.8	17.65	21	29.05	26.1
2	27.05	17.35	28.7	28.95	18.5	12.3	28.45	26.8	18.35	27.35	29.3	25.45	24.45	18.9	27.85
3	14.75	29.1	15.1	18.8	28.65	16.9	19	23.75	13.3	16.65	24.45	20.35	16.75	27.15	26.55
4	28.35	15.25	27	30.1	16.55	19.7	25.05	27.45	16.1	25.8	21.05	27	25.05	16.85	23.75
5	30.4	26.5	29.75	24.1	30.05	28.4	11.7	15.45	27.8	28.5	30.05	30.05	26.45	26.8	17.45
6	13.45	28.7	17.85	31.4	26.75	16.95	19.4	26.2	22.1	18.3	24.8	20.4	19.75	27.8	26.5
7	27.45	18.6	31.05	26.15	15.3	24.45	29	29.05	20.4	27	19.05	29.05	27.75	31.4	26.8
8	17.2	24.8	16.5	14.35	28.4	18.55	16.7	28.05	25.4	16.85	28.65	18.65	17.45	30.45	28.15
9	28.95	16.35	30	27.15	14.95	26.15	22.05	29	18.3	26.2	20.75	21.05	28.45	28.65	29.8
10	31.1	11.3	26.45	28.3	26.15	25.45	26.45	16.9	21.4	26.5	28	29.45	30	27.4	17.5
11	17.95	25.1	12.4	19.75	25.8	16.55	14.65	26.55	25.85	19.6	28	14.8	19.6	26.75	27.2
12	26.2	25.75	28.4	28.65	12.1	27.75	27.8	20.05	27.35	25.15	27.4	28.1	28.75	28.4	15.2
13	30.4	20.15	26.05	29.05	17.3	24.75	28.45	29.35	16.05	25.1	18.9	27.1	30	29.4	25.7
14	19.8	19.4	17.4	19	19	14.5	22.4	28.7	12.3	13.45	28.35	17.45	14.25	29.3	30.45
15	30.05	30.1	28.7	29.75	30.35	27.5	27.05	18.8	24.75	29.05	26.35	12.65	27.05	28.35	30.4

Table 3-16 The total cost for each element in the second numerical example (columns 16 to 30)

m/n	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	11.75	13.6	29.1	14.15	15.1	25.45	25.75	17	28.75	25.7	27.45	16.6	25.7	26.4	17.85
2	15.25	30.35	20.15	20.75	28.75	11.65	28.5	28.1	28.5	16.05	25.45	27.1	17.9	18.7	30.4
3	20.15	15.25	28.05	18.25	13.65	27.7	26.7	14.6	30.05	26.75	25.75	12.3	27.85	30.4	28
4	15.6	27.75	30.05	28.5	28.95	16.2	27.35	30.7	30.4	14.05	10.7	28.3	15.95	11.35	26.15
5	30.45	26.4	29.1	25.8	25.5	26.1	29.75	25.4	17.2	29.7	15.7	27.8	24.75	30.45	30.4
6	10.65	16.6	23.75	13.8	14.1	26.1	25.15	19.95	30.45	27.7	26.45	17.75	25.8	28.3	16.25
7	19.15	28.4	19.25	13.3	26.1	15.1	25.4	25.7	28.15	17.95	22.75	28.8	11.65	16.3	28.7
8	20.45	21.45	30	13.8	13.35	27.15	29.65	13.45	26.55	29.75	25.7	16	26.75	30.35	14.65
9	18.35	26.4	13.3	28.05	26.05	17	27.8	27.15	26.5	16.65	12.3	27.15	18.85	20.05	25.05
10	29.8	28.5	30.35	26.85	25.1	28.95	13.1	30.05	31.05	25.15	18.3	27.5	28.7	25.15	28.7
11	26.45	15.25	29.1	13.35	13.6	27.15	25.5	15.9	31.05	27.5	28.1	14.1	30.1	27.7	14.95
12	27.05	31.05	27.15	26.75	29.1	24.45	31.1	24.4	13.7	24.45	17.85	27.8	27.2	30.7	27.2
13	15.6	27.15	15.65	16.65	28.95	19.8	27.05	26.05	28.1	18	22.05	25.85	14.4	20.35	27.7
14	28.3	12.95	26.05	14.65	18.25	28	27	18.8	25.75	23.75	27.45	29.35	26.55	23.75	17.3
15	26.75	27.8	28.15	21.05	25.8	31.05	12.3	26.1	17.05	28.75	13.65	27	28.7	27.85	27.2

Now we select the lowest 159 v_{nm} values in the matrix M_N (coloured in blue in Table 3-17 and Table 3-18).

Table 3-17 The lowest selected values in the second numerical example (columns 1 to 15)

m/n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	17.85	28.05	30.75	13.75	26.05	17.8	16.05	29.75	27.85	18.4	25.8	17.65	21	29.05	26.1
2	27.05	17.35	28.7	28.95	18.5	12.3	28.45	26.8	18.35	27.35	29.3	25.45	24.45	18.9	27.85
3	14.75	29.1	15.1	18.8	28.65	16.9	19	23.75	13.3	16.65	24.45	20.35	16.75	27.15	26.55
4	28.35	15.25	27	30.1	16.55	19.7	25.05	27.45	16.1	25.8	21.05	27	25.05	16.85	23.75
5	30.4	26.5	29.75	24.1	30.05	28.4	11.7	15.45	27.8	28.5	30.05	30.05	26.45	26.8	17.45
6	13.45	28.7	17.85	31.4	26.75	16.95	19.4	26.2	22.1	18.3	24.8	20.4	19.75	27.8	26.5
7	27.45	18.6	31.05	26.15	15.3	24.45	29	29.05	20.4	27	19.05	29.05	27.75	31.4	26.8
8	17.2	24.8	16.5	14.35	28.4	18.55	16.7	28.05	25.4	16.85	28.65	18.65	17.45	30.45	28.15
9	28.95	16.35	30	27.15	14.95	26.15	22.05	29	18.3	26.2	20.75	21.05	28.45	28.65	29.8
10	31.1	11.3	26.45	28.3	26.15	25.45	26.45	16.9	21.4	26.5	28	29.45	30	27.4	17.5
11	17.95	25.1	12.4	19.75	25.8	16.55	14.65	26.55	25.85	19.6	28	14.8	19.6	26.75	27.2
12	26.2	25.75	28.4	28.65	12.1	27.75	27.8	20.05	27.35	25.15	27.4	28.1	28.75	28.4	15.2
13	30.4	20.15	26.05	29.05	17.3	24.75	28.45	29.35	16.05	25.1	18.9	27.1	30	29.4	25.7
14	19.8	19.4	17.4	19	19	14.5	22.4	28.7	12.3	13.45	28.35	17.45	14.25	29.3	30.45
15	30.05	30.1	28.7	29.75	30.35	27.5	27.05	18.8	24.75	29.05	26.35	12.65	27.05	28.35	30.4

Table 3-18 The lowest selected values in the second numerical example (columns 16 to 30)

m/n	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	11.75	13.6	29.1	14.15	15.1	25.45	25.75	17	28.75	25.7	27.45	16.6	25.7	26.4	17.85
2	15.25	30.35	20.15	20.75	28.75	11.65	28.5	28.1	28.5	16.05	25.45	27.1	17.9	18.7	30.4
3	20.15	15.25	28.05	18.25	13.65	27.7	26.7	14.6	30.05	26.75	25.75	12.3	27.85	30.4	28
4	15.6	27.75	30.05	28.5	28.95	16.2	27.35	30.7	30.4	14.05	10.7	28.3	15.95	11.35	26.15
5	30.45	26.4	29.1	25.8	25.5	26.1	29.75	25.4	17.2	29.7	15.7	27.8	24.75	30.45	30.4
6	10.65	16.6	23.75	13.8	14.1	26.1	25.15	19.95	30.45	27.7	26.45	17.75	25.8	28.3	16.25
7	19.15	28.4	19.25	13.3	26.1	15.1	25.4	25.7	28.15	17.95	22.75	28.8	11.65	16.3	28.7
8	20.45	21.45	30	13.8	13.35	27.15	29.65	13.45	26.55	29.75	25.7	16	26.75	30.35	14.65
9	18.35	26.4	13.3	28.05	26.05	17	27.8	27.15	26.5	16.65	12.3	27.15	18.85	20.05	25.05
10	29.8	28.5	30.35	26.85	25.1	28.95	13.1	30.05	31.05	25.15	18.3	27.5	28.7	25.15	28.7
11	26.45	15.25	29.1	13.35	13.6	27.15	25.5	15.9	31.05	27.5	28.1	14.1	30.1	27.7	14.95
12	27.05	31.05	27.15	26.75	29.1	24.45	31.1	24.4	13.7	24.45	17.85	27.8	27.2	30.7	27.2
13	15.6	27.15	15.65	16.65	28.95	19.8	27.05	26.05	28.1	18	22.05	25.85	14.4	20.35	27.7
14	28.3	12.95	26.05	14.65	18.25	28	27	18.8	25.75	23.75	27.45	29.35	26.55	23.75	17.3
15	26.75	27.8	28.15	21.05	25.8	31.05	12.3	26.1	17.05	28.75	13.65	27	28.7	27.85	27.2

After completing the steps 9, 10 and 11 of the algorithm, the new selection becomes as shown in Table 3-19 and Table 3-20.

Table 3-19 The new selections in the second numerical example (columns 1 to 15)

m/n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	(14,25)	(27,30)	(29,34)	(12,17)	(25,28)	(15,23)	(15,18)	(28,33)	(24,35)	(17,21)	(23,31)	(18,17)	(21,21)	(28,31)	(24,30)
2	(26,29)	(17,18)	(28,30)	(30,27)	(15,25)	(13,11)	(26,33)	(24,32)	(18,19)	(27,28)	(30,28)	(23,30)	(22,29)	(21,15)	(24,35)
3	(13,18)	(27,33)	(13,19)	(16,24)	(29,28)	(12,26)	(19,19)	(22,27)	(14,12)	(17,16)	(22,29)	(20,21)	(15,20)	(24,33)	(22,35)
4	(28,29)	(17,12)	(27,27)	(28,34)	(19,12)	(19,21)	(24,27)	(25,32)	(14,20)	(23,31)	(20,23)	(27,27)	(24,27)	(13,24)	(22,27)
5	(29,33)	(23,33)	(28,33)	(22,28)	(29,32)	(27,31)	(11,13)	(13,20)	(25,33)	(25,35)	(29,32)	(29,32)	(24,31)	(24,32)	(15,22)
6	(11,18)	(28,30)	(14,25)	(30,34)	(25,30)	(18,15)	(18,22)	(22,34)	(20,26)	(19,17)	(22,30)	(19,23)	(18,23)	(25,33)	(23,33)
7	(25,32)	(20,16)	(30,33)	(23,32)	(16,14)	(22,29)	(29,29)	(28,31)	(19,23)	(27,27)	(18,21)	(28,31)	(26,31)	(30,34)	(24,32)
8	(13,25)	(22,30)	(13,23)	(14,15)	(27,31)	(21,14)	(16,18)	(27,30)	(24,28)	(20,11)	(29,28)	(19,18)	(15,22)	(28,35)	(25,34)
9	(30,27)	(16,17)	(30,30)	(24,33)	(16,13)	(23,32)	(21,24)	(29,29)	(19,17)	(22,34)	(19,24)	(20,23)	(26,33)	(29,28_	(27,35)
10	(29,35)	(12,10)	(24,31)	(29,27)	(23,32)	(23,30)	(24,31)	(12,26)	(20,24)	(23,33)	(28,28)	(27,34)	(30,30)	(26,30)	(21,11)
11	(19,16)	(23,29)	(11,15)	(18,23)	(23,31)	(19,12)	(15,14)	(22,35)	(22,33)	(21,17)	(28,28)	(12,20)	(21,17)	(25,30)	(23,35)
12	(22,34)	(24,29)	(27,31)	(29,28)	(10,16)	(26,31)	(25,33)	(19,22)	(27,28)	(22,31)	(26,30)	(26,32)	(27,32)	(27,31)	(11,23)
13	(29,33)	(17,26)	(25,28)	(28,31)	(18,16)	(23,28)	(26,33)	(29,30)	(15,18)	(23,29)	(21,15)	(25,31)	(30,30)	(28,32)	(25,27)
14	(17,25)	(18,22)	(16,20)	(19,19)	(19,19)	(11,21)	(21,25)	(28,30)	(13,11)	(11,18)	(28,29)	(15,22)	(16,11)	(30,28)	(28,35)
15	(29,32)	(28,34)	(28,30)	(28,33)	(30,31)	(24,34)	(26,29)	(16,24)	(23,28)	(28,31)	(26,27)	(13,12)	(26,29)	(28,29)	(29,33)

Table 3-20 The new selections in the second numerical example (columns 16 to 30)

m/n	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	(10,15)	**(15,11)**	(27,33)	**(11,20)**	**(13,19)**	(23,30)	(24,29)	**(17,17)**	(27,32)	(25,27)	(25,32)	**(18,14)**	(25,27)	(25,29)	**(21,12)**
2	**(17,12)**	(30,31)	**(17,26)**	(19,24)	(27,32)	**(12,11)**	(25,35)	(26,32)	(25,35)	**(15,18)**	(23,30)	(25,31)	**(20,14)**	**(18,20)**	(29,33)
3	(17,26)	**(17,12)**	(27,30)	**(20,15)**	**(14,13)**	(27,29)	(26,28)	**(16,12)**	(29,32)	(25,30)	(24,29)	**(13,11)**	(24,35)	(29,33)	**(28,28)**
4	**(17,13)**	(26,31)	**(29,32)**	(25,35)	(30,27)	**(19,11)**	(27,28)	(30,32)	(29,33)	**(13,16)**	(10,12)	(29,27)	**(17,14)**	**(11,12)**	(23,32)
5	(28,35)	(25,29)	(27,33)	(23,31)	(22,32)	(24,30)	**(28,33)**	(24,28)	**(20,12)**	(29,31)	**(15,17)**	(25,33)	(23,28)	(28,35)	(29,33)
6	(11,10)	**(18,14)**	(22,27)	**(11,19)**	**(12,18)**	(24,30)	(22,31)	**(21,18)**	(28,35)	(27,29)	(24,31)	**(16,21)**	(23,31)	(29,27)	**(11,26)**
7	**(16,25)**	(27,31)	**(21,16)**	(14,12)	(24,30)	**(13,19)**	(24,28)	(25,27)	(25,34)	**(19,16)**	(21,26)	(26,34)	**(12,11)**	**(17,15)**	(28,30)
8	(18,25)	**(19,26)**	(30,30)	**(11,19)**	**(13,14)**	(24,33)	(30,29)	**(11,18)**	(22,35)	(28,33)	(25,27)	**(16,16)**	(25,30)	(30,31)	**(15,14)**
9	**(18,19)**	(25,29)	**(14,12)**	(27,30)	(25,28)	**(17,17)**	(25,33)	(24,33)	(23,33)	**(17,16)**	(13,11)	(24,33)	**(15,26)**	**(19,22)**	(24,27)
10	(27,35)	(25,35)	(30,31)	(23,34)	(23,29)	(30,27)	**(11,17)**	(29,32)	**(30,33)**	(22,31)	**(19,17)**	(24,34)	(28,30)	(22,31)	(28,30)
11	(24,31)	**(17,12)**	(27,33)	**(13,14)**	**(15,11)**	(24,33)	(22,32)	**(18,12)**	(30,33)	(24,34)	(26,32)	**(12,18)**	(28,34)	(27,29)	**(16,13)**
12	(26,29)	(30,33)	(24,33)	(25,30)	(27,33)	(22,29)	**(29,35)**	(23,27)	**(13,15)**	(22,29)	**(21,12)**	(25,33)	(23,35)	(30,32)	(23,35)
13	**(17,13)**	(24,33)	**(16,15)**	(17,16)	(30,27)	**(17,25)**	(26,29)	(25,28)	(26,32)	**(18,18)**	(21,24)	(22,33)	**(13,17)**	**(20,21)**	(27,29)
14	(29,27)	**(14,11)**	(25,28)	**(15,14)**	**(20,15)**	(28,28)	(27,27)	**(16,24)**	(24,29)	(22,27)	(25,32)	**(29,30)**	(22,35)	(22,27)	**(18,16)**
15	(25,30)	(25,33)	(25,34)	(20,23)	(23,31)	(30,33)	**(13,11)**	(24,30)	**(16,19)**	(27,32)	**(14,13)**	(27,27)	(28,30)	(24,35)	(23,35)

After reverting the matrix to its original form which consists of ones and zeros, the routing of the parts, which is shown in Table 3-21, was obtained.

Table 3-21 The incidence matrix of the second numerical example

m/n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	1		1	1		1	1			1		1	1				1		1	1			1				1			1
2		1			1				1		1			1		1		1			1				1			1	1	
3	1		1	1		1	1			1		1	1				1		1	1			1				1			1
4		1			1				1		1			1		1		1			1				1			1	1	
5								1							1							1		1		1				
6	1		1	1		1	1			1		1	1				1		1	1			1				1			1
7		1			1				1		1			1		1		1			1				1			1	1	
8	1		1	1		1	1			1		1	1				1		1	1			1				1			1
9		1			1				1		1			1		1		1			1				1			1	1	
10								1							1							1		1		1				
11	1		1	1		1	1			1		1	1				1		1	1			1				1			1
12								1							1							1		1		1				
13		1			1				1		1			1		1		1			1				1			1	1	
14	1		1	1		1	1			1		1	1				1		1	1			1				1			1
15								1							1							1		1		1				

After making the sum of costs of the selected elements, we obtain a total cost of $C_{t1} = 2740$ and a total duration of $D_{t1} = 3001$. At this stage, we can apply another algorithm such as the binary digit grouping algorithm presented by Mroue and Dao (2014) in order to construct the manufacturing cells. As a result, we obtain the following matrix presented in Table 3-22.

Table 3-22 The manufacturing cells of the second numerical example

m/n	9	21	11	25	18	29	5	16	28	2	14	20	3	6	7	17	13	12	1	30	4	10	19	23	27	24	15	8	26	22
2	1	1	1	1	1	1	1	1	1	1	1																			
4	1	1	1	1	1	1	1	1	1	1	1																			
13	1	1	1	1	1	1	1	1	1	1	1																			
9	1	1	1	1	1	1	1	1	1	1	1																			
7	1	1	1	1	1	1	1	1	1	1	1																			
11												1	1	1	1	1	1	1	1	1	1	1	1	1	1					
6												1	1	1	1	1	1	1	1	1	1	1	1	1	1					
14												1	1	1	1	1	1	1	1	1	1	1	1	1	1					
1												1	1	1	1	1	1	1	1	1	1	1	1	1	1					
8												1	1	1	1	1	1	1	1	1	1	1	1	1	1					
3												1	1	1	1	1	1	1	1	1	1	1	1	1	1					
12																										1	1	1	1	1
15																										1	1	1	1	1
10																										1	1	1	1	1
5																										1	1	1	1	1

Since there are no exceptional elements, C_{a1} as well as D_{a1} are equal to zero. Hence, $C_{f1} = C_{t1} + C_{a1} = 2740 < C = 3000$, and $D_{f1} = D_{t1} + D_{a1} = 3001 < 3500$. That is why, no more iterations are needed, and the obtained solution is the final one and the factory should accept the command.

3.6 A review of the obtained results

The 2 numerical examples demonstrated in this paper prove that the algorithm is able to provide efficient final solutions for both small and big size problems. In fact, it takes into considerations the constraints of costs and production times imposed by the factory; thereafter, it searches for an acceptable part routing. Afterwards, it uses another algorithm in order to form manufacturing cells. At this stage, it verifies the quality of these cells with respect to the aforementioned constraints. This evaluation takes also into consideration the resulting additional charges and production durations coming from the exceptional elements (if there are any). If the results are okay, it considers the obtained solution as a final one (as happened in the second numerical example); otherwise, it returns to the first step and re-routes the parts again and again until getting an efficient final solution (as occurred in the first numerical example). It is important to note also that the algorithm has proven its ability to decrease the number of exceptional elements through the re-routing procedure. For instance, it succeeded to decrease the number of exceptional elements from 2 to 1 in the first numerical example.

3.7 Conclusion

A new part routing algorithm that aims to reduce the fabrication time and cost was developed and presented in this paper. It uses thereafter another algorithm in order to construct manufacturing cells. The quality of the obtained solution is used to determine if more iterations are needed. The procedure continues in this manner until the obtainment of an acceptable solution. The algorithm presents 3 important innovations in the literature which have industrial reflections. The first one is providing a balanced production time and cost reductions. The second consists of feed backing to the part routing the quality of the formed manufacturing cells. The last one consists of calculating and considering the additional charges and production times resulting from the appearance of exceptional elements. In addition, it can be used as a decisional fabrication tool (accept or reject) for a factory that receives new customers' requests while it is fully occupied treating other demands. It was tested through two numerical examples and succeeded to give satisfactory results. As a future work this algorithm can be developed further by linking it to the production scheduling that can provide another feedback for the previous routing of the parts.

CHAPTER 4

PROFIT MAXIMIZATION THROUGH A MACHINE SELECTION PROCEDURE IN A FLEXIBLE MANUFACTURING SYSTEM

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4.1 Abstract

This paper provides a new mathematical algorithm that constitutes a tool for maximizing the profits through a machine selection procedure in a new or an upgrading flexible manufacturing system. The technological advances and the diversity of the machines in the market increases the need of the managers of the factories for such a tool. The algorithm tends to increase the net profits of the factory while considering the elimination of the exceptional elements through a cost-time model based on the part routing and on the manufacturing cell formation procedure. Although the concepts of machine selection, the increase of the net profits, the exceptional elements and the routing of parts have been addressed in the literature, this paper presents for the first time an algorithm that is able to join them in an inter-related manner. The algorithm was tested with numerical examples and proved its ability to provide optimal or near optimal final solutions.

Keywords: profit maximization, machine selection, flexible manufacturing system, part routing, manufacturing cell

4.2 Introduction

The flexible manufacturing systems are allowing firms to take advantage of diversified, low volume production of products with short life-cycles and improve the ability of a system to respond to a change (Gupta and Goyal, 1992). The basic step of setting up a new system or upgrading an existing one consists of effecting a feasibility study that involves on one hand the selection of the machines which are suitable with the expected production, and the planning of the whole system on the other hand. In other words, the flexible manufacturing system should contain the machines that can answer all the expected customers' demands at reasonable prices and within acceptable durations of fabrication. With the recent technological advances, the manufacturing machines are getting more and more diversified in a wide pricing ranges and with various operational modes and speeds. That is why, the selection procedure of the right machines is becoming more and more confusing which increases the need for an algorithm that helps the managers of the enterprises make convenient decisions. The problematic gets further branched when taking into consideration that the types of products and the quantities that need to be fabricated vary between one factory and another. On the other hand, a flexible manufacturing factory has the option to make machine substitutions and consequently redesigning the system in a much easier manner than a non-flexible one (hence the word flexible). That is why, an efficient approach for the selection procedure consists of effecting a case study according to the expected customers' demands through a set of traditional machines. According to the results, the managers identify the deficiencies in order to know what the machines that need to be replaced are and with which alternatives. In fact, the fabrication of any set of parts requires certain durations as well as costs. In order to linearize the problem, an index can be associated to the duration of the fabrication of each part on each machine. This index allows according to a precise logic to convert the duration to the terms of costs. Thereafter, the parts are routed in order to end up with a solution that minimizes the costs while respecting the number of required operations on each part. This routing leads to the formation of an incidence matrix. The next step consists of applying the concept of group technology. This concept leads to the formation of manufacturing cells (Asokan *et al.,* 2001). In some cases, this formation causes to the appearance of exceptional elements. The exceptional elements are defined as the parts that are left outside the cells as they are assigned to bottleneck machines. Consequently, these elements have to pass across two or more cells in order to be treated, which results in additional manufacturing costs and delays (Shafer *et al.,* 1992). Since a flexible manufacturing system already requires high investments, the mathematical algorithm presented in this paper re-routes the parts again and again which may lead to the elimination of these elements. After testing a predefined number of conventional customers' demands, the algorithm stops and selects the optimal set of machine specifications according to the highest resulting net profits. The increase of the profits within the context of flexible fabrication, the search for a solution for the machine selection, the treatment of the exceptional elements as well as the routing of the parts are not new concepts in the literature. Although some authors addressed these subjects separately, the relative innovation and the industrial importance of the algorithm presented in this paper is that it links them all together. Shishir Bhat (2008) used a heuristic algorithm in order to maximize the profits by optimizing the manufacturing system design. Almutawa *et al.* (2005) developed a methodology that searches for the optimal number of machines to purchase for each stage in a multistage manufacturing system. Myint and Tabucanon (1994) presented a framework that can be used for the pre-investment period in a flexible manufacturing system in order to help managers evaluate various possibilities for a certain number of configurations each of which consists of different machine types and degrees of flexibility. Wang *et al.* (2000) used a fuzzy approach in order to select the machines for a manufacturing cell. Regarding the treatment of exceptional elements, Xiangyong *et al*. (2010) noted that one possible way is to duplicate some machines in a flexible manufacturing system, another one consists of transferring the operations on the exceptional elements to one of the cells as mentioned in (Pachayappan and Panneerselvam, 2015). A third approach is to subcontract these elements to another manufacturer as described in (Mansouri *et al.,* 2003). On the other hand, the routing of the parts has been also addressed by some authors. A genetic algorithm approach can be used to determine the best processing plan for each part. This solution allows the factory to select the appropriate machines for each operation according to the determined plan. In addition, it leads to finding the solution that minimizes the total average flow times for all parts (Geyik *et al.*, 2013). Another approach based on a heuristic algorithm was proposed by Tiwari *et al.* (2000); the purpose of which is to solve the machine loading problem of a random type flexible manufacturing system by determining the part type sequence and the machine allocation that guarantees the optimal solution to the problem. Finally, Chen *et al.* (1992) proposed a part routing procedure which depends on a customer demand that is varying with time.

4.3 The new algorithm

Each factory is specialized in a set of productions. When it wants to establish a new manufacturing system or to upgrade an existing one, it needs to decide which machines to choose and how to plan the system. If it consists of upgrading an existing system, the algorithm presented in this paper uses an efficient compare/contrast technique by making such a study on the existing machines in order to decide if there is a need to upgrade them and how. In the same manner, if it consists of establishing a new system, the study will take place on a set of traditional well-known machines in order to decide if there is a need to buy more efficient ones. In both cases, the managers of the factory can have a clear idea according to the results about what and how to buy and/or to upgrade. In fact, the processing of any part on any machine requires a certain run time in addition to some costs. Besides the direct costs such as those of direct materials, other ones such as those related to the labor in addition to some manufacturing overhead depend on the duration of the fabrication. For instance, when the run time gets bigger, the factory needs to work for longer durations or to hire more employees which in turn increases the labors' as well as other relevant costs. That is why, the run time can be expressed in terms of dollars. In this case, each part costs the amount of money which is equivalent to the sum of the direct costs on one hand, and all the other costs that depend on the run time on the other hand.

Thus, let:

- dc_{nm} be the direct costs of processing the part number n on the machine m
- rt_{nm} be the required run time for processing the part n on the machine m
- x_1 be the average index of conversion into costs of the run-time for a certain factory
- x_2 is the indicator for the required machines' processing speeds. In other words, it is the average inverse optimization index for the processing duration of the parts on the new machines with respect to the traditional ones. If the calculations lead at the end to a value of x_2 which is equal to 0.8 this means that each of the new machines to buy has to be at least 1 / 0.8 = 1.25 times faster than the one to replace
- mrt_{nm} be the maximum allowable run-time for each operation
- crt_{nm} is the resulting run-time to cost conversion value
- tc_{nm} is the total cost that is defined as the sum of the direct costs and the resulting run-time to cost conversion values

$$mrt_{nm} = x_2 \times rt_{nm} \tag{4.1}$$

$$crt_{nm} = x_1 \times x_2 \times rt_{nm} = x_1 \times mrt_{nm} \tag{4.2}$$

$$tc_{nm} = dc_{nm} + crt_{nm} \tag{4.3}$$

The first step consists of constructing a matrix which contains the information about the direct costs and the run time for each part. For a better understanding, the theoretical aspects are explained step by step in parallel with the application of a numerical example.

Suppose that a factory wants to make a study about the machines to buy according to the expected customers' demands. This factory is specialized in the production of 4 types of tables such as the parsons, altar, drop-leaf and eglantine tables. Each of these types is composed of 5 parts and the factory contains 4 multitask machines where each machine can process any of these parts. We begin the study with the parsons tables by constructing the matrix in Table 4-1 that specifies the direct cost (dc_{nm}) and the required run time (rt_{nm}) for each part.

Table 4-1 Direct costs and run times for the first type of products in the first iteration of the numeric example

n / m	1	2	3	4	5
1	(dc_{11},rt_{11}) = (89,31)	(dc_{21},rt_{21}) = (92,24)	(dc_{31},rt_{31}) = (96,93)	(dc_{41},rt_{41}) = (87,56)	(dc_{51},rt_{51}) = (77,57)
2	(dc_{12},rt_{12}) = (72,96)	(dc_{22},rt_{22}) = (52,27)	(dc_{32},rt_{32}) = (64,17)	(dc_{42},rt_{42}) = (53,59)	(dc_{52},rt_{52}) = (59,60)
3	(dc_{13},rt_{13}) = (65,47)	(dc_{23},rt_{23}) = (95,39)	(dc_{33},rt_{33}) = (36,61)	(dc_{43},rt_{43}) = (79,58)	(dc_{53},rt_{53}) = (32,94)
4	(dc_{14},rt_{14}) = (38,90)	(dc_{24},rt_{24}) = (74,32)	(dc_{34},rt_{34}) = (91,41)	(dc_{44},rt_{44}) = (74,83)	(dc_{54},rt_{54}) = (96,67)

The numbers included in the matrix are unit less since they are presented for explanation and demonstration purposes. Surely, the unit of direct costs can be the American dollar or any other currency and that of the run time can be hour, minute, etc. Supposing that the parts number 1, 2, 3 and 5 require 2 operations whereas 3 operations are needed on the part number 4. After making an internal case study that includes the number of required employees, the electric bills, etc. the factory gets a value of x_1 equal to 1.5. The objective function is to determine the optimal value of x_2 which leads to the highest final profits through a machine set selection procedure. The problematic can be treated by beginning with an original value of x_2 equal to 1 in order to route accordingly the parts and construct thereafter the manufacturing cells. Afterwards, the value of x_2 will be decreased by a certain amount such as 0.1 for the next iteration and the parts will be re-routed in order to obtain new manufacturing cells and so forth. For each manufacturing cell design, the associated costs will be deducted from the revenues in order to end up with the net profits.

Thus, we begin by $x_2 = 1$:

1. Replace the values of rt_{nm} by crt_{nm} in order to obtain the matrix in Table 4-2.

Table 4-2 Direct costs and the resulting run time to cost conversion values for the first type of products in the first iteration of the numeric example

m/n	1	2	3	4	5
1	(89,46.5)	(92,36)	(96,139.5)	(87,84)	(77,85.5)
2	(72,144)	(52,40.5)	(64,25.5)	(53,88.5)	(59,90)
3	(65,70.5)	(95,58.5)	(36,91.5)	(79,87)	(32,141)
4	(38,135)	(74,48)	(91,61.5)	(74,124.5)	(96,100.5)

2. Let O be the total number of required operations on all the parts. In this example, $O = 2 + 2 + 2 + 3 + 2 = 11$
3. For each element, calculate the tc_{nm} and we obtain the matrix in Table 4-3.

Table 4-3 Total costs for the first type of products in the first iteration of the numeric example

m/n	1	2	3	4	5
1	135.5	128	235.5	171	162.5
2	216	92.5	89.5	141.5	149
3	135.5	153.5	127.5	166	173
4	173	122	152.5	198.5	196.5

4. Select the lowest O values (in this example, O = 11) in the matrix (highlighted in gray in Table 4-4)

Table 4-4 First selection of the smallest elements for the first type of products in the first iteration of the numeric example

m/n	1	2	3	4	5
1	135.5	128	235.5	171	162.5
2	216	92.5	89.5	141.5	149
3	135.5	153.5	127.5	166	173
4	173	122	152.5	198.5	196.5

5. Locate the columns that have either a surplus or a shortage in the selected with respect to the required number of operations. In the current example, the second column has a surplus of 2 elements, the third one has a surplus of a single element, the fourth has a shortage of 2 and the fifth column has a shortage of 1 element.

6. Begin with the biggest surplus element and subtract it from all the unselected elements in the columns that have shortages. In the current example, 153.5 is the biggest surplus element whereas 171, 166, 198.5, 162.5, 173 and 196.5 are the unselected elements in the columns that have shortages. The subtraction procedure gives the results which highlighted in turquoise in Table 4-5.

Table 4-5 Mathematical operations on the elements of the first type of products in the first iteration of the numeric example

m/n	1	2	3	4	5
1	135.5	128	235.5	153.5 – 171 = – 17.5	153.5 – 162.5 = – 9
2	216	92.5	89.5	141.5	149
3	135.5	153.5	127.5	153.5 – 166 = – 12.5	153.5 – 173 = – 15.5
4	173	122	152.5	153.5 – 198.5 = – 45	153.5 – 196.5 = – 43

7. Substitute the selection between the biggest surplus element in consideration and the element from which the subtraction has given the greatest value in the last step. The substitution in the current example will then be made between 153.5 and 162.5.

8. Repeat the steps 6 and 7 until completing all the required substitutions (i.e. until getting equal numbers of selected and required operations in each column). In our example, the other 2 substitutions will be made between 152.5 and 166 on one hand and 128 and 171 on the other hand. The main goal of these substitutions is to select for each column (part) exactly the required number of operations at the lowest possible costs. The new selection is highlighted in grey in Table 4-6.

Table 4-6 Final selection of the elements for the first type of products in the first iteration of the numeric example

m/n	1	2	3	4	5
1	135.5	128	235.5	171	162.5
2	216	92.5	89.5	141.5	149
3	135.5	153.5	127.5	166	173
4	173	122	152.5	198.5	196.5

9. The next step consists of reverting the matrix to its original form and to include the elements in the form of ones instead of the selected elements in the last step and zeros instead of the unselected elements as shown in Table 4-7.

Table 4-7 Incidence matrix of the first type of products in the first iteration of the numeric example

m/n	1	2	3	4	5
1	1	0	0	1	1
2	0	1	1	1	1
3	1	0	1	1	0
4	0	1	0	0	0

10. At this stage, the routing of the parts is completed, we use another relevant algorithm such as the genetic algorithm for manufacturing cell formation presented by Mak *et al.* (2000) in order to form the manufacturing cells (highlighted in blue) as shown in Table 4-8.

Table 4-8 Manufacturing cell design for the first type of products in the first iteration of the numeric example

m/n	2	1	3	5	4
2	1	0	1	1	1
1	0	1	0	1	1
3	0	1	1	0	1
4	1	0	0	0	0

11. At this stage, the first iteration is completed. If there are exceptional elements, this means that there will be additional required costs in order to treat them. In our example, we suppose that these costs are the double.

12. Begin the next iterations after decreasing x_2 by a certain value and repeat the steps 1 till 11. The values of x_2 should stay within a reasonable range according to the available

operational speeds of the machines in the market. In this example, we are going to decrease the value of x_2 by 0.1 per iteration until getting a value of x_2 which is equal to 0.1. After repeating the relevant steps, we obtain the following final results for the next 9 iterations as shown consequently in Table 4-9 to Table 4-17.

- For $x_2 = 0.9$

Table 4-9 Manufacturing cell design for the first type of products in the second iteration of the numeric example

m/n	2	1	3	5	4
1	0	1	0	1	1
2	1	0	1	1	1
3	0	1	1	0	1
4	1	0	0	0	0

- For $x_2 = 0.8$

Table 4-10 Manufacturing cell design for the first type of products in the third iteration of the numeric example

m/n	2	1	3	5	4
1	0	1	0	0	1
2	1	0	1	1	1
3	0	1	1	1	1
4	1	0	0	0	0

- For $x_2 = 0.7$

Table 4-11 Manufacturing cell design for the first type of products in the fourth iteration of the numeric example

m/n	2	1	3	5	4
1	0	1	0	0	1
2	1	0	1	1	1
3	0	1	1	1	1
4	1	0	0	0	0

- For $x_2 = 0.6$

Table 4-12 Manufacturing cell design for the first type of products in the fifth iteration of the numeric example

m/n	1	2	3	5	4
4	1	1	0	0	0
1	0	0	0	0	1
2	0	1	1	1	1
3	1	0	1	1	1

- For $x_2 = 0.5$

Table 4-13 Manufacturing cell design for the first type of products in the sixth iteration of the numeric example

m/n	1	2	3	4	5
1	0	0	0	1	0
2	0	1	1	1	1
3	1	0	1	1	1
4	1	1	0	0	0

- For $x_2 = 0.4$

Table 4-14 Manufacturing cell design for the first type of products in the seventh iteration of the numeric example

m/n	1	2	3	4	5
1	0	0	0	1	0
2	0	1	1	1	1
3	1	0	1	1	1
4	1	1	0	0	0

- For $x_2 = 0.3$

Table 4-15 Manufacturing cell design for the first type of products in the eighth iteration of the numeric example

m/n	1	2	3	4	5
4	1	1	0	1	0
1	0	0	0	0	0
2	0	1	1	1	1
3	1	0	1	1	1

- For $x_2 = 0.2$

Table 4-16 Manufacturing cell design for the first type of products in the ninth iteration of the numeric example

m/n	1	2	3	4	5
4	1	1	0	1	0
1	0	0	0	0	0
2	0	1	1	1	1
3	1	0	1	1	1

- For $x_2 = 0.1$

Table 4-17 Manufacturing cell design for the first type of products in the tenth iteration of the numeric example

m/n	1	2	3	4	5
4	1	1	0	1	0
1	0	0	0	0	0
2	0	1	1	1	1
3	1	0	1	1	1

It is to note that for x_2 = 0.3, 0.2 and 0.1, we have exceptionally gotten zero values for the machine number 1. This means that this machine is not needed for these x_2 values for the first type of products but it cannot be eliminated since it is needed for the other types according to the later calculations and results.

13. Analyze the results and select the best value(s) of x_2.

In the current example, the parameters of the analysis over a certain period of time are:

- The manufacturing costs designated by M_c
- The costs of buying new machines or upgrading the existing ones C_m
- The estimated revenues R
- The net profits P

$$P = R - M_c - C_m \tag{4.4}$$

We begin by calculating the manufacturing costs and we define the following parameters:

- n_e is the number of exceptional elements obtained for a solution that is gotten at a certain value of x_2
- nn_e is the number of non-exceptional elements at the same value of x_2
- c is the total cost of processing a part on a machine. It is to note that the significance of c here is the same as that of tc_{nm} presented earlier

$$Mc = \sum_{i=1}^{ne} c_i + \sum_{j=1}^{nne} c_j \tag{4.5}$$

Since we have assumed that the cost of fabricating an exceptional element is the double of its initial price, the manufacturing costs M_c for $x_2 = 1$ will be $M_c = (135.5 + 135.5 + 122 + 89.5 + 127.5 + 171 + 141.5 + 166 + 162.5 + 149) + (2 \times 92.5) = 1585$

The costs of buying new machines or upgrading the existing ones depend to a certain extent on the value of x_2. The lower is the value of x_2 the greater is the required operational speeds of the machines and consequently, the greater are generally these costs. On the other hand, the estimated revenues depend strongly on the value of x_2. In other words, these revenues increase with the increase of the operational speeds of the machines and vice versa. In the current numerical example, we are going to suppose that each value of x_2 requires the buying of a certain set of machines at a certain price or to change the operational speeds of one or more of these machines if such an option is available. Hence, without going into the technical details of each machine, we are going to assign a unique price for all the machines at a certain value of x_2.

Table 4-18 summarizes the final results in order to obtain the following expected net profits for the first type of products (i.e. for the fabrication of the parsons' tables).

Table 4-18 Net profits for the first type of products in the numeric example

x_2	Manufacturing costs	Costs of buying new machines or of upgrading the existing ones	Estimated revenues	Net profits
1	1585	2854	6762	2323
0.9	1505.2	2975	7513.33	3033.13
0.8	1424.8	3223	8452.5	3804.7
0.7	1339.45	4090	9660	4230.55
0.6	1363.5	5353	11270	4553.5
0.5	1262.25	7698	13524	4563.75
0.4	1161	12952	16905	2792
0.3	1170.25	20520	22540	849.75
0.2	1052.5	30325	33810	2432.5
0.1	934.75	65523	67620	1162.25

We can see that the value for x_2 that gives the highest profits for the production of the first type of tables is 0.5. The plot shown in Figure 8 illustrates the results for the net profits versus the indicator for the required machines' processing speeds.

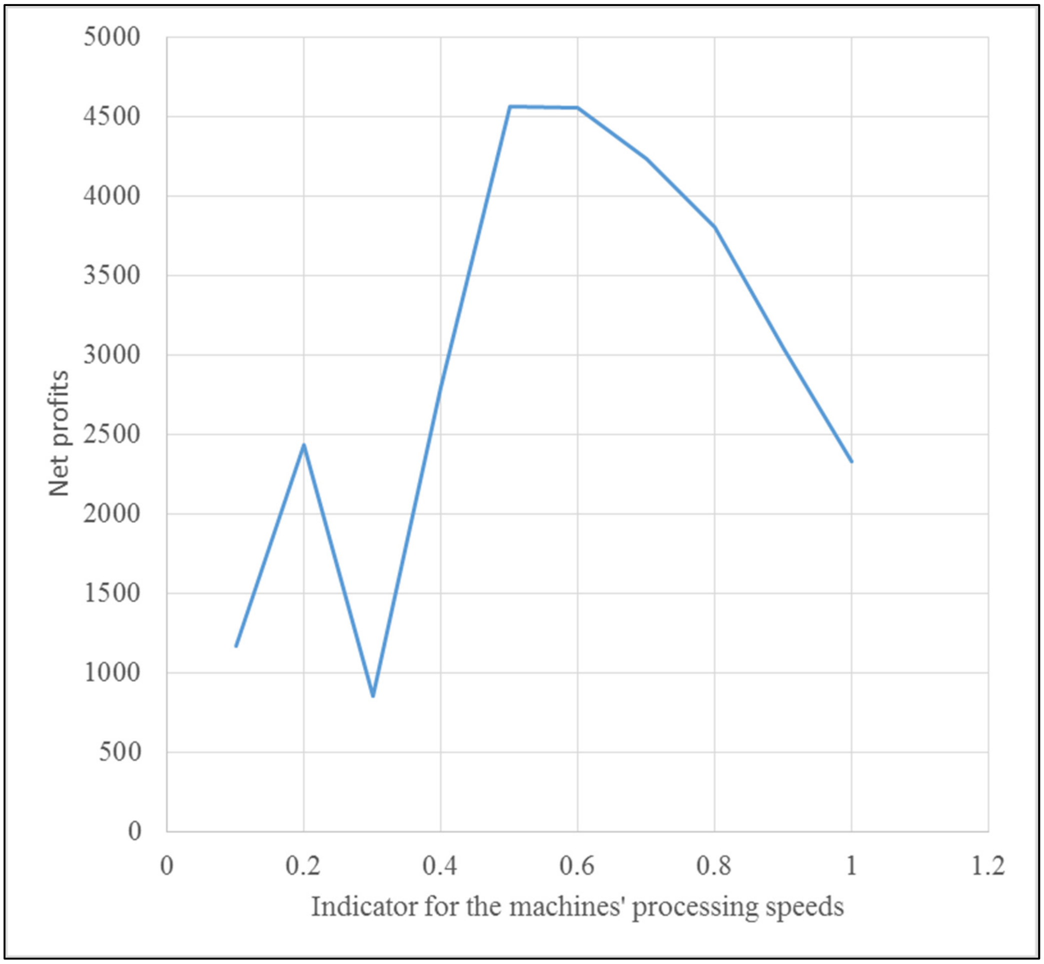

Figure 8 Net profits vs the indicator for the machines' processing speeds for the first type of products in the numeric example

Until now, all the study was made only on the first type of products. The factory has to continue this study in order to involve the other types. After repeating the steps 1 till 13 the results and plots shown in Table 4-19 to Table 4-21 and Figure 9 to Figure 11 were obtained for the next types of products which are consequently the altar, drop-leaf and eglantine tables.

Table 4-19 Net profits for the second type of products in the numeric example

x_2	Manufacturing costs	Costs of buying new machines or of upgrading the existing ones	Estimated revenues	Net profits
1	15236	2854	18654	564
0.9	13546	2975	20064	3543
0.8	11966	3223	21365	6176
0.7	11024	4090	22635	7521
0.6	10863	5353	23679	7463
0.5	9654	7698	24132	6780
0.4	9176	12952	26135	4007
0.3	8765	20520	29647	362
0.2	6795	30325	43651	6531
0.1	5436	65523	76543	5584

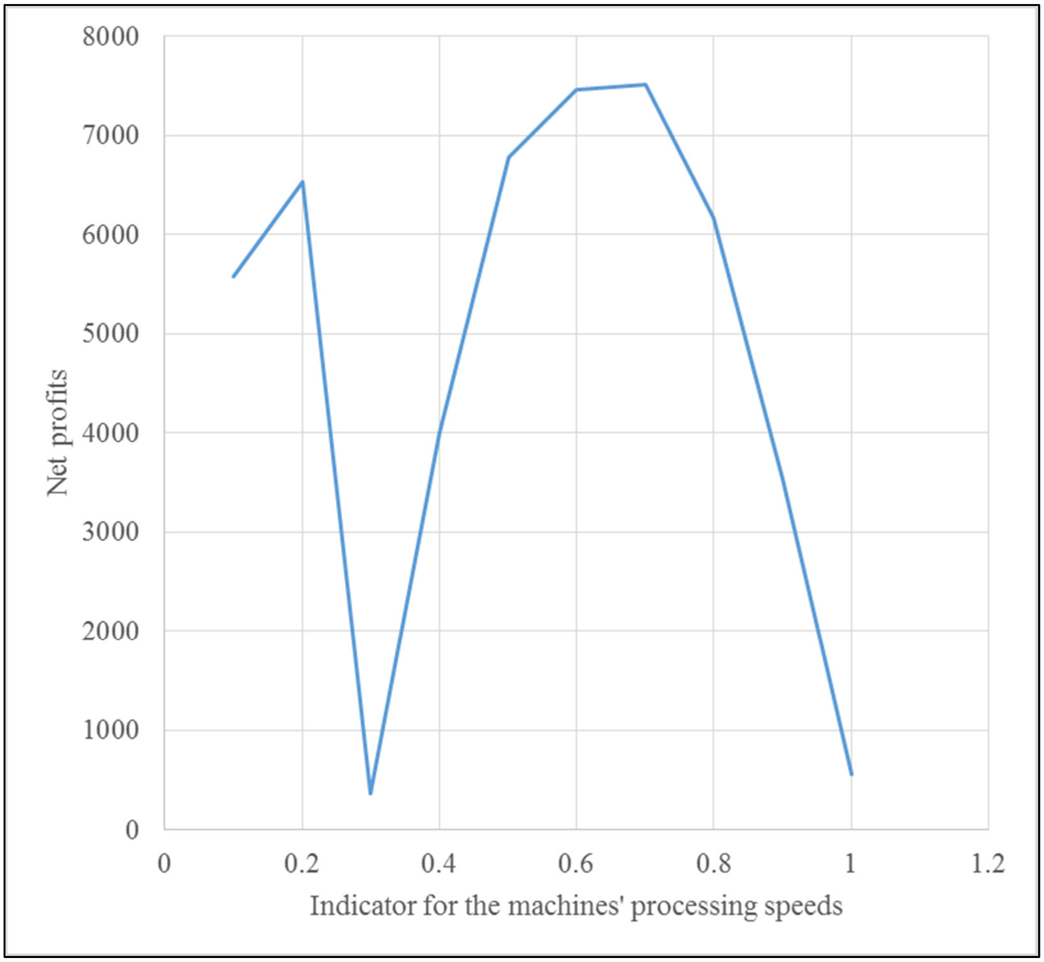

Figure 9 Net profits vs the indicator for the machines' processing speeds for the second type of products in the numeric example

Table 4-20 Net profits for the third type of products in the numeric example

x_2	Manufacturing costs	Costs of buying new machines or of upgrading the existing ones	Estimated revenues	Net profits
1	15486	2854	18798	458
0.9	13574	2975	21256	4707
0.8	12036	3223	22014	6755
0.7	11412	4090	22752	7250
0.6	10564	5353	23968	8051
0.5	9562	7698	24852	7592
0.4	9541	12952	26577	4084
0.3	8631	20520	29854	703
0.2	6498	30325	42965	6142
0.1	5321	65523	76856	6012

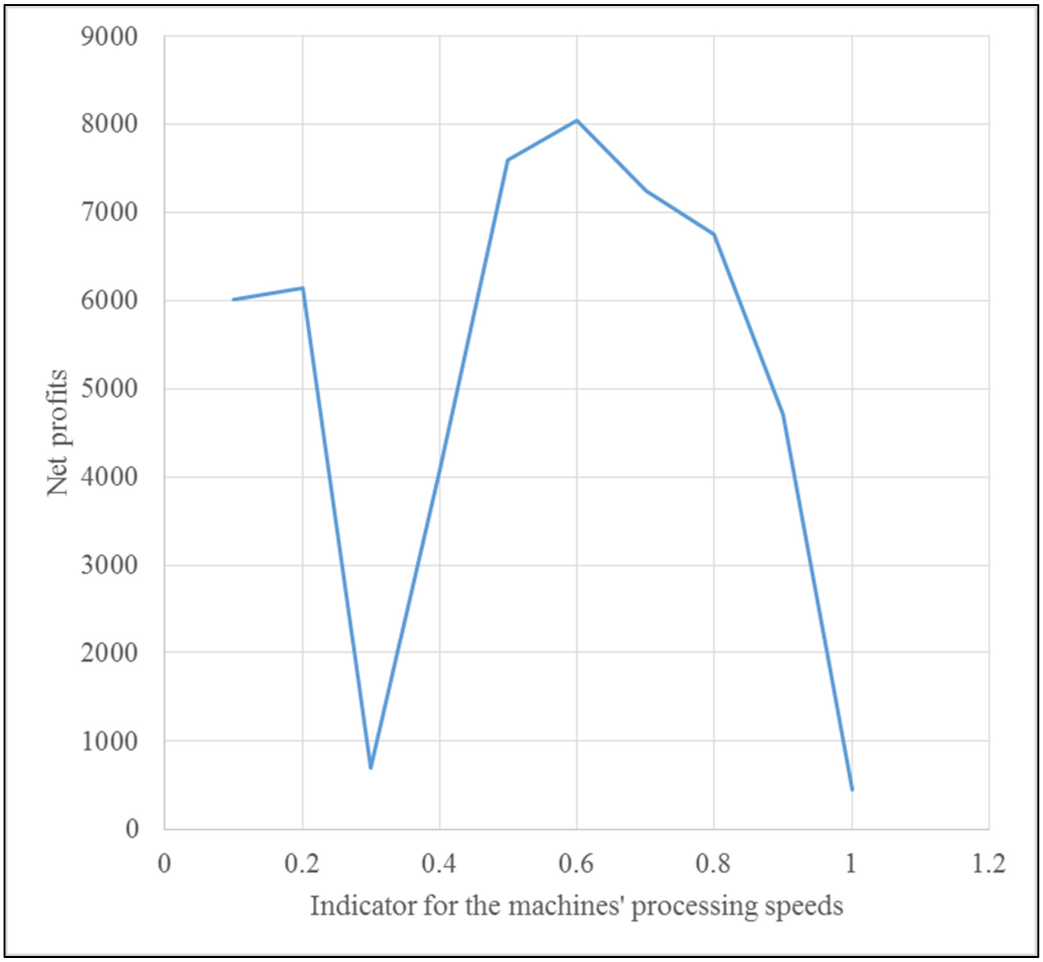

Figure 10 Net profits vs the indicator for the machines' processing speeds for the third type of products in the numeric example

Table 4-21 Net profits for the fourth type of products in the numeric example

x_2	Manufacturing costs	Costs of buying new machines or of upgrading the existing ones	Estimated revenues	Net profits
1	1652	2854	6762	2256
0.9	1535	2975	7523	3013
0.8	1402	3223	8563	3938
0.7	1336	4090	9745	4319
0.6	1352	5353	11598	4893
0.5	1198	7698	14632	5736
0.4	1153	12952	16901	2796
0.3	1090	20520	22536	926
0.2	1049	30325	33621	2247
0.1	929	65523	67524	1072

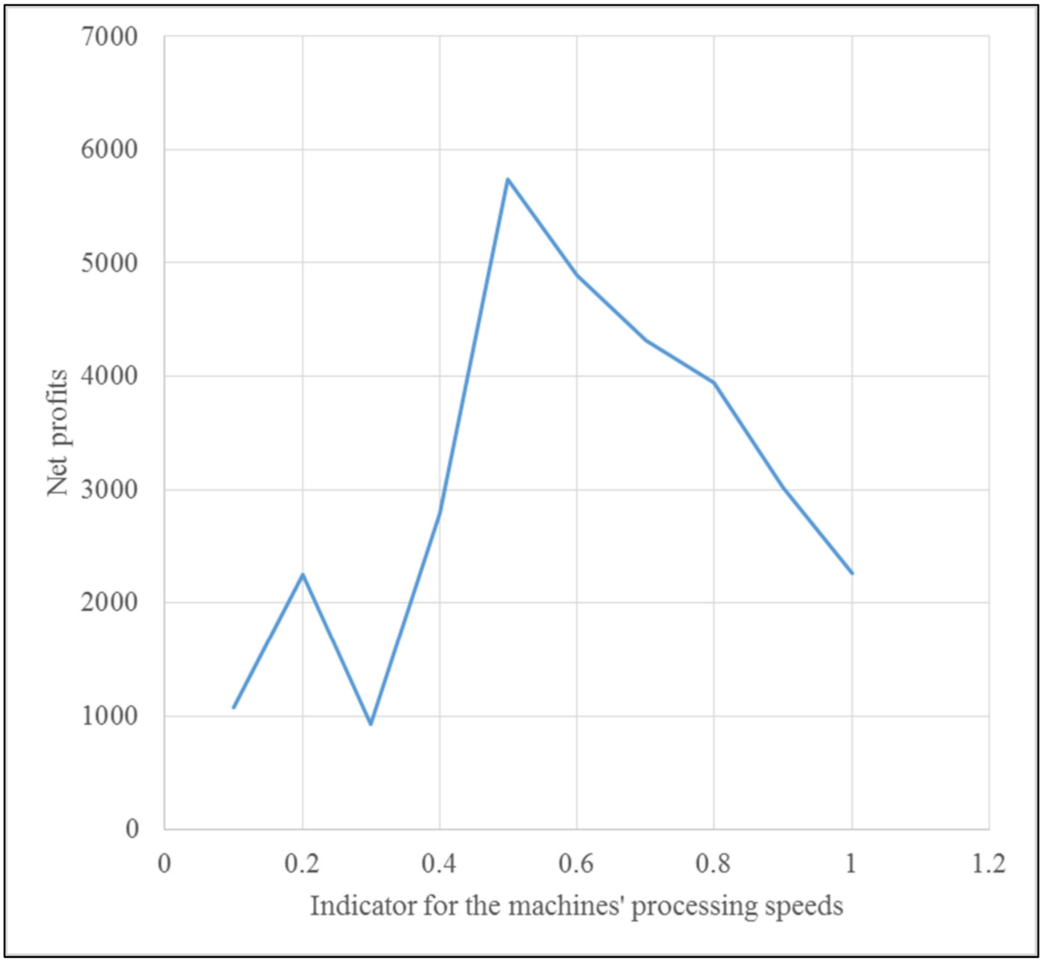

Figure 11 Net profits vs the indicator for the machines' processing speeds for the fourth type of products in the numeric example

In order to get more obvious results, all of the 4 plots are shown together in Figure 12.

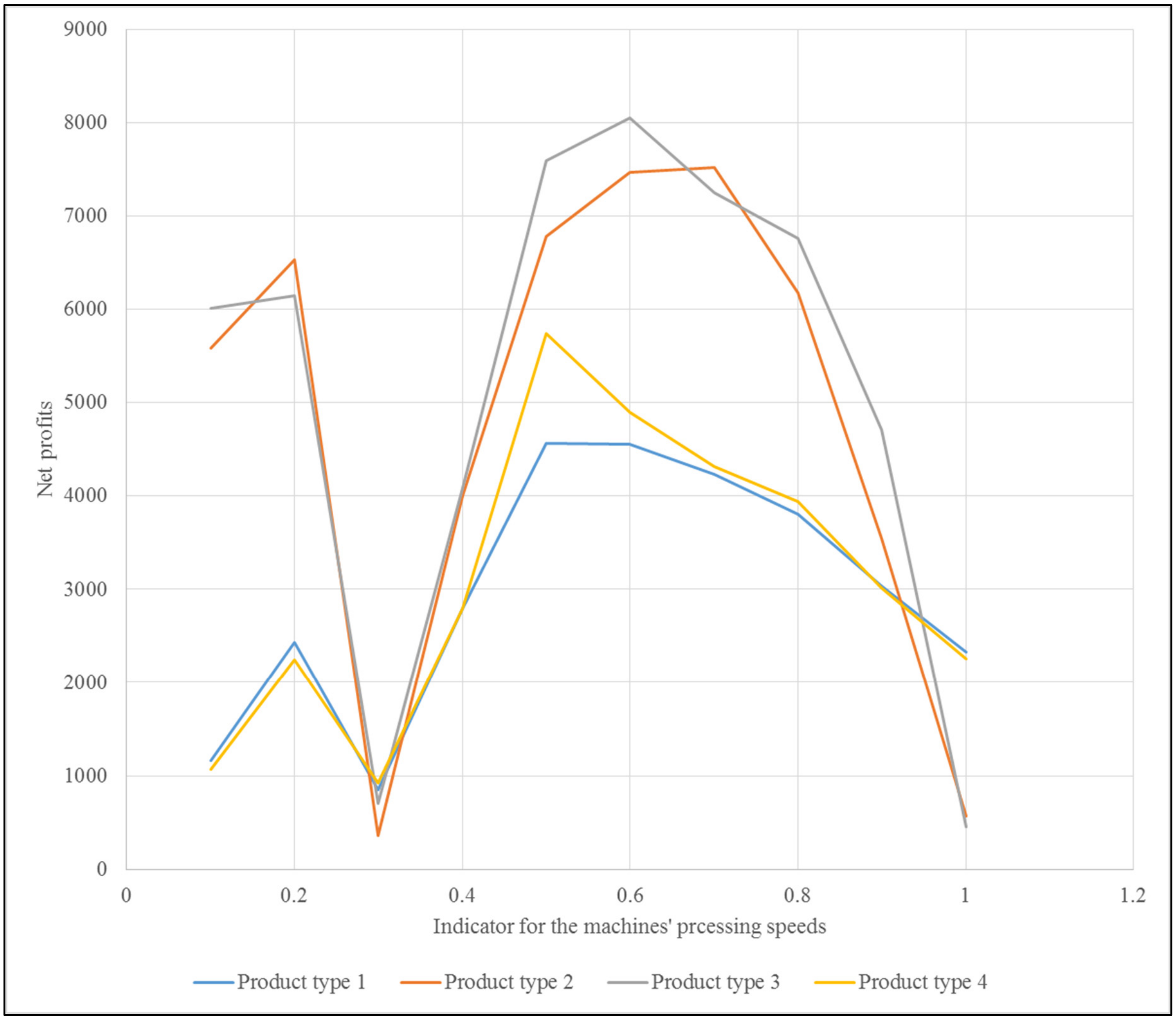

Figure 12 Net profits vs the indicator for the machines' processing speeds for the four types of products in the numeric example

According to the results, the values of the indicator for the required machines' processing speeds that generate the highest profits for each of the 4 types of products are shown in Table 4-22.

Table 4-22 Best indicators for the required machines' processing speeds in the numeric example

Type of product	Indicator for the required machines' processing speeds
1	0.5
2	0.7
3	0.6
4	0.5

Since a single value of x_2 has to be obtained at the end, all the resulting net profits must be added together for each value of x_2 as follows:

- Let Fp designates the final net profits at a certain value of x_2
- Let t designates the number of types of products (which is equal to 4 in the numeric example)

$$F_p = \sum_{1}^{t} p_t \tag{4.6}$$

The final net profits for each indicator of the machines' required processing speeds are shown in Table 4-23.

Table 4-23 Final net profits for each indicator for the required machines' processing speeds in the numeric example

Indicator for the machines' required processing speeds	Final net profits
1	5601
0.9	14296.13333
0.8	20673.7
0.7	23320.55
0.6	24960.5
0.5	24671.75
0.4	13679
0.3	2840.75
0.2	17352.5
0.1	13830.25

The greatest final net profit is equal to 24960.5 and it was obtained at $x_2 = 0.6$. That is why, the factory has to buy a set of machines the processing speed of each of which must be greater than that of the equivalent traditional one by at least $(1/0.6 - 1) \times 100\% = 67\%$. As stated earlier, this paper has provided a general study that involves only five parameters which are common between the industries. Usually, each industry has much more parameters and it can implement them in the same study by following the same logic and procedures. On the other hand, the values of x_2 that were used do not represent always the case because a decrement of 0.1 (i.e. 10%) was considered for theoretical and demonstration purposes. Each factory has its own required types of machines. The availability and the characteristics of the existing machines in the market decide which values of x_2 to consider. If the study will succeed to take into consideration all the parameters that have influences (which is never usually the case due to the unexpected events), the obtained final results will be considered as the optimal ones. Otherwise, they are near-optimal. It is to also to note that a special attention has to be held when performing such a study because as shown in the obtained results, there exists some cases where the net profits change a lot between two consecutive values of x_2.

This is mainly because even a small change in the value of x_2 may increase or decrease considerably the expenses as well as the revenues. For instance, a certain machine may be able to process the parts at a certain speed. A small increment in the value of x_2 may require to buy another one at a little higher processing speed but at a much higher price. In addition, a small increment in the value of x_2 may also lead to an important change in the configuration of the factory and as well as to a need of more or less employees resulting in a much higher or lower expenses. The algorithm presented in this chapter is illustrated in Figure 13.

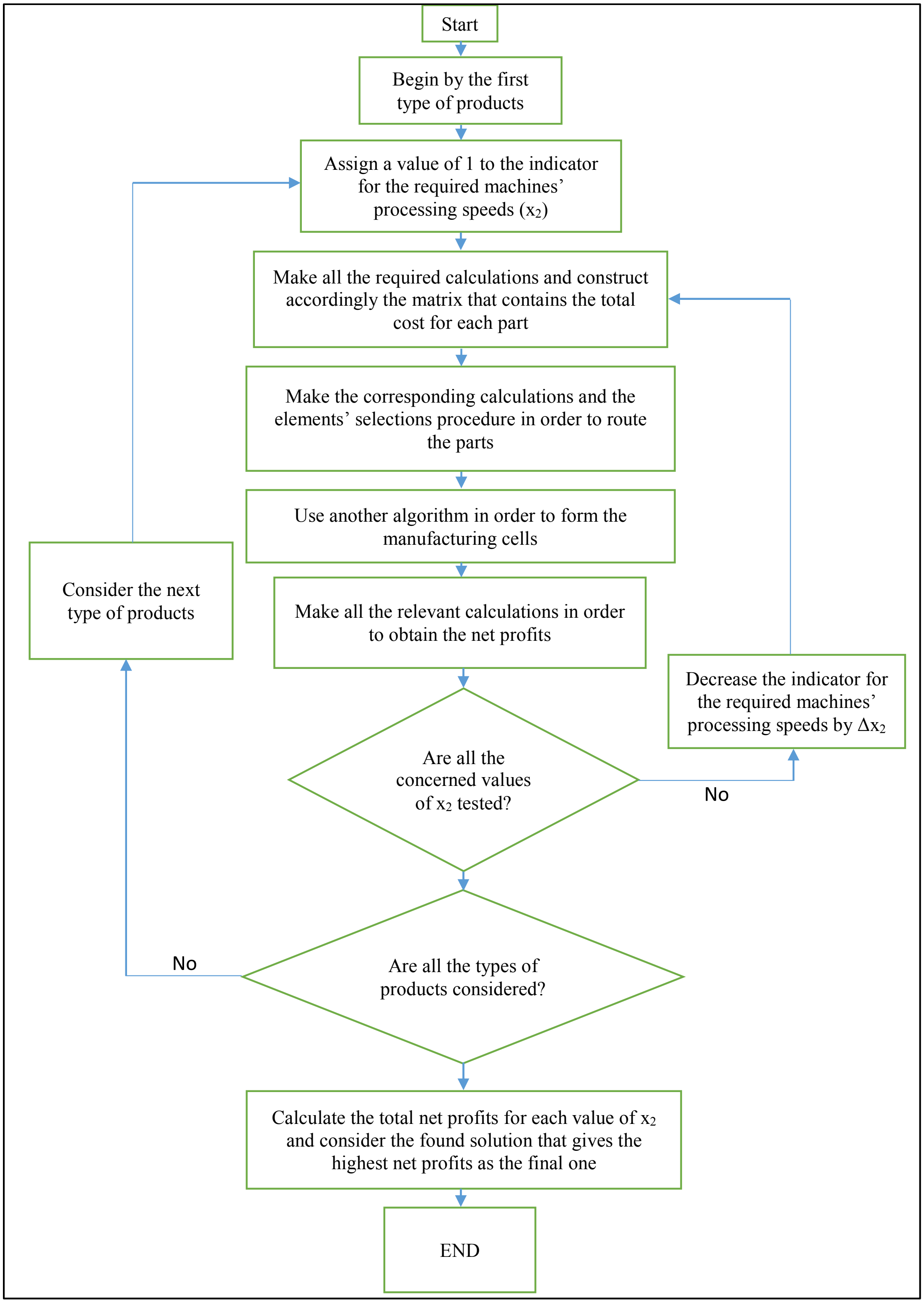

Figure 13 The algorithm

4.4 Conclusion

A new algorithm that deals with the machine selection procedure through a mathematical model in the context of flexible fabrication is presented in this paper. The industrial need for such an algorithm comes from the diversity of the machines that are available in the market at various processing speeds and huge ranges of different prices. Each factory has its specific types of products and it needs such an algorithm in order to decide what machines to buy and/or to upgrade according to its customers' demands. The methodology presented linked the processing costs and run times through the part routing procedure and the manufacturing cells to the overall costs and revenues in order to calculate the final net profits resulting from the selection of each set of machines. Only the parameters that are common between all the industries were considered in this paper through a numeric example and the obtained final results can be considered as optimal or near optimal. The detailed consideration of additional parameters that are related to each specific industry such as the lifetimes of the machines and the number of the required employees together with their salaries for each selection of a set of machines, etc. can constitute the subject of a futuristic supplementary research activity.

CONCLUSION

A flexible manufacturing system consists mainly of a flow path surrounded by cells and it is a combination of a job shop and manufacturing cells. The system is composed mainly of machine centers, buffer station(s), controllers, automatic guided vehicles and material handling equipment. There are many types of flexible manufacturing systems depending on each industry. A manufacturing system is known as flexible when it is able to sufficiently respond to the changes. There are many kinds of flexibilities such as the machine, the routing and the process flexibility. The efficient design of such systems and the efficient routing of parts are critical issues on the industrial level because the opposite cases lead to production conflicts as well as to losses in both time and money. In this thesis, four chapters which introduced three new algorithms were presented for these purposes. The second chapter presented a new algorithm in the literature which aims to optimally design the manufacturing and fractional cells. The algorithm involves a set of theoretical tools which accelerates the procedure of the search for candidate solutions and consequently, it leads to a quick obtainment of a final solution. In addition, it succeeded to prove its ability to give results which are better than those of well-known algorithms in the literature. The third chapter introduced a second new algorithm in order to efficiently route the parts while taking into consideration the production durations and costs as parameters. The algorithm links the routing of the parts to the design of the cells in order to ensure the obtainment of an efficient results that lead at the end to an optimal cell formation. The main goal is to find the optimal ways for the parts which have to be processed into the system according to the best possible allocations of these parts to the machines in the cells. This algorithm is useful as well for the enterprises which are fully busy processing customers' commands to decide whether to accept or to refuse a new fabrication request. The last chapter presented a third new algorithm which constitutes a tool that can be used in order to maximize the profits of the enterprises which are looking to select new machines or to upgrade the existing ones for their flexible manufacturing systems. It establishes direct relations between the machine selection and the routing of the parts and combines engineering to economic aspects in order to end up with multidimensional final solutions. The three algorithms presented in the last three chapters may have great industrial benefits when used together. For instance, an enterprise which wants to implant its own flexible manufacturing system can benefit consequently from the fourth, third and second chapters in order to select its convenient machines, route the parts that need to be processed within the system, and design the cells in an optimal manner.

RECOMENDATIONS

The current thesis did not treat all the aspects of the flexible manufacturing system design since it is a wide domain which involves and needs the implication of the mechanical, industrial, manufacturing, electric, electronic… engineering fields. Further researches can be done in order to combine the external layout, the transport system and the scheduling of the FMS to the part routing, cell design and machine selection procedures in a dynamic manner. In other words, there is a possibility to develop an integral algorithm which inputs the shop floor dimensions, the nature and the volume of the products to fabricate, the machines to be used, while considering as well the economic, electric and electronic aspects of the system in order to end up with a final design. In addition, the algorithm presented in the third chapter can be further developed in a standalone manner by considering the production scheduling. Finally, an additional research can be done on the algorithm presented in the last chapter in order to make it more compatible with a specific industry by involving all the economic and technical aspects which are related to that industry.

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