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A Cell Formation Algorithm for Sequential Processes with Alternative Machine Selection in the Automotive Lighting Industry

Victor Manuel Loya Garnica
University of Texas at El Paso, victor.mlg@hotmail.com

A CELL FORMATION ALGORITHM FOR SEQUENTIAL PROCESSES WITH ALTERNATIVE MACHINE SELECTION IN THE AUTOMOTIVE LIGHTING INDUSTRY

VICTOR MANUEL LOYA GARNICA

Department of Industrial, Manufacturing & Systems Engineering

APPROVED:

Tzu-Liang (Bill) Tseng, Ph.D., CMfgE

Jianguo Wu, Ph.D.

Eric D. Smith, Ph.D.

Charles Ambler, Ph.D.
Dean of the Graduate School

Para mis padres, mi hermano y Priscila. Gracias por estar ahi siempre para mi.

For my parents, my brother and Priscila. Thanks for always being there for me.

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VICTOR MANUEL LOYA GARNICA, B.S.M.E.

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Abstract

At the present time, there are more than 12 big companies dedicated to design and produce OEM lighting systems for cars and trucks. The manufacturing processes for headlamps, tail lamps and any other exterior vehicle lighting are very common in the auto industry. Still, every automotive lamp assembly is different from brand to brand and even between the different vehicle models. Indeed, there are car headlamps with less than 30 sub-components and others with up to 300 elements. This implies creating diverse part numbers which share or hold varying manufacturing methods within a specific facility. Management of the plant resources becomes highly challenging when the parts to be created and the machines to be operated are not organized in family groups. A great amount of time and effort has to be invested in production planning related to associating parts to machines. Consequently, the foundation of Group Technology (GT) has to be utilized with the purpose of dividing a relatively large system into smaller and more-manageable manufacturing cells. However, existing GT methods have not shown a practical application in the target scenario. This study pretends to find a better approach to the concept of GT throughout the use of a customized cell formation algorithm for the automotive lighting field or any other area that may be pertained.

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Chapter 1: Introduction

1.1 General

The automotive lighting systems are aimed to improve the visibility and help drivers to predict other drivers' intentions on the road. The quality, safety, and performance of driving a motor vehicle is totally enhanced by the use of headlamps, tail lamps, side markers, fog lamps, and any other source of illumination in the cars. Additionally, the lighting systems has been used to communicate the brand's language and it works as the corporation signature in many cases. Evidently, the automobile lamps are now used for several purposes.

The history of automotive lighting has evolved alongside to the history of the automobile. First used for horse-drawn coaches, the gas lights began to be utilized in cars as a result of the increased need to drive during night time. Dynamos were introduced in 1908 and likewise the utilization of red tail and brake lights became a requirement for a safe and more efficient driving in 1915. Soon, glare turned out to be a problem and hence the dipped headlamps were created to produce a low beam. In 1925, the functions of high and low beam were separated thanks to the invention of the double filament bulbs. In the thirties and forties, the first projection systems were originated parallel to the sealed beam lamps, flashing turn signals, and headlamps integrated into the vehicle's body. The introduction of the first halogen lamps took place first in Europe in 1960 and in US until 1979. Lamps with replaceable-bulbs were permitted by 1983. The next big step on the evolution of automotive headlamps was the development of the high intensity discharge (HID) bulbs in 1991. These produced a brighter white light and gained customer acceptance rapidly. Two years later, tail lamps upgraded to LED technology. Both HID and LED have become almost standards in today's designs due to their increasing

popularity. Latest innovations embrace steerable dipped beam headlamps and laser lights [1]. Anyhow, the current automotive lighting products are highly advanced.

After more than one hundred years since the first head light for a vehicle was invented, in today's scenario it is a fact that the particular use of polymers plays an important role for the material selection process in the automotive industry. In the past, coach lights housings were constructed with metals such as brass but today's lamps are predominantly made of plastic. Similarly happened with the outer lenses, which moved from glass to polycarbonate. It was, however, in tail lamps were plastic materials began their successful adoption during the second half of the 20th century better known as the "age of plastics". Thanks to their optical properties, versatility, lower cost, and resistance the plastics have replaced most of the existing materials used for automotive lamps. It can be affirmed that all the vehicle's brands have a strong relationship with the use of polymers when it comes to design their lighting units.

Normally, big carmakers appeal for the services of companies dedicated to exclusively produce lighting systems. Some of the largest corporations dedicated to this business are Automotive Lighting, Hella Group, Farba, Valeo, Fiem Industries Ltd, Ichikoh Industries Ltd, SL Corporation Stanley Electric Co., Visteon, Wipac Limited, and Zizala Lichtsysteme GmbH. These companies make most of the plastic components and then assemble them into a final product. Due to all the functions that are collected into these products, the complexity of design and manufacturability of the headlamps and tail lamps has increased considerably over the years. Currently, a large number of components have to be assembled in order to obtain a desired unit able to meet both customer and federal agencies' requirements. Evidently, every company dedicated to this industry deals with a varying mix of parts for different lighting systems that do not have a perceptible intention to become simpler.

Illustration 1.1: Exterior vehicle lamps with different lighting technologies

1.2 Problem Statement and Rationale

The automotive lighting industry is experiencing a rapid growth that calls for better means to improve its manufacturing environment. The research titled *Automotive Lighting Market by Technology (Halogen, Xenon, & LED), Adaptive Lighting (Front, Rear & Ambient), Position (Front, Rear, Side & Interior), Two-Wheelers (Front, Rear, & Side), by Region & Vehicle Type - Industry Trends & Forecast to 2020* predicts a 7.95% CAGR (compound annual growth rate) for the automotive lighting industry to 2020 .[2] According to this study, OEMs are opting for manufacturing facilities in Mexico, which is a highly advanced and matured automotive market, owing to low costs of labor and production. The political volatility of Asian countries and Russia has also benefited the vehicle production volume in Mexico, thus increasing the demand for automotive lighting products. Undoubtedly, the upturning number of parts and

manufacturing techniques are the harvest of the highly-demanding automotive market. In turn, global leading players of this sector have to deal with the accelerating complexity these products generate.

Typically, the companies dedicated to this field build headlamps, rear and turn lights, and interior lighting applications. Each of these final assemblies is composed of lenses, housings, reflectors, projectors, bezels, bulbs, harnesses, light guides, trims, modules, PCB's, and miscellaneous. For this reason, the complexity of a plant equipment is proportional to the intricacy of the products. Plastic molding machines, metalizing chambers, and coating chambers are some of the most popular manufacturing resources in this area.

A great problem arises while optimizing the use manufacturing resources within the company and hence the need for planning and management of equipment. Industrial, manufacturing, and design engineers have to collaborate with members of the departments of quality, planning and supply chain in order to determine the most appropriate use of equipment which ultimately builds a finished good. However, most of the planning process is still done manually and requires the input of experienced users. Thus, this activity is not only highly time-consuming but it also drives to different results depending on the specialist conducting this process.

There could be hundreds of parts to be produced and dozens of machines to be operated in a factory. The inevitable product variations force designers to create many different parts. This signifies a high investment in tooling and equipment, transportation means, skilled personnel, and specialized software. Parallel to this, the lack of sorting represents the origin of several quality, production, and communication problems. Strictly speaking, the absence of cellular layouts turns down the lean production.

1.3 Objective

Every company is constantly seeking to maximize the use of its resources in order to boost productivity and reduce costs. Cellular manufacturing brings big advantages to reduce the flow time and distance using less floor space and material handling. Management and planning becomes also easier.

The objective of this study is to develop an efficient method to classify the factory resources (parts and machines) into smaller and more-versatile sub-systems. By using the existing knowledge of Group Technology, it is intended to evolve the current manufacturing environment of the automotive lighting systems. Truly, a novel clustering technique has to be developed by taking as a baseline the present knowledge of the cell-formation methods. As in any other Group Technology technique, the ultimate goal is and has to be the decrease of the production costs by reducing material handling and transportation, work-in-process, and by simplifying production management. It is as well expected to reduce the bottleneck machines, ease the part-to-machine assignment task, and minimize the interaction among groupings. Eventually, it is planned to efficiently apply the findings of this research to the target field through a study case.

1.4 Contribution

The capabilities of the present cluster analysis methods using matrix formulations are limited and cannot be directly implemented in a more realistic industrial scenario such as the automotive lighting field. Insufficient research has been made to generate a suitable and efficient method able to deal with sequential processes (parts must follow a defined process sequence) and an alternative machine selection (parts have more than one machine option to perform an operation). For this reason, a more-focused study of these needs and weaknesses is conducted with the purpose of attaining a better clustering algorithm. The outcome has a practical application in the automotive lighting industry and any other field with similar structure. Certainly, the attained method is an advantageous tool which can be used by designers, manufacturing and industrial engineers, planners, managers, and anybody involved in the resources management duty.

1.5 Scope and Limitation

The scope of this paper is to deal with the clustering problem present in the automotive lighting industry. However, any industrial environment with sequential processes and an alternative machine selection can be benefited by the findings of this study.

1.6 Thesis Outline

The complete paper is strategically divided into five chapters. Basically, the entire document discusses two topics that complement each other: Group Technology and manufacturing of automotive lighting systems.

Chapter 1 “Introduction” presents the general idea, problem statement, objective, contribution, and scope and limitation.

Chapter 2 “Literature Review” defines the design aspects of the automotive lamps, the concept of Group Technology and GT in the automotive lighting industry. Here, an analysis of the existing methodologies applied to the target scenario is presented.

Chapter 3 “Methodology” proposes and explains a new algorithm and two examples are solved by means of this method. Performance measurement is conducted as well.

Chapter 4 “Case Study” illustrates how the proposed methodology is applied to a real case scenario.

Chapter 5 “Conclusion” summarizes the complete theory and describes the area to be enriched within the findings of this paper.

Chapter 2: Literature Review

2.1 Design Aspects of Automotive Lamps

In order to understand the complexity of the automotive lighting products, which are the main focus of this paper, the design aspects of these are explained first. An infinite number of lamp versions exist today, ranging from simple side indicator lamps to advanced Laser-light headlamps. Still, the basic guidelines of design do not vary from one to another. Most of the lamps work under the same principles using alike functional systems. These structures or systems can be grouped into different categories according to their function:

▪ Reflector

A reflection system allows to distribute the light of a bulb or LED into the road traffic space. Reflectors are the most common geometries in automotive lamps. They are made of plastic (Duroplast, Thermoplastic), sheet metal, glass, aluminum and, most recently, from magnesium die casting as well. Depending on the surface texture of the material, the reflector is either layered with aluminum directly or coated with a primer previously. Subsequently it is always coated with a protective layer.

▪ Housing

The housing is the 'skeleton' of the whole lamp. Besides of supporting the assembly of all the components it also serves as a shell that protects the whole system from external threats. Polypropylene with different filling materials (glass-fiber or talk reinforcing) is mainly used for headlamps and PC-ABS is typically employed for tail lamps housings. Important optimization possibilities with regard to weight, use of material and cycle time are the result of mold-flow analysis and stiffness calculations with the aid of finite-element method (FEM).

▪ Cover lens

For a long time, soda-lime glass was molded to build the cover lenses. However, polycarbonate has become the standard material to create more free-style designs among all headlamps. Lenses made of this polymer are also more resistant to impact than glass, they weigh less and adapt to tighter tolerances. Cover lenses made of polycarbonate receive special type of external and internal coatings. For the case of tail lamps and other lamps, it is more commonly used PMMA. Parts made of this polymer do not require any type of coating and can be molded using various colors, i.e. lenses of car tail lamps composed of three colors (red, amber and clear) to perform different functions.

▪ Decorative elements

Bezels, trims, covers, frames, and any other parts which main function is merely decorating and improve the stylish of the lamp. These parts are regularly made of PC and receive a sort of metallization.

▪ Light source

Bulbs and LED arrays.

▪ Electronics

PCB's and modules.

▪ Adjusting elements and attachments

Standard components such as screws, pivots, rivets, clamps, plates, gaskets, foams, and caps.[1]

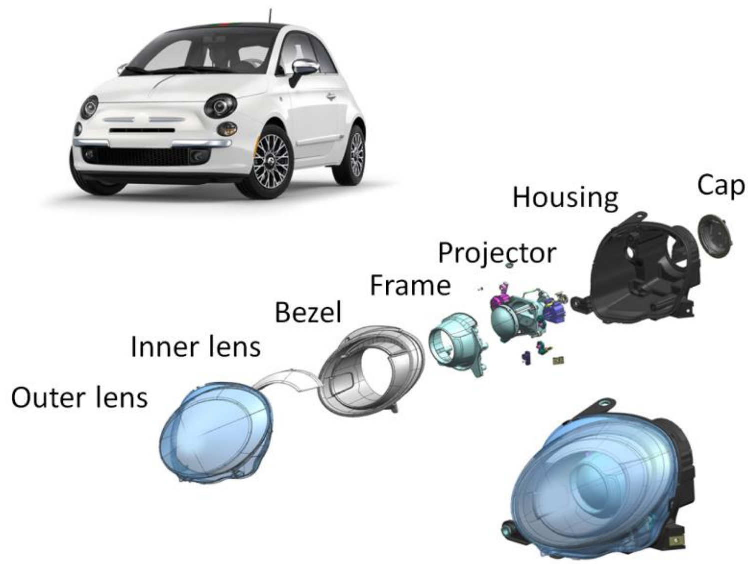


Figure 2.1: Main components of a typical car headlamp

Some of these parts, however, receive a type of treatment before they are assembled. Figure 2.2 shows the most common plastic parts made in a factory and how they are classified into different categories according to the surface treatment they receive.

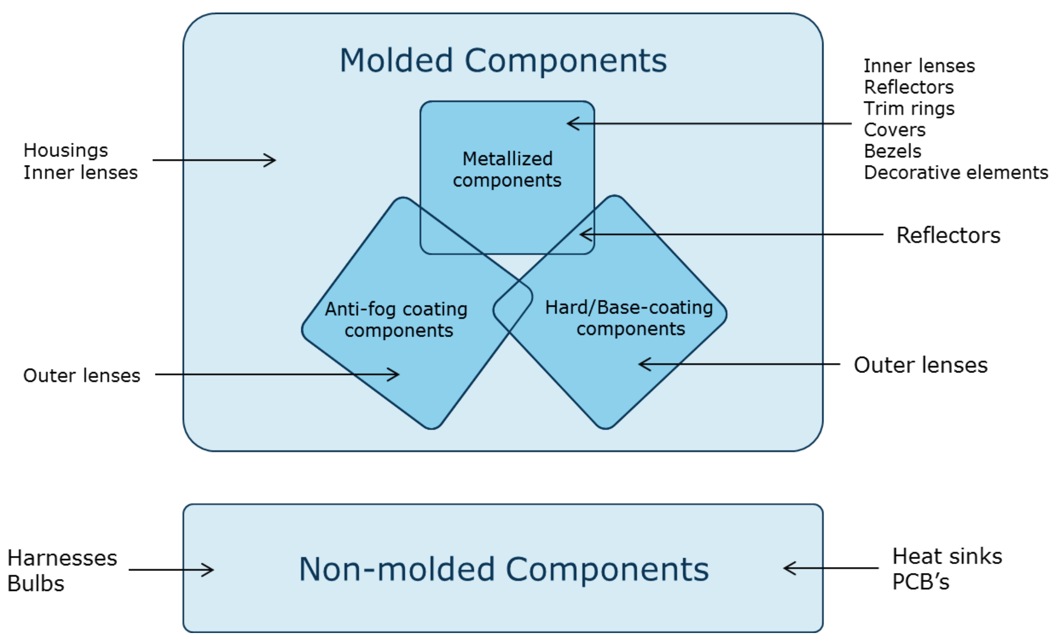


Figure 2.2: Plastic-molded and non-molded components of automotive lamps

Every single structure or system present in an automotive headlamp or tail lamp has an impact on all the areas of the final product listed below (Wördenweber, 116):

- Technical performance (luminous flux, efficiency, light distribution)
- Design (appearance when illuminated and not illuminated)
- Quality (process safety, durability, reliability0
- Vehicle integration (weight, size)
- Development time and costs

After plastic components are made (molded and surface-treated) they proceed to the assembly lines where they build up a finished product.

2.2 Group Technology

The basis of Group Technology lies on decomposing a manufacturing system into smaller and thus more-manageable subsystems. Elements within each subsystem share common characteristics defined before the problem is solved. Some of the most common groups resulting from the application of this technique are the machine cells and part families. Ideally, there should not be flow of parts between machine cells. Group Technology becomes highly advantageous in facilities producing similar but not identical goods. Its implementation has the following benefits:

· Reduced production lead time
· Reduced work-in-progress inventory
· Reduced labor
· Reduced tooling
· Reduced rework and scrap materials
· Reduced setup time
· Reduced order time delivery
· Reduced paperwork
· Improved human relations

Group Technology allows to structure an organized data base with all the information of a given facility needed to operate it. In fact, data bases are highly advantageous for a corporate competitiveness since they are able to react faster to the customer demand using less resources and energy without compromising the quality.

Under the concept of Group Technology, Cellular Manufacturing (CM) is a production system that consists on dividing the facility resources into manufacturing cells and part families. Cells should be self-contained with all necessary equipment and resources and the groupings of parts must share common features in terms of manufacturability such as size, weight, surface treatment, color, and material. Cellular layouts are an important element of lean production on which physical proximity and a common mission enhance teamwork.

The Group Technology problems, which ultimate goal is to obtain manufacturing cells, are solved by means of the two methods Classification and Cluster Analysis and likewise are divided as shown in the diagram below:

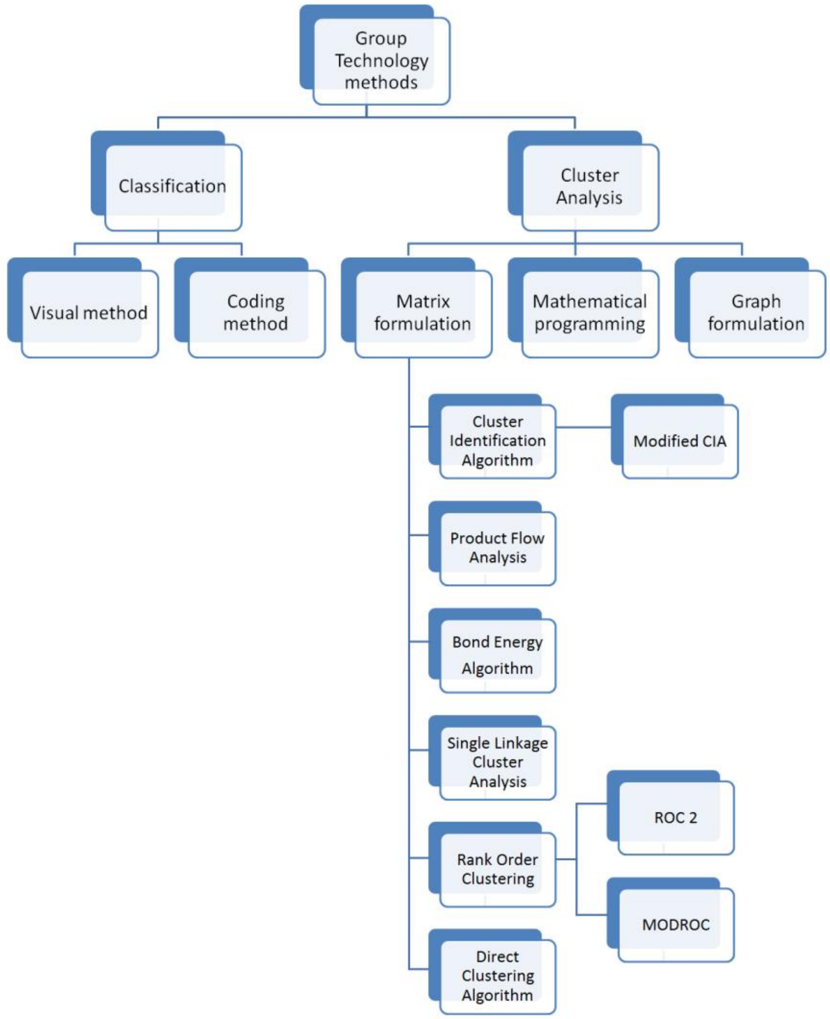


Figure 2.3: Group Technology methods

Since the 1920s, it was perceived that using product-oriented cells in a factory helped to reduce unnecessary transportation of parts. From here different researches spent great efforts to develop diverse methods of cluster analysis through a matrix formulation. This paper emphasizes primarily on the matrix manipulation methods also referred as Design Structure Matrix formulations.

Next, Table 2.1 shows some of the contributions that have been made to Group Technology in the area of matrix formulation. However, modifications and alternative methods exist but this table intends to display the most relevant ones only.

Table 2.1: Relevant contributions in the cell formation methods using part-machine matrixes

Method	Researchers	Description
Cluster Identification Algorithm (CIA)	Iri (1968), Kusiak and Chow (1987)	Identify perfect block diagonals (if existing) using a masking technique
Production Flow Analysis (PFA)	Burbidge (1971)	Loads are calculated for each part family to obtain the equipment requirements for each cell
Bond Energy Algorithm (BEA)	McCormick, Schweitzer, and White (1972)	Identify clusters within complex data arrays using a measure of effectiveness (ME)
Single Linkage Cluster Analysis (SLCA)	McAuley, Carrie, Waghodekar (1972)	Machines are grouped according to a similar coefficient
Rank Order Clustering (ROC)	King (1980)	Convert binary numbers to values and rearranges columns and rows based on the PFA matrix
Direct Clustering Algorithm (DCA)	Chan and Milner (1982)	Count the number of 1's in each column and row and rearrange them in decreasing order to form diagonal clusters
Rank Order Clustering (ROC 2)	King and Nakornchai (1982)	Overcomes the computational limitations of ROC
Modified Rank Order Clustering (MODROC)	Chandrasekaran and Rajagopalan (1986)	Similar to ROC but it does not need to be performed a number of times with progressively smaller matrices.
Modified CIA	Boctor (1991)	Each element of the matrix is scanned once instead of twice as in original CIA

Commonly, the cell formation problems are represented by part-machine incident matrixes. Indeed, all the existing methods described before use this type of medium as a start point. Parts to be manufactured are arranged in columns and machines for processing are

arranged in rows. The matrix is completed using binary elements (1, 0). A '0' or empty space denotes no operation and '1' denotes the presence of an operation.

Parts

Machines	P1	P2	P3	P4	P5	P6
M1			1			1
M2	1		1			
M3		1		1		
M4	1		1			1
M5		1		1	1	

Figure 2.4: Original part-machine matrix

In a simple case like this, it is easy to see the relationships and manually rearrange the matrix entries to form groupings. Figure 2.5 shows the same matrix after manipulating the rows and columns to create two 'cells'.

Parts

Machines	P2	P4	P5	P3	P1	P6
M5	1	1	1			
M3	1	1				
M4				1	1	1
M2				1	1	
M1				1		1

Figure 2.5: Part-machine matrix with mutually separable clusters

In a further example, Figure 2.6 shows a relationship matrix of 4 machines and 5 parts:

Part

Machine	P1	P2	P3	P4	P5
M1	0	1	1	0	1
M2	1	0	1	0	0
M3	1	0	0	1	0
M4	0	0	1	0	1

Figure 2.6: Unarranged part-machine matrix

Since the sequence of operations is neglected at this point, the physical layout representation of Figure 2.6 can be expressed as below.

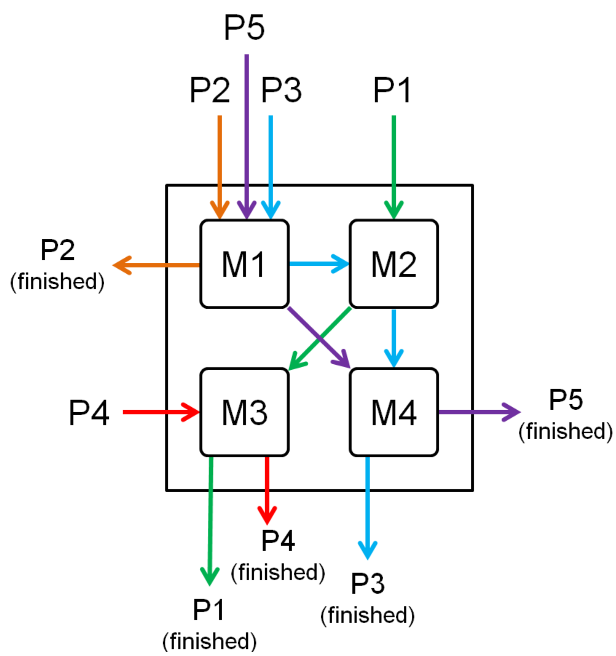
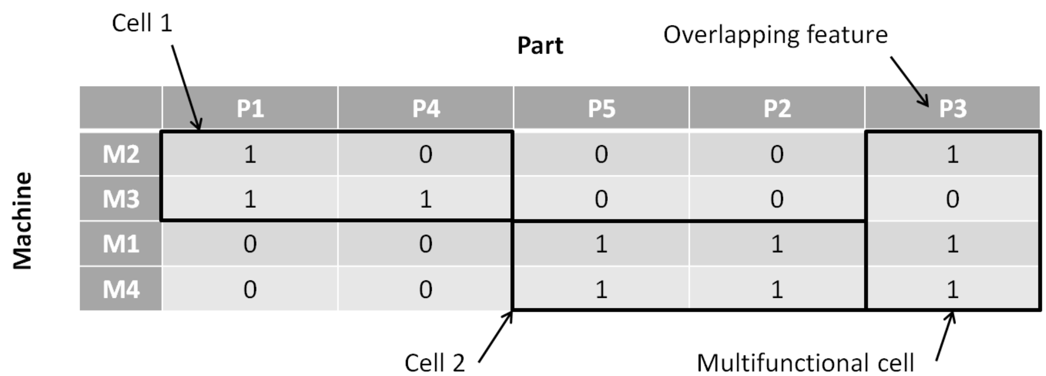


Figure 2.7: Unarranged manufacturing layout

Ideally, all ‘1’ elements inside clusters in a block diagonal structure are obtained as a solution of the clustering methods. These are also known as mutually exclusive regions. In this case, matrixes attaining results with no 1-elements outside the clusters (such as in Figure 2.5) are known as decomposable matrixes and each cluster symbolize one machine cell and one part

family. When no ideal solution exists, the resulting groupings vary depending on the algorithm used. Such is the case of the Figure 2.6 representing a non-decomposable matrix with overlapping features. Figure 2.8 below is a clustering solution of this problem:



	P1	P4	P5	P2	P3
M2	1	0	0	0	1
M3	1	1	0	0	0
M1	0	0	1	1	1
M4	0	0	1	1	1

Figure 2.8: Clustering of a matrix with overlapping features

For this scenario, a multifunctional cell requires to duplicate the machines processing the overlapping features. This implies acquiring new equipment to process the parts that do not fit into any other cell. In this case, the multifunctional cell involves machines M2, M1, and M4 in order to make part P3. Figure 2.9 pictures the physical layout of these clusters:

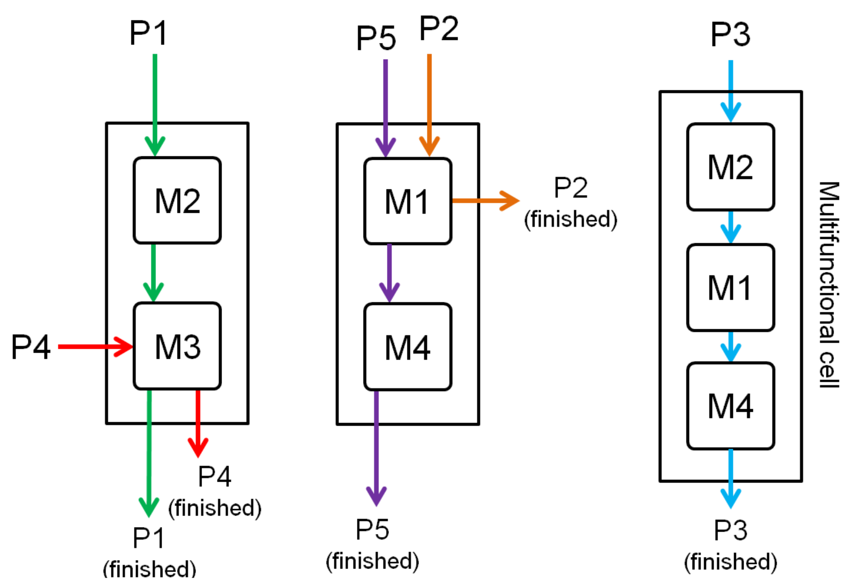


Figure 2.9: Rearranged manufacturing layout with a multifunctional cell

Evidently, creating a multifunctional cell in order to process 'overlapping' parts calls for the investment in new equipment (duplicate M2, M1, and M4) and therefore a consumption of more physical space. There is also the need for more workers and higher costs of maintenance. Thus, multifunctional cells are not always the best approach to deal with this type of scenarios.

Figure 2.10 shows another possible answer to the given problem. A '0' or empty space inside a cluster is known as 'void' and a '1' outside a cluster is called an exceptional element:

Machine	P1	P4	P3	P5	P2
M2	1	0	1	0	0
M3	1	1	0	0	0
M1	0	0	1	1	1
M4	0	0	1	1	0

Figure 2.10: Rearranged part-machine matrix

The rearranged physical layout has two cells as shown below:

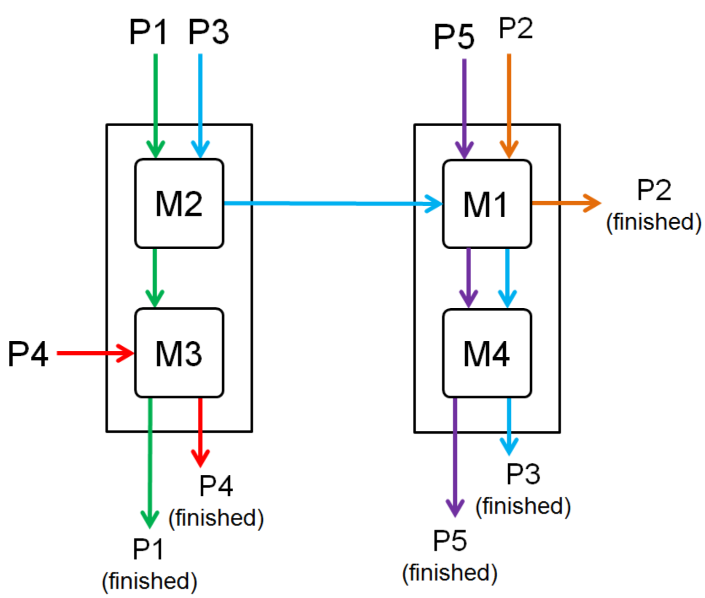


Figure 2.11: Path alternative 1 of rearranged manufacturing layout

Exceptional parts and bottleneck machines represent the most common problem in Group Technology algorithms. 'Neat' cells like the ones obtained in decomposable matrixes are not always guaranteed after conducting clustering methods and the results vary from one algorithm to another. Exceptional parts, which are processed in more than one cell, imply intercellular transportation. This is equal to more handling cost and coordination effort among cells. Part 3 (P3) shown in Figure 2.11, for example, has to be processed in machine M2 that is inside Cell 1. Then, it has to be transported to Cell 2 to be processed in machines M1 and M4. Likewise, a void indicates that a machine within a cell is not used for processing a part. This in theory produces unnecessary handling through a large and inefficient cell. Similarly, bottleneck machines processing overlapping-parts 'saturate' their capacity and reduce their availability to produce the parts within their assigned cell. Thus, by reducing the number of voids and exceptional elements (and thus the bottleneck machines) a better result is achieved. Whether or not a pure diagonal array of clusters is obtained, cell formation problems are considered NP-hard (Lenstra 1974).

The main goal of Group Technology cells is to reduce the transportation and delay within established clusters. A fast throughput can be expected by setting common features within cells. Both, process and product, have to be considered when designing manufacturing cells. Understandably, cell formation is essential when designing cellular manufacturing systems. Cell formation methods in the existing literature assume different conditions when making a complex part:

1) There may be various alternative process plans for making the part disregarding the sequence order.

2) There is a single process plan (fixed sequence) for making the part.

3) The combination of both.

Most of the traditional methods assume condition 1. In reality, the conventional clustering methods disregard the sequence of operations (condition 2). Equipment is organized according to feature similarities but there is no emphasis on the order of machines. Thus, the matrix in Figure 2.6 could have an alternative and still equivalent physical layout:

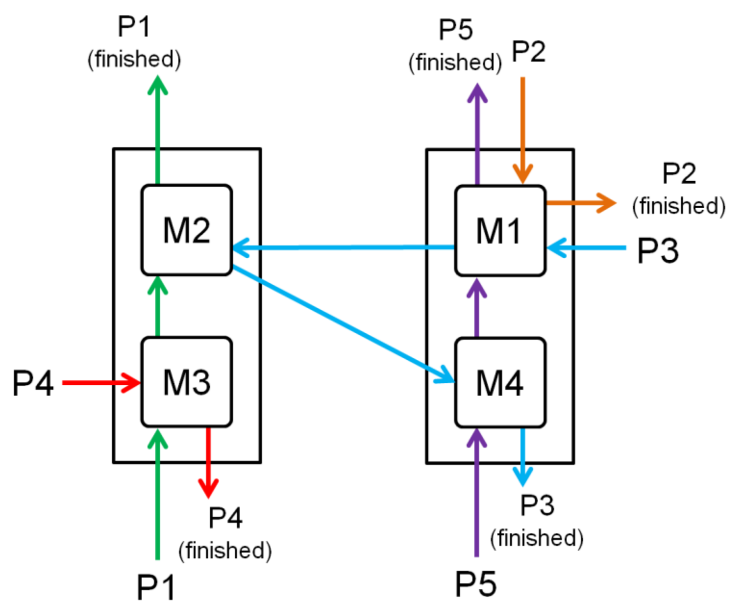


Figure 2.12: Path alternative 2 of rearranged manufacturing layout

Both Figures 2.11 and 2.12 are possible representations of the physical layout of the matrix from Figure 2.6. In Figure 2.12 , however, parts P1 and P5 have a different sequence and part P3 requires more transportation if sequence M1-M2-M4 is assumed to be mandatory. At this point, the parts and machines designated to each cell may be appropriately disposed but the processing of exceptional elements (such as Part 3) may not be considered. Evidently, the order

of operations is not considered when clusters are created by the existing methodologies and the most optimal solution is not guaranteed.

Considering parts process routings in the formation of machine-part families in addition to other production data is more accurate and can produce more independent manufacturing cells with less intercellular moves between them. Yet, exceptional elements must be considered after clusters have been defined.

2.3 Group Technology in the Automotive Lighting Industry

Figure 2.13 illustrates the standard process to make the plastic components of a vehicle lamp.

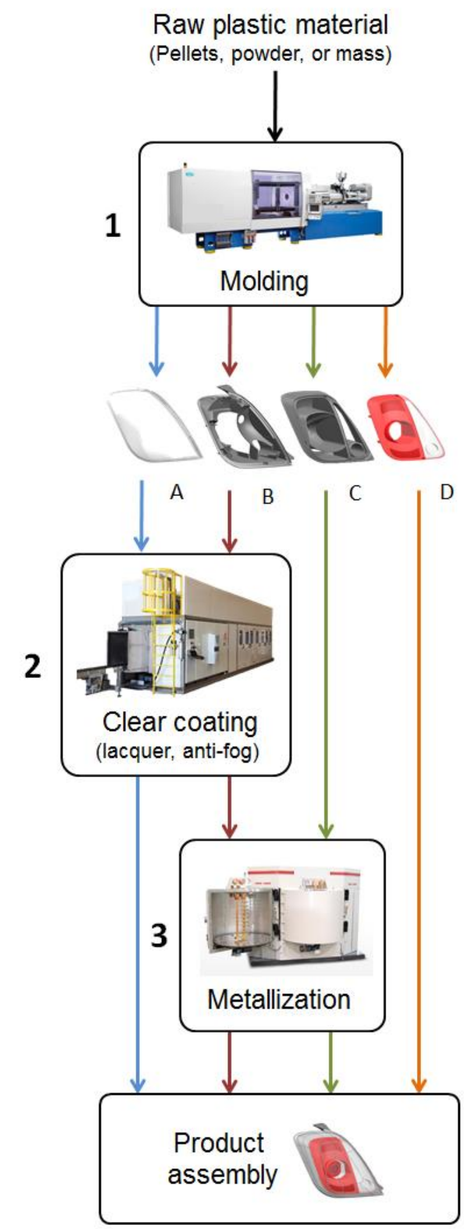


Figure 2.13: Manufacturing process of plastic components for automotive lights

The nature of the current clustering algorithms yield to nonspecific results. As mentioned before, input manufacturing processes are assumed to be order-less. As of today, there are

numerous and more realistic cases of single-process parts which must follow a strict sequence. Truly, components used for automotive lamps are complex and their making process is highly constrained. It is obvious that all parts have to be 'molded' before any other activity can occur. This is the reason why molding is the first action in the sequence. From here, there are four types of components divided according to the processing they require. Components of type A (called this way only explanation purposes) such as headlamp outer lenses need an anti-fog coating before they are completed. Components of type B like reflectors or any other components made of thermoset polymers require a lacquer coating before they are metallized. These represent the most complex parts in terms of manufacturability since they are processed in all the machines. Components of type C 'skip' the coating process and go directly to the metallization process. Parts classified under this type include bezels, frames, and other decorative elements. Lastly, Components of type D are only molded and directly sent to the assembly lines. Outer lens for tail lamps, supports, some bezels, and other non-coated parts are within this category and they represent the most simple parts to make.

It should be noticed that this layout possess characteristics of both job shop and flow shop. In essence, a job shop group together similar equipment such as in this layout where all the machines are located according to their function (molding, hard-coating, metalizing). Indeed grouping is made based on function.

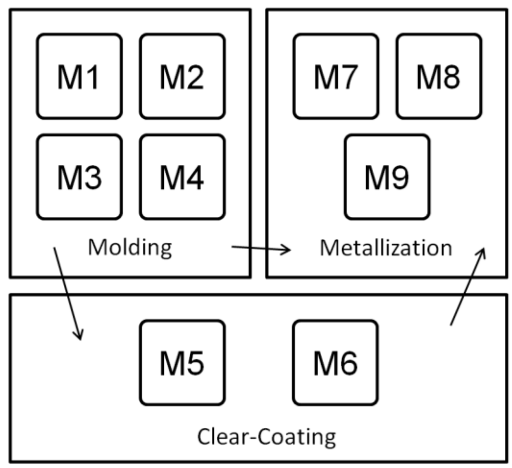


Figure 2.14: Layout arrangement according to job shop concept

On the other hand, a flow shop depends on the sequence of operations to set the machines layout. Grouping is made based on sequence. Here, molding machines go always first, then hard-coating machines and finally metalizing machines.

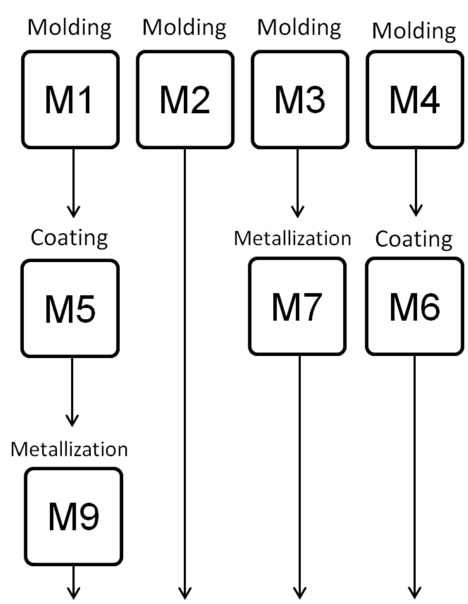


Figure 2.15: Layout arrangement according to flow shop concept

Next, an unarranged layout of a manufacturing facility of automotive lighting systems is presented (Figure 2.16). Undoubtedly, it shares the essence of both job shop and flow shop. It

shows an actual industrial arrangement of machines with their corresponding parts to be manufactured.

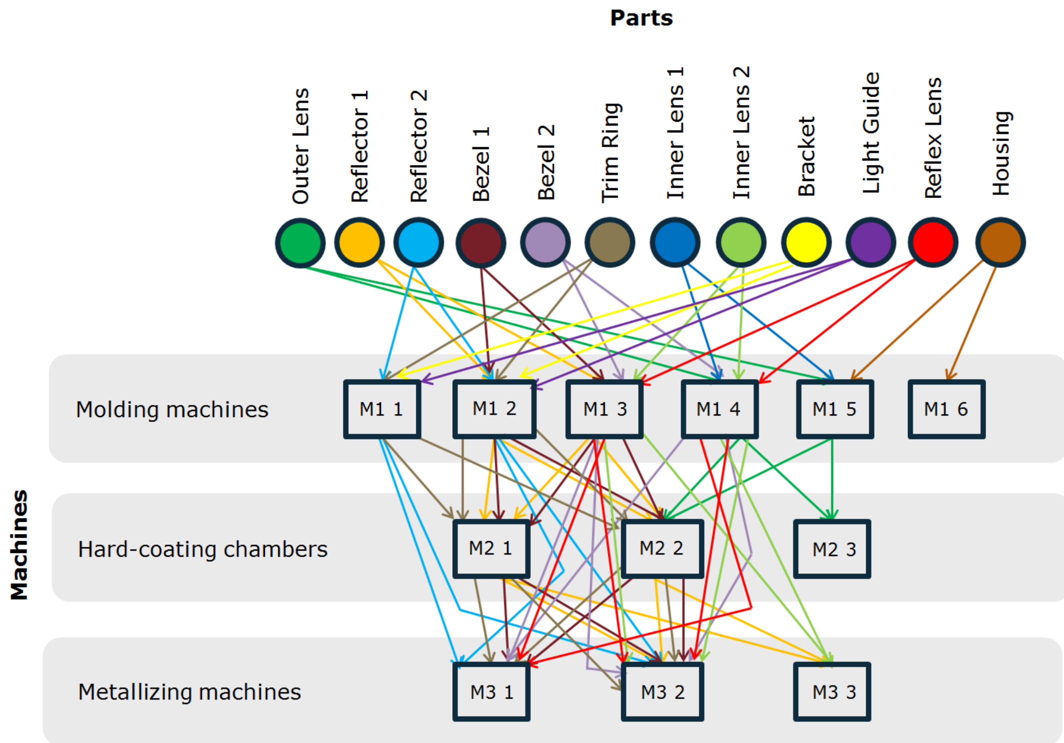


Figure 2.16: Sequence of operations for some parts in an automotive lighting facility

For the give diagram, 12 parts have to be processed in 12 machines (molding, hard-coating, and metalizing) using different sequences. For a distinctive reference, the nomenclature of each machine starts with "M" and it is followed by the order sequence (in this case 1, 2, or 3) and then it is followed by the machine number. Depending on the case, the manufacturing of each part starts with one molding machine. Since all the parts are "molded" plastic parts, all must begin with one option from the 6 molding machines available. At this point, some parts are complete such as the Inner Lens 1, Bracket, Light Guide, and Housing since they do not require any additional treatment. On the other hand, the rest of the parts need to go through further processes like hard-coating and metalizing in order to be finished. It can be noticed that each

part has 2 machine options for each process. It is designed this way to have a higher availability of equipment for all the parts. Moreover, it should be considered that parts must follow a sequence; Molding goes first, then hard-coating (if needed), and lastly metalizing (if needed). Parts cannot be created using a different sequence order. Though, parts can flow from molding machines (sequence order 1) to metallization (sequence order 3).

If the traditional format of matrix formation is used, a machine-part incidence matrix [aij] from the given diagram would look like this:

Machine\Part	Outer lens	Reflector 1	Reflector 2	Bezel 1	Bezel 2	Trim Ring	Inner Lens 1	Inner Lens 2	Bracket	Light Guide	Reflex Lens	Housing
Molding machine 1			1			1			1	1		
Molding machine 2		1	1	1		1			1	1		
Molding machine 3		1		1	1			1			1	
Molding machine 4	1				1		1	1			1	
Molding machine 5	1						1					1
Molding machine 6												1
Hard-coating chamber 1		1		1		1						
Hard-coating chamber 2	1	1		1		1						
Hard-coating chamber 3	1											
Metallizing machine 1			1	1	1	1					1	
Metallizing machine 2		1	1	1	1	1		1			1	
Metallizing machine 3		1						1				

Figure 2.17: Part-machine matrix with 1-0 elements

However, sequence of operations and machine selection (preference) of machines is not considered. Obviously, conducting a clustering process will not obtain a rational solution. For this reason, a fixed order of actions has to be employed in the new matrix.

In addition to a machine sequence, the proposed matrix also introduces non-binary entries. This matrix [aij] consists of 0 (empty), A and B entries, where an entry **A** indicates that machine i is the ideal source of equipment to process part j, entry **B** indicates that machine i is

the alternative option when A is not available, and **0** (empty) specifies that machine *i* cannot be used to process part *j*.

Sequence order	Machine\Part	Outer lens	Reflector 1	Reflector 2	Bezel 1	Bezel 2	Trim Ring	Inner Lens 1	Inner Lens 2	Bracket	Light Guide	Reflex Lens	Housing
1	Molding machine 1			A			A			B	A		
	Molding machine 2		B	B	A		B			A	B		
	Molding machine 3		A		B	A			B			B	
	Molding machine 4	B				B		B	A			A	
	Molding machine 5	A						A					B
	Molding machine 6												A
2	Hard-coating chamber 1		B		A		A						
	Hard-coating chamber 2	B	A		B		B						
	Hard-coating chamber 3	A											
3	Metalizing machine 1			B	A	A	A					B	
	Metalizing machine 2		B	A	B	B	B		B			A	
	Metalizing machine 3		A						A				

Figure 2.18: Proposed part-machine matrix with A-B-0 elements

Reflector 1, for example, has an alternative machine selection in its three manufacturing stages. There are 2 molding machines (M1 3 is preferred), 2 hard-coating chambers (M2 2 is preferred), and 2 metallizing machines (M3 3 is preferred).

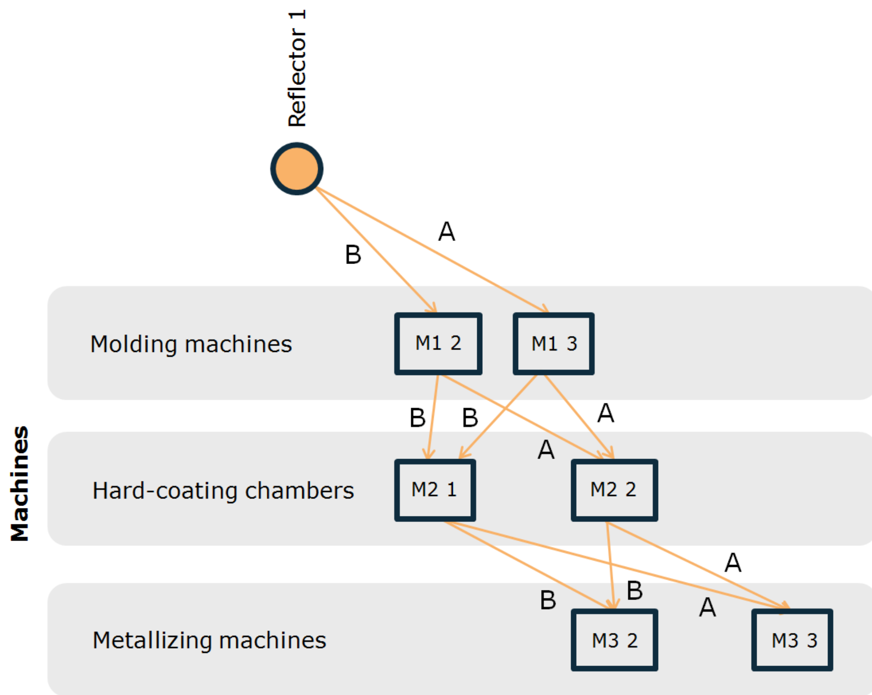


Figure 2.19: Alternative machine selection of one component

Certainly, the nature of this manufacturing set contributed to determine part of the title of this thesis: sequential processes with alternative machine selection.

The difference between the original matrix structure (Figure 2.17) and the proposed part-machine matrix (Figure 2.18) is evident. The new matrix has more constraints but it resembles a more realistic scenario, in particular the automotive lighting industry. Still, this technique can also be applied to different areas. The next step is to conduct the existing algorithms (if possible) using the proposed part-machine matrix. Then, the performance and results of this exercise will help to develop a customized clustering method for this case.

2.3.1 Production Flow Analysis overview

Most of the work that has been done in the cell formation area has its basis in the Production Flow Analysis developed by Burbidge (1971). Basically, there are various stages to conduct this analysis that may be represented by a machine-component matrix. First, machines have to be classified according to their type of operation. Here, machines performing minor and ancillary operations are not considered since it has been proven by experienced users that they only cause distortion. Following, components to be manufactured have to be studied. Process routing and critical characteristics are considered. Then the called *factory flow analysis* is conducted. It basically examines the relationship between machines and components to later decompose into groups. Lastly, machine-component sub groupings are formed to yield a group technology layout. Solving this type of cell formation problem becomes that of manipulating rows and columns of the matrix in order to create a neat diagonal array of groups. Burbidge's original approach was heavily manual but it has been adapted to be solved by means of computer applications. Example illustrated by Figure 2.5 in Section 2.2 was solved by using this type of analysis.

2.3.2 The Single Linkage Cluster analysis method applied to the proposed matrix

Sneath developed the method of single linkage cluster analysis (SLCA) for numerical taxonomy applications first in 1968. Four years later, McAuley used this concept for the grouping problem of the production flow analysis. This method utilizes the computed similarity coefficients of machine pairs to create groupings within the part-machine matrix.

According to McAuley, the similarity coefficient for any pair of machines is defined as "the number of components which visit both machines, divided by the sum of components which

visit one or other of the machines". Certainly, *similarity coefficient* = [*common parts*] / [*total number of parts*]. The similarity coefficient of machine pair M1-M2 from the matrix depicted in Figure 2.20 is 1 / (1 + 2) = 0.33 since there is one common part (P3) and the total number of parts processed in both machines M1 and M2 is 3 (P1, P3, and P6).

Common part

Parts

Machines	P1	P2	P3	P4	P5	P6
M1			1			1
M2	1		1			
M3		1		1		
M4	1		1			1
M5		1		1	1	

Figure 2.20: Similarity between two machines shown in matrix

Next, the similarity coefficients of all the pair combinations of machines within the matrix are calculated (see Appendix I) and tabulated below.

Table 2.2: Similarity coefficients of all machine pair combinations

Machine Pair	M1 M2	M1 M3	M1 M4	M1 M5	M2 M3	M2 M4	M2 M5	M3 M4	M3 M5	M4 M5
Similarity Coefficient	0.33	0	0.66	0	0	0.66	0	0	0.66	0

From the obtained results it is then constructed a dendrogram which is a graphical representation of the similarities between machines. The points of convergence between two branches (projected to the left scale) in this tree-shape graph denote the degree of similarity between the two machines at the bottom.

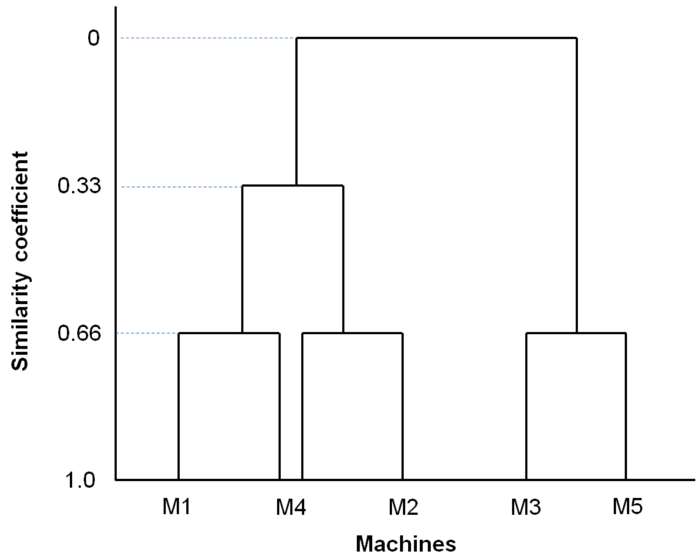


Figure 2.21: Dendrogram illustrating the arrangement of clusters produced by SLCA

Machines involved in different pairings with different similarity coefficients are dominated by the higher coefficients. For instance, machine pair M1-M2 with a similarity coefficient of 0.33 is overlapped by pairings M1-M4 and M2-M4 which have a higher similarity of 0.66. As a result, pairs M1-M4 and M2-M4 form a single group since have one machine in common (M4). M3-M5 represent another group. Final result then divides the machines into two groups M1-M4-M2 and M3-M5.

Similarity coefficient = 0.66

Parts

Machines	P2	P4	P5	P3	P1	P6
M5	1	1	1			
M3	1	1				
M4				1	1	1
M2				1	1	
M1				1		1

Similarity coefficient = 0.66

Figure 2.22: Cells created according to similarity coefficients

The level of difficulty to construct a dendrogram increases proportionally to the number of machines and parts. Thus, for larger problems the use of Jaccards similarity coefficient method, Ross's Minimum Spanning Trees (MST) or other alternative methods is necessary.

If SLCA is conducted using the proposed part-machine matrix (Figure 2.18), the following similarity relationships are resulted (see Appendix II):

Machines	Machines											
	Mol 1	Mol 2	Mol 3	Mol 4	Mol 5	Mol 6	Coa 1	Coa 2	Coa 3	Met 1	Met 2	Met 3
Mol 1	0	0.666	0	0	0	0	0.166	0.142	0	0.666	0.222	0
Mol 2		0	0.222	0	0	0	0.5	0.429	0	0.375	0.444	0.125
Mol 3			0	0.429	0	0	0.333	0.286	0	0.429	0.714	0.4
Mol 4				0	0.333	0	0	0.125	0.2	0.25	0.333	0.166
Mol 5					0	0.333	0	0.166	0.333	0	0	0
Mol 6						0	0	0	0	0	0	0
Coa 1							0	0.75	0	0.333	0.429	0.25
Coa 2								0	0.25	0.286	0.375	0.2
Coa 3									0	0	0	0
Met 1										0	0.714	0
Met 2											0	0.286
Met 3												0

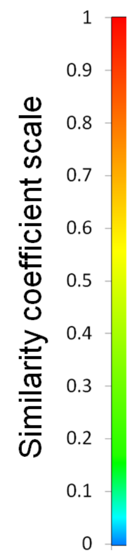


Figure 2.23: Similarity coefficient relationships between all machines

In this case, it can be noticed that some parts have a 75%-similarity (Coating machine 1 & 2) and many other are simply not related to each other (0%-similarity).

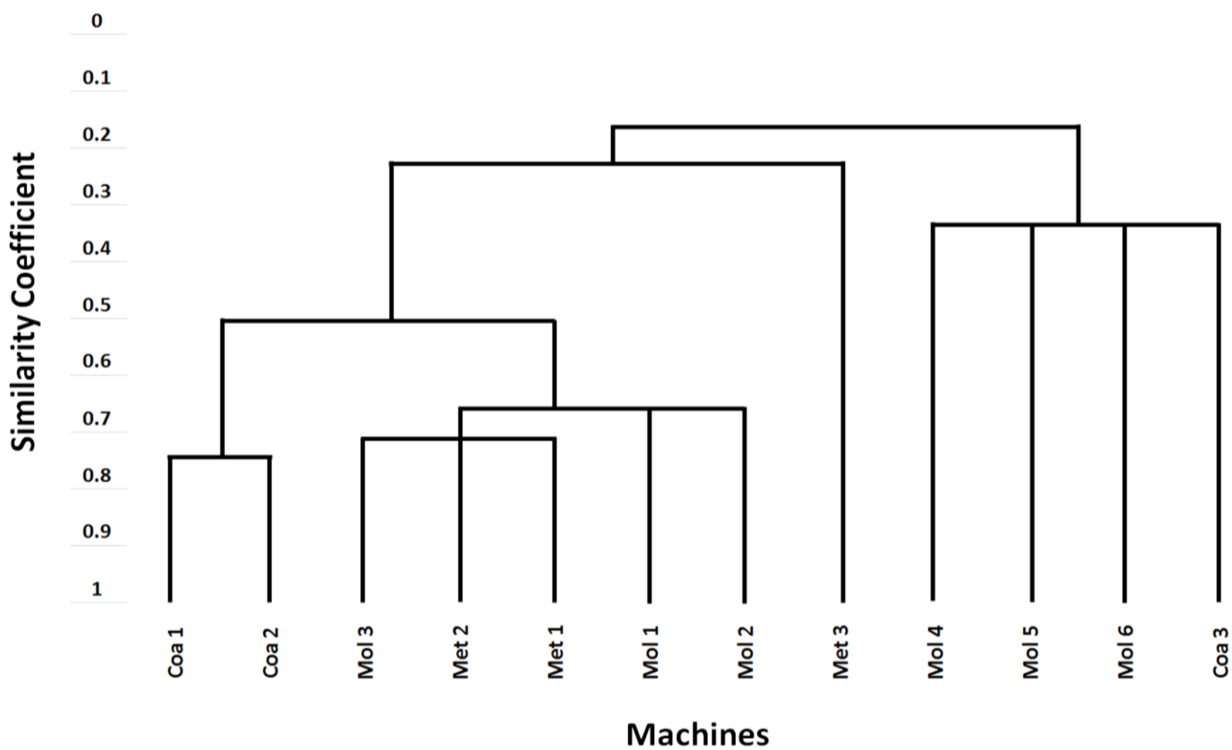


Figure 2.24: Dendrogram obtained from applying the SLCA to the proposed part-machine matrix

The major disadvantage of SLCA is the problem called chaining. In chaining, two groups are tied together merely because two machines (one in each group) are related. Consequently, a few or even a single big cluster is generated including machines that may have low similarity among them.

Although this algorithm provides different alternatives for grouping based on the similarity coefficient, it is not guaranteed that all parts would be processed in a single machine cell implying intercellular transportation. Part families are not determined neither and it is difficult to assign the components to the created clusters.

non-exclusive part "family" of Machine Cell 1

non-exclusive part "family" of Machine Cell 2

Cell	Machine\Part	Outer lens	Reflector 1	Trim Ring	Bezel 1	Inner Lens 2	Reflex Lens	Bezel 2	Reflector 2	Bracket	Light Guide	Inner Lens 1	Housing
Machine cell 1 SC = 75%	Hard-coating chamber 1		B	A	A								
	Hard-coating chamber 2	B	A	B	B								
Machine cell 2 SC = 71.4%	Molding machine 3		A		B	B	B	A					
	Metallizing machine 2		B	B	B	B	A	B	A				
	Metallizing machine 1			A	A		B	A	B				
	Molding machine 1			A					A	B	A		
	Molding machine 2		B	B	A				B	A	B		
	Metallizing machine 3		A			A							
	Molding machine 4	B				A	A	B				B	
	Molding machine 5	A										A	B
	Molding machine 6												A
	Hard-coating chamber 3	A											

Figure 2.25: Rearranged matrix considering clusters with similarity coefficients of 70% or more

2.3.3 The Bond Energy method applied to the proposed matrix

McCormick first developed the Bond Energy Algorithm (BEA) for the production flow analysis. Basically, it finds the strongest 'bonds' between the elements in a part-machine matrix. A bond between a pair of two adjacent elements exists as a product of them. In other words, the bond energy is generated by multiplying the neighbor elements within the matrix in a predefined horizontal or vertical mode. The following alternatives of product are possible:

Adjacent row elements x_{ij}, $x_{i,j+1}$

Alternative	x_{ij}	$x_{i,j+1}$	Bond energy
a	0	0	0
b	0	1	0
c	1	0	0
d	1	1	1

Adjacent column elements xij, xi+1,j

Alternative	x_{ij}	$X_{i-1,j}$	Bond energy
a	0	0	0
b	0	1	0
c	1	0	0
d	1	1	1

In this method, rows and columns must be manipulated to attain 'positive' products and therefore a higher total bond energy. Results depend on how the elements within the part-machine matrix are disposed and thus the most optimal solution is the one with the maximum total bond energy. McCormick's algorithm is as follows:

Step 1. Place one of the columns randomly. Set i = 1.

Step 2. Iterate by placing individually each of the N-i columns in each of the i + 1 possible positions and compute each column's contribution to the total bond energy. Rearrange the columns such that the total bond energy is maximized. Increment i by 1 and repeat until i = N (N being the total number of columns)

Step 3. Repeat procedure on Step 2 with the rows (replace N with M, being the total number of rows)

Following, matrix from Figure 2.26 is used to determine a grouping result using the BEA.

Parts

Machines	P1	P2	P3	P4	P5	P6	Bond Energy (Row)
M1			1			1	
M2	1		1				
M3		1		1			
M4	1		1			1	
M5		1		1	1		1
Bond Energy (Column)			1				Total Bond Energy: 2

Figure 2.26: Adjacent elements contributing to total bond energy

Evidently, the unarranged elements of the original matrix lead to a low bond energy value. Parts and machines have to be manipulated several times until the highest total bond energy is attained. Figure 2.27 shows the optimized solution to this problem.

Parts

Machines	P2	P4	P5	P6	P3	P1	Bond Energy (Row)
M5	1	1	1				2
M3	1	1					1
M4				1	1	1	2
M2					1	1	1
M1				1	1		1
Bond Energy (Column)	1	1			2	1	Total Bond Energy: 12

Figure 2.27: SLCA Optimal solution

A benefit of this method is its independence to the initial decision of the algorithm. This becomes highly advantageous for inexperienced users dealing with this type of data. The bond energy algorithm guarantees the formation of tight-knit groups and, if they exist, mutually exclusive clusters along the diagonal of the part-machine matrix.

Next, the SLCA is conducted using the proposed part-machine matrix.

Machine\Part	Outer lens	Reflector 1	Reflector 2	Bezel 1	Bezel 2	Trim Ring	Inner Lens 1	Inner Lens 2	Bracket	Light Guide	Reflex Lens	Housing	Bond Energy (row)
Molding machine 1			A			A			B	A			1
Molding machine 2		B	B	A		B			A	B			3
Molding machine 3		A		B	A			B			B		1
Molding machine 4	B				B		B	A			A		1
Molding machine 5	A						A					B	
Molding machine 6												A	
Hard-coating chamber 1		B		A		A							
Hard-coating chamber 2	B	A		B		B							1
Hard-coating chamber 3	A												
Metallizing machine 1			B	A	A	A					B		3
Metallizing machine 2		B	A	B	B	B		B			A		4
Metallizing machine 3		A						A					
Bond Energy (column)	2	3	2	3	2	3	1	2	1	1	2	1	37 Total BE

Figure 2.28: Unarranged part-machine matrix with corresponding BE values

Machine\Part	Bracket	Light Guide	Reflector 2	Trim Ring	Bezel 1	Reflector 1	Inner Lens 2	Bezel 2	Reflex Lens	Outer lens	Inner Lens 1	Housing	Bond Energy (row)
Molding machine 1	B	A	A	A									3
Molding machine 2	A	B	B	B	A	B							5
Metallizing machine 2			A	B	B	B	B	B	A				6
Metallizing machine 1			B	A	A			A	B				3
Hard-coating chamber 1				A	A	B							2
Hard-coating chamber 2				B	B	A				B			2
Metallizing machine 3						A	A						1
Molding machine 3					B	A	B	A	B				4
Molding machine 4							A	B	A	B	B		4
Molding machine 5										A	A	B	2
Molding machine 6												A	
Hard-coating chamber 3										A			
Bond Energy (column)	1	1	3	5	4	4	2	2	2	1	1	1	**59** Total BE

Figure 2.29: Rearranged part-machine matrix set to maximize total BE

Two possible clusters are created by using the BE method. Evidently, three B-elements are excluded from the groupings. However, this situation is acceptable since B-elements are the

machine alternatives when A's are not available. Result has to be evaluated by comparing the performance indicators before and after this exercise was conducted.

2.3.4 Rank Order Clustering applied to proposed part-machine matrix

The development of the Rank Order Clustering (ROC) method is attributed to King (1980).

ROC algorithm steps:

Step 1. For each row of the given part-machine matrix compute the decimal equivalent by reading the entries as binary words. Sort the rows in decreasing order (higher values on top). Rows with the same value should keep the original order.

Step 2. For each column of the given part-machine matrix compute the decimal equivalent by reading the entries as binary words. Sort the columns in decreasing order (higher values on left). Columns with the same value should keep the original order.

Step 3. Stop.

The initial arrangement of machines and parts do not affect the final answer since the process is iterative and sorts the rows and columns in a decreasing order. The result again is pictured as a diagonal array of 1-elements.

Figure 2.30 show the initial part-machine matrix with their equivalent decimal values.

Binary weights

Machines	P1 (2^5)	P2 (2^4)	P3 (2^3)	P4 (2^2)	P5 (2^1)	P6 (2^0)	Decimal value	Rank order
M1			1			1	9	5
M2	1		1				40	2
M3		1		1			20	4
M4	1		1			1	41	1
M5		1		1	1		22	3

Figure 2.30: Initial part-machine matrix with corresponding row decimal values

Following, rows are sorted based on their rank order and the decimal values of columns are computed, too.

Binary weights	Machines	P1	P2	P3	P4	P5	P6	Decimal value	Rank order
2^4	M4	1		1			1	41	1
2^3	M2	1		1				40	2
2^2	M5		1		1	1		22	3
2^1	M3		1		1			20	4
2^0	M1			1			1	9	5
	Decimal value	24	6	25	6	4	16		
	Rank order	2	4	1	5	6	3		

Figure 2.31: Part-machine matrix after sorting rows

Columns are now reorganized based on their rank order.

Parts

Machines	P3	P1	P6	P2	P4	P5
M4	1	1	1			
M2	1	1				
M5				1	1	1
M3				1	1	
M1	1		1			
Decimal value	25	24	16	6	6	4
Rank order	1	2	3	4	5	6

Figure 2.32: Part-machine matrix after sorting columns

Again, decimal values of rows are calculated and ranked. It can be seen that different values are obtained from initial part-machine matrix (Figure 2.31).

Binary weights

	2^5	2^4	2^3	2^2	2^1	2^0		
Machines	**Parts**							
	P3	P1	P6	P2	P4	P5	Decimal value	Rank order
M4	1	1	1				56	1
M2	1	1					48	2
M5				1	1	1	7	4
M3				1	1		6	5
M1	1		1				40	3

Figure 2.33: Recalculation of row decimal values

Lastly, clusters are determined by including related part and machines (element 1-intersections). Figure 2.34 below shows the mutually exclusive cells.

Machines \ Parts	P3	P1	P6	P2	P4	P5	Decimal value	Rank order
M4	1	1	1				56	1
M2	1	1					48	2
M1	1		1				40	3
M5				1	1	1	7	4
M3				1	1		6	5

Figure 2.34: Final part-machine matrix after sorting rows

Subsequently, ROC is used to determine a result using the proposed part-machine matrix.

Binary weights

Machine\Part	Outer lens	Reflector 1	Reflector 2	Bezel 1	Bezel 2	Trim Ring	Inner Lens 1	Inner Lens 2	Bracket	Light Guide	Reflex Lens	Housing	Decimal value	Rank order
	2^{11}	2^{10}	2^{9}	2^{8}	2^{7}	2^{6}	2^{5}	2^{4}	2^{3}	2^{2}	2^{1}	2^{0}		
Hard-coating chamber 2	B	A		B		B							3,392	1
Molding machine 4	B				B		B	A			A		2,226	2
Molding machine 5	A						A					B	2,081	3
Hard-coating chamber 3	A												2,048	4
Metallizing machine 2		B	A	B	B	B		B			A		2,002	5
Molding machine 2		B	B	A		B			A	B			1,868	6
Molding machine 3		A		B	A			B			B		1,426	7
Hard-coating chamber 1		B		A		A							1,344	8
Metallizing machine 3		A						A					1,040	9
Metallizing machine 1			B	A	A	A					B		962	10
Molding machine 1			A			A			B	A			588	11
Molding machine 6												A	1	12

Figure 2.35: Part-machine matrix after sorting rows

Machine\Part	Outer lens	Reflector 1	Bezel 1	Trim Ring	Inner Lens 1	Inner Lens 2	Bezel 2	Reflex Lens	Housing	Reflector 2	Bracket	Light Guide	Binary weights
Hard-coating chamber 2	B	A	B	B									2^0
Molding machine 4	B				B	A	B	A					2^1
Molding machine 5	A				A				B				2^2
Hard-coating chamber 3	A												2^3
Metallizing machine 2		B	B	B		B	B	A		A			2^4
Molding machine 2		B	A	B						B	A	B	2^5
Molding machine 3		A	B			B	A	B					2^6
Hard-coating chamber 1		B	A	A									2^7
Metallizing machine 3		A				A							2^8
Metallizing machine 1			A	A			A	B		B			2^9
Molding machine 1				A						A	B	A	2^{10}
Molding machine 6									A				2^{11}
Decimal value	3,840	2,296	2,292	2,262	1,536	1,192	1,188	1,188	513	198	66	66	
Rank order	1	2	3	4	5	6	7	7	8	9	10	10	

Figure 2.36: Part-machine matrix after sorting columns

Machine\Part	Outer lens	Reflector 1	Bezel 1	Trim Ring	Inner Lens 1	Inner Lens 2	Bezel 2	Reflex Lens	Housing	Reflector 2	Bracket	Light Guide	Decimal value	Rank order
Hard-coating chamber 2	B	A	B	B									3840	1
Molding machine 4	B				B	A	B	A					2288	2
Molding machine 5	A				A				B				2184	3
Hard-coating chamber 3	A												2048	4
Metallizing machine 2		B	B	B		B	B	A		A			1908	5
Molding machine 2		B	A	B						B	A	B	1799	6
Hard-coating chamber 1		B	A	A									1792	7
Molding machine 3		A	B			B	A	B					1648	8
Metallizing machine 3		A				A							1088	9
Metallizing machine 1			A	A			A	B		B			820	10
Molding machine 1				A						A	B	A	263	11
Molding machine 6									A				8	12

Figure 2.37: Part-machine matrix after sorting rows

Performance of ROC is not suitable for this type of matrix and therefore is discarded.

2.3.5 Cluster Identification Algorithm applied to proposed part-machine matrix

The Cluster Identification Algorithm (CIA) was developed by Kusiak and Chow (1987) based on the concept generated by Iri (1968).

Algorithm steps:

Step 0: Set iteration number $k = 1$

Step 1: Select any row i of the incidence matrix $A^{(k)}$ (where $A^{(k)}$ denotes matrix A at iteration k) and draw a horizontal line h_i through it.

Step 2: For each entry 1 on the intersection with the horizontal line h_i, draw a vertical line v_j.

Step 3: For each entry 1 crossed by the vertical line v_j, draw a horizontal line h_l.

Step 4: Repeat steps 2 and 3 until no crossed-once entries 1 are left. All crossed-twice entries 1 form a cluster *O-k* and *F-k*.

Step5: Transform the incidence matrix A^k into $A^{(k+1)}$ by removing all the crossed-twice entries 1.

Step 6: If matrix $A^{(k+1)} = \mathbf{0}$ ($\mathbf{0}$ denotes matrix with all elements equal to zero), stop; otherwise, set $k = k + 1$ and go to Step 1.

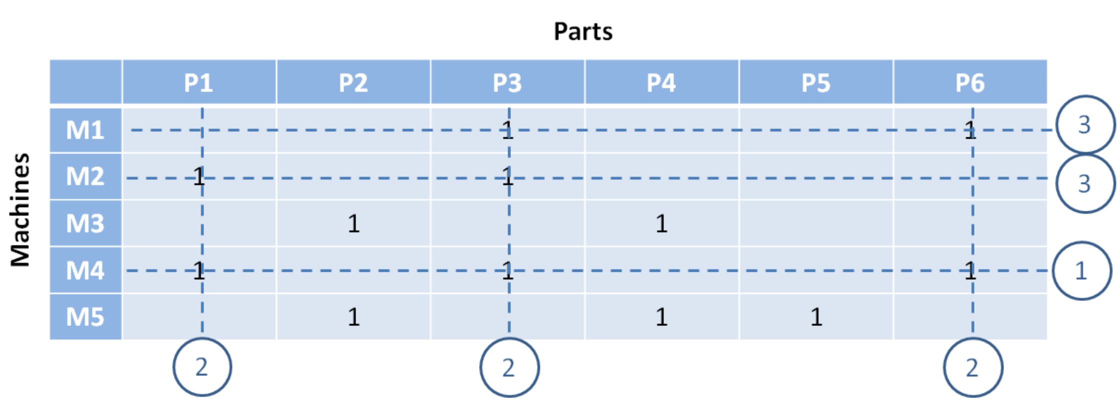


Figure 2.38: CIA Iteration 1

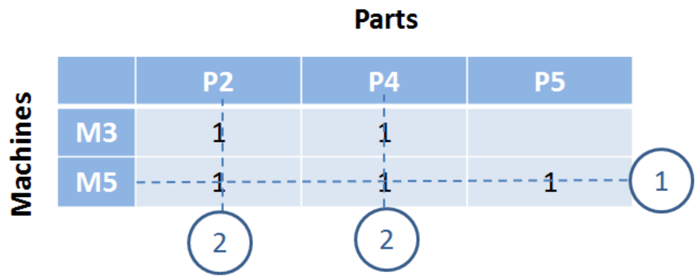


Figure 2.39: CIA Iteration 2

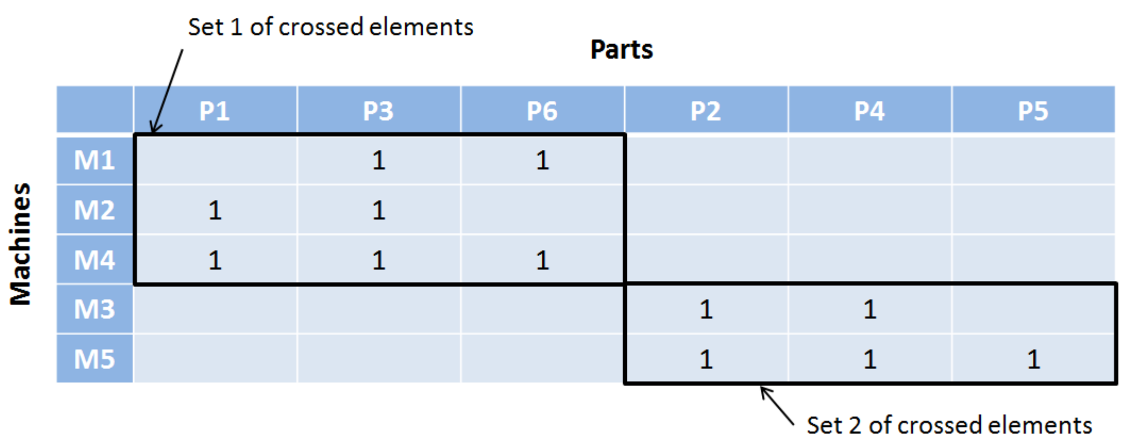


Figure 2.40: CIA mutually exclusive clusters

The Cluster Identification Algorithm scans every entry 1 of the matrix A exactly twice and for this reason its computational time complexity is $O(2mn)$. Conducting the CIA using the proposed part-machine matrix results in Figure 2.41.

Sequence order	Machine\Part	Outer lens	Reflector 1	Reflector 2	Bezel 1	Bezel 2	Trim Ring	Inner Lens 1	Inner Lens 2	Bracket	Light Guide	Reflex Lens	Housing
1	Molding machine 1			A			A			B	A		
	Molding machine 2		B	B	A		B			A	B		
	Molding machine 3		A		B	A			B			B	
	Molding machine 4	B				B		B	A			A	
	Molding machine 5	A						A					B
	Molding machine 6												A
2	Hard-coating chamber 1		B		A		A						
	Hard-coating chamber 2	B	A		B		B						
	Hard-coating chamber 3	A											
3	Metalizing machine 1			B	A	A	A					B	
	Metalizing machine 2		B	A	B	B	B		B			A	
	Metalizing machine 3		A						A				

Figure 2.41: CIA performed on proposed part-machine matrix

As a result of applying Kusiak's method, horizontal and vertical lines are drawn through the single-crossed elements which eventually become double-crossed elements. Clearly, all entries of matrix are "connected" and the final result do not form machine cells nor part families. Further work has to be done in order to obtain mutually separable sub matrices.

2.3.6 Extended Cluster Identification Algorithm applied to proposed part-machine matrix

The extended CIA is derived from the original method and utilizes the user's input to make decisions. In other words, the algorithm is manipulated based on the user expertise in the field. This allows to set constraints and initial conditions in the environment to be analyzed avoiding the result to depend merely in the algorithm computation.

If extended CIA is applied to the example matrix, a different result is therefore obtained. It is assumed that the user defines the condition of having at least one machine of each type per cell. In this case, the smaller manufacturing cell would have three machines (1 for molding, 1

for coating, and 1 for metallizing). If the algorithm is conducted as indicated by Kusiak, the conceptual layout of the manufacturing system is shown below. It can be seen that the machine cells and part families generated are not satisfactory, requiring further work for a better result.

			PF-1		PF-2	Functional machining facility								
	Sequence order	Machine\Part	Bracket	Light Guide	Housing	Reflector 2	Trim Ring	Reflector 1	Bezel 1	Bezel 2	Inner Lens 2	Reflex Lens	Outer lens	Inner Lens 1
MC-1	1	Molding machine 1	B	A		A	A							
	1	Molding machine 2	A	B		B	B	B	A					
	2	Hard-coating chamber 1					A	B	A					
	3	Metalizing machine 2				A	B	B	B	B	B	A		
MC-2	1	Molding machine 3						A	B	A	B	B		
	1	Molding machine 4								B	A	A	B	B
	2	Hard-coating chamber 3											A	
	3	Metalizing machine 1				B	A		A	A		B		
MC-3	1	Molding machine 5			B								A	A
	1	Molding machine 6			A									
	2	Hard-coating chamber 2					B	A	B				B	
	3	Metalizing machine 3						A			A			

Figure 2.42: Extended CIA matrix result

Although the data for this method can be manipulated based on the user's preference and knowledge on the field, an optimal result does not embrace the essence of Group Technology. Also, a functional machining facility is not the best option when cost and layout space are key factors of the problems. A functional facility implies placing at least 2 equal machines of a specific type to meet the productivity requirements.

2.3.7 Specialized Software

Students from the University of Texas at El Paso developed a software able to solve CI algorithm problems. Figure 2.43 shows the input values as it is seen using this program.

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
C1			X			X			X	X		
C2		X	X	X		X			X	X		
C3		X		X	X			X			X	
C4	X				X		X	X			X	
C5	X						X					X
C6												X
C7		X		X		X						
C8	X	X		X		X						
C9	X											
C10			X	X	X	X					X	
C11		X	X	X	X	X		X			X	
C12		X						X				

Figure 2.43: Binary input values in matrix

	A3	A6	A9	A10	A2	A4	A5	A8	A11	A1	A7	A12
C1	X	X	X	X								
C2	X	X	X	X	X	X						
C7		X			X	X						
C8		X			X	X				X		
C10	X	X				X	X		X			
C11	X	X			X	X	X	X	X			
C3					X	X	X	X	X			
C4							X	X	X	X	X	
C12					X			X				
C5										X	X	X
C6												X
C9										X		

Figure 2.44: Result conducted by software

Results were not as desired since the input (X) cannot be classified with priority (as A & B).

		A3	A6	A9	A10	A2	A4	A5	A8	A11	A1	A7	A12
	Machine\Part	Reflector 2	Trim Ring	Bracket	Light Guide	Reflector 1	Bezel 1	Bezel 2	Inner Lens 2	Reflex Lens	Outer lens	Inner Lens 1	Housing
C1	Molding machine 1	A	A	B	A								
C2	Molding machine 2	B	B	A	B	B	A						
C7	Hard-coating chamber 1		A			B	A						
C8	Hard-coating chamber 2		B			A	B				B		
C10	Metalizing machine 1	B	A				A	A		B			
C11	Metalizing machine 2	A	B			B	B	B	B	A			
C3	Molding machine 3					A	B	A	B	B			
C4	Molding machine 4							B	A	A	B	B	
C12	Metalizing machine 3					A			A				
C5	Molding machine 5										A	A	B
C6	Molding machine 6												A
C9	Hard-coating chamber 3										A		

Figure 2.45: Resulting matrix with A-B equivalent values

2.4 Results

In the context of the automotive lighting industry, the participation of skilled and experienced users is still mandatory during the planning and management processes. Unfortunately, the present clustering methods have demonstrated to be non-practical and highly empirical to be effectively used in this field. Moreover, the lack of machines sequence order does not permit to appropriately deal with exclusive elements. In other words, the almost-always existing intercellular transportation of parts cannot be controlled. An alternative selection of machines available for parts processing is not considered neither. Based on this findings, next chapter defines a customized cell formation algorithm adapted to the standing constraints and able to generate feasible solutions.

Chapter 3: Methodology

3.1 Proposed Cell Formation Algorithm

The study and analysis of existing clustering methods show that these cannot be effectively applied to a part-machine matrix composed of sequential processes with an alternative machine selection. A clustering algorithm that transforms an initial incidence matrix into a more structured (possibly block diagonal) form is expected. Therefore, a modified procedure is proposed to achieve better and even optimal solutions.

Before a new procedure can be developed, several rules must be considered:

▪ First, all parts (columns) have one **A** and one **B** machine options (rows) for its manufacturability. Entry **A** indicates the ideal source of equipment to process a part, entry **B** indicates the alternative option when A is not available. This applies to each process type (in this case molding, coating, and metallizing) if it is required by the part.

▪ When a machine *i* is considered to be added to a machine cell, at least 50% of the parts processed by this machine must be common to the other machines within this cell.

▪ All entries **A** must be assigned to at least one machine cell; entries **A** should not be excluded from machine cells or functional machining cells (if existing). Thus, rows and columns with **A**-intersections must be included in the target cell. In contrast, entries **B** can be left outside of the manufacturing cells.

Now that these rules have been defined, the algorithm steps are stated as follows:

Step 1. Begin with the incidence matrix taking into consideration the *s sequence order* machines only.

Step 2. Set i = iteration+1. Calculate a vector e_m which counts the number of entries (A=2, B=1) in the incidence matrix for each machine (row) and find the maximum of the elements of vector e_m. If there are more than one maximum elements, select the machine (row) with more A-entries. This machine is the first element of the machine cell c.

Step 3. Calculate the *percentage of parts shared* (P_{pm}) between the machine(s) in cell c and all other machines. This is computed by dividing the parts that are common by the total number of parts processed by each machine (use values of A=2 and B=1 of the machine being compared).

Step 4. Select the machine with more than 50 % *of parts shared* ($P_{pm} \geq 0.5$). If there are more than one, select the machine with the higher P_{pm}. Add this machine to machine cell c.

Step 5. Repeat process starting from Step 3. If no change follows, then close the manufacturing cell c.

Step 6. Rearrange the selected machines within the closed manufacturing cell c with their corresponding parts (columns) in the top left most part of the incidence matrix as best as possible (it becomes more difficult as *sequence order* increases). Only columns (parts) with A-intersections must be included in the target cell. Machines in closed manufacturing cells are not considered for subsequent iterations.

Step 7. Repeat process starting from Step 2. If no change follows, then repeat process starting from Step 1. If no change follows, then STOP.

Next in Figure 3.1, a flow chart illustrates the process steps of the proposed algorithm:

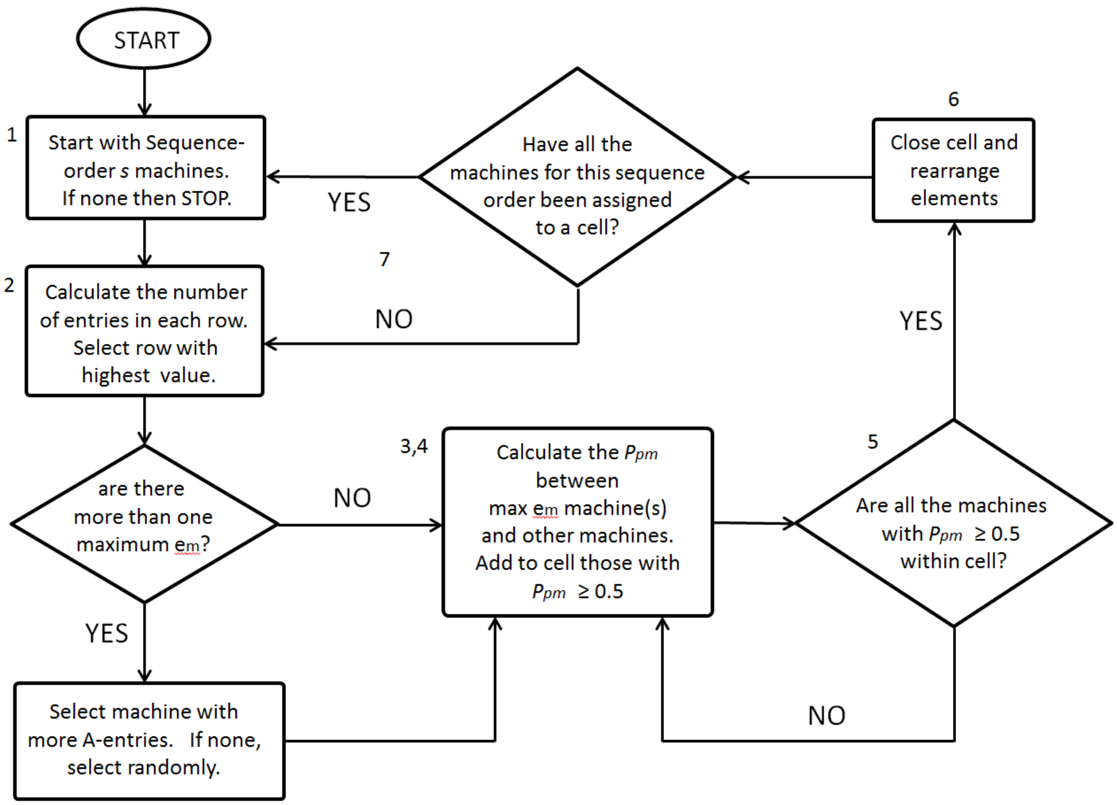


Figure 3.1: Flow chart of proposed cell formation algorithm

3.1.1 Example 1

The succeeding example gives a better insight of how the suggested method performs using the previously proposed part-machine incidence matrix.

Step 1. Begin with the incidence matrix taking into consideration the *sequence order* **1** machines only. In this case, the molding machines only.

Sequence Order	Machine\Part	Outer lens	Reflector 1	Reflector 2	Bezel 1	Bezel 2	Trim Ring	Inner Lens 1	Inner Lens 2	Bracket	Light Guide	Reflex Lens	Housing
1	Molding machine 1			A			A			B	A		
	Molding machine 2		B	B	A		B			A	B		
	Molding machine 3		A		B	A			B			B	
	Molding machine 4	B				B		B	A			A	
	Molding machine 5	A						A					B
	Molding machine 6												A
2	Hard-coating chamber 1		B		A		A						
	Hard-coating chamber 2	B	A		B		B						
	Hard-coating chamber 3	A											
3	Metallizing machine 1			B	A	A	A					B	
	Metallizing machine 2		B	A	B	B	B		B			A	
	Metallizing machine 3		A						A				

Figure 3.2: Machines of sequence order 1

Iteration 1

Step 2. Calculate a vector e_m which counts the number of entries (A=2, B=1) in the incidence matrix for each machine (row) and find the maximum of the elements of vector e_m. In this case, molding machine 2 has $\max(e_m) = 8$. This machine is the first element of the machine cell 1.

$$e_m: [7\ 8\ 7\ 7\ 5\ 2]$$

$$\max(e_m) = 8$$

Sequence Order	Machine\Part	Outer lens	Reflector 1	Reflector 2	Bezel 1	Bezel 2	Trim Ring	Inner Lens 1	Inner Lens 2	Bracket	Light Guide	Reflex Lens	Housing	e_m
1	Molding machine 1			A			A			B	A			7
	Molding machine 2		B	B	A		B			A	B			8
	Molding machine 3		A		B	A			B			B		7
	Molding machine 4	B				B		B	A			A		7
	Molding machine 5	A						A					B	5
	Molding machine 6												A	2

Figure 3.3: Computations of number of entries A-B of each machine

Step 3. Calculate the *percentage of parts shared* (P_{pm}) between the molding machine 2 and all other machines of *sequence order* 1. This is computed by dividing the parts that are common by

the total number of parts processed by each machine (use values of A=2 and B=1 of the machine being compared).

Molding machine	**1**	**2**	**3**	**4**	**5**	**6**
P_{pm}	7/7		3/7	0/7	0/5	0/2

Contrary to the SLCA *similarity*, the *percentage of parts shared* focus on the fraction of the total number of parts to be processed by one machine and that is common to other machine instead of calculating the total resemblance between both machines.

<u>Step 4</u>. Select the machine with more than 50 % *of parts shared* (P_{pm} ≥ 0.5). In this case, only molding machine 1 has P_{pm} $= 7/7 = 1 \geq 0.5$. Hence, molding machine 1 is added to cell 1.

Sequence Order	Machine\Part	Outer lens	Reflector 1	Reflector 2	Bezel 1	Bezel 2	Trim Ring	Inner Lens 1	Inner Lens 2	Bracket	Light Guide	Reflex Lens	Housing
1	Molding machine 1			A			A			B	A		
	Molding machine 2		B	B	A		B			A	B		
	Molding machine 3		A		B	A			B			B	
	Molding machine 4	B				B		B	A			A	
	Molding machine 5	A						A					B
	Molding machine 6												A

Figure 3.4: Molding machine 1 with a P_{pm} ≥ 0.5 with respect to machine 2

<u>Step 5</u>. Repeat process starting from Step 3.

<u>Step 3</u>. The *percentage of parts shared* (P_{pm}) between the molding machine 1 and all other machines of *sequence order* 1 is calculated. Subsequently, the 'cumulative' *percentage of parts shared* (P_{pm}) between the molding machine 1-and-2 and all other machines of *sequence order* 1

is calculated. This cumulative *Ppm* represents the comparison of the molding machines within the cell (1 and 2) and the rest of the machines.

Molding machine	1	2	3	4	5	6
Ppm between machine 1 and others			0/7	0/7	0/5	0/2
Ppm between machine 1-and-2 and others (Cumulative *Ppm*)			3/7	0/7	0/5	0/2

Step 4. Since there are no more machines with more than 50 % *of parts shared* (*Ppm* ≥ 0.5) then proceed to next step.

Step 5. No change takes places by repeating step 3 then the manufacturing cell 1 is closed.

Step 6. Rearrange the selected machines (1 and 2) within the closed manufacturing cell 1 with their corresponding parts in the top left most part of the incidence matrix as best as possible. Only parts (columns) with A-intersections must be included in the target cell. Indeed, *Reflector 1* is not added to this cell because it only has a B-intersection.

Sequence Order	Machine\Part	Reflector 2	Trim Ring	Light Guide	Bracket	Bezel 1	Reflector 1	Outer lens	Bezel 2	Inner Lens 1	Inner Lens 2	Reflex Lens	Housing
1	Molding machine 1	A	A	A	B								
	Molding machine 2	B	B	B	A	A	B						
	Molding machine 3					B	A		A		B	B	
	Molding machine 4							B	B	B	A	A	
	Molding machine 5							A		A			B
	Molding machine 6												A

Figure 3.5: Closed manufacturing cell 1

End of Iteration 1 results in the formation of:

Machine cell MC-1 = {molding machine 1, molding machine 2}

Part group PG-1 = {Reflector 1, Trim Ring, Light Guide, Bracket, Bezel 1}

Molding machines 1 and 2 in manufacturing cell 1 are not considered for subsequent steps.

Step 7. Repeat process starting from Step 2.

Iteration 2

Step 2. Calculate a vector e_m which counts the number of entries (A=2, B=1) in the incidence matrix for the rest of the machines (rows) and find the maximum of the elements of vector e_m. Since there are more than one maximum elements (e_m = 7 for molding machines 3 and 4), machine 3 is selected randomly. This machine is the first element of the machine cell 2.

e_m: [7 7 5 2]
max(e_m) = 7

Sequence Order	Machine\Part	Reflector 2	Trim Ring	Light Guide	Bracket	Bezel 1	Reflector 1	Outer lens	Bezel 2	Inner Lens 1	Inner Lens 2	Reflex Lens	Housing	e_m
1	Molding machine 1	A	A	A	B									7
	Molding machine 2	B	B	B	A	A	B							8
	Molding machine 3					B	A		A		B	B		7
	Molding machine 4							B	B	B	A	A		7
	Molding machine 5							A		A			B	5
	Molding machine 6												A	2

Figure 3.6: Computations of number of entries A-B of each machine

Step 3. Calculate the *percentage of parts shared* (P_{pm}) between the molding machine 3 and all other machines of *sequence order* 1 (recall that molding machines 1 and 2 are not considered).

Molding machine	1	2	3	4	5	6
P_{pm}				5/7	0/5	0/2

Step 4. Select the machine with more than 50 % *of parts shared* ($P_{pm} \geq 0.5$). In this case, only molding machine 4 has $P_{pm} = 5/7 = 0.714 \geq 0.5$. Hence, molding machine 4 is added to machine cell 2.

Sequence Order	Machine\Part	Reflector 2	Trim Ring	Light Guide	Bracket	Bezel 1	Reflector 1	Outer lens	Bezel 2	Inner Lens 1	Inner Lens 2	Reflex Lens	Housing
1	Molding machine 1	A	A	A	B								
	Molding machine 2	B	B	B	A	A	B						
	Molding machine 3					B	A		A		B	B	
	Molding machine 4							B	B	B	A	A	
	Molding machine 5							A		A			B
	Molding machine 6												A

Figure 3.7: Molding machine 4 with a $P_{pm} \geq 0.5$ with respect to machine 3

Step 5. Repeat process starting from Step 3.

Step 3. The *percentage of parts shared* (P_{pm}) between the molding machine 4 and all other machines of *sequence order* 1 is calculated. Subsequently, the 'cumulative' *percentage of parts shared* (P_{pm}) between the molding machine 3-and-4 and all other machines of *sequence order* 1 is calculated.

Molding machine	1	2	3	4	5	6
P_{pm} between machine 4 and others					4/5	0/2
P_{pm} between machine 3-and-4 and others (Cumulative P_{pm})					4/5	0/2

Step 4. Molding machine 5 possesses a $P_{pm} = 4/5 = 0.8 \geq 0.5$ and therefore it is added to machine cell 2.

Sequence Order	Machine\Part	Reflector 2	Trim Ring	Light Guide	Bracket	Bezel 1	Reflector 1	Outer lens	Bezel 2	Inner Lens 1	Inner Lens 2	Reflex Lens	Housing
1	Molding machine 1	A	A	A	B								
	Molding machine 2	B	B	B	A	A	B						
	Molding machine 3					B	A		A		B	B	
	Molding machine 4							B	B	B	A	A	
	Molding machine 5							A		A			B
	Molding machine 6												A

Figure 3.8: Addition of molding machine 5 to manufacturing cell 2

Step 5. Repeat Step 3.

Step 3. The *percentage of parts shared* (P_{pm}) between the molding machine 5 and all other machines of *sequence order* 1 is calculated. Subsequently, the 'cumulative' *percentage of parts shared* (P_{pm}) between the molding machine 3-4-5 and all other machines of *sequence order* 1 is calculated.

Molding machine	1	2	3	4	5	6
P_{pm} between machine 5 and others						0/2
P_{pm} between machine 3-4-5 and others (Cumulative P_{pm})						2/2

Step 4. Molding machine 6 possesses a $P_{pm} = 2/2 = 1 \geq 0.5$ and therefore it is added to machine cell 2.

Step 5. No change takes places by repeating step 3 then the manufacturing cell 2 is closed.

Step 6. Rearrange the selected machines (3, 4, 5 and 6) within the closed manufacturing cell 2 with their corresponding parts in the top left most part of the incidence matrix as best as possible. Only parts (columns) with A-intersections must be included in the target cell.

Sequence Order	Machine\Part	Reflector 2	Trim Ring	Light Guide	Bracket	Bezel 1	Reflector 1	Outer lens	Bezel 2	Inner Lens 1	Inner Lens 2	Reflex Lens	Housing
1	Molding machine 1	A	A	A	B								
	Molding machine 2	B	B	B	A	A	B						
	Molding machine 3					B	A		A		B	B	
	Molding machine 4							B	B	B	A	A	
	Molding machine 5							A		A			B
	Molding machine 6												A

Figure 3.9: Addition of molding machine 6 to manufacturing cell 2

End of Iteration 2 results in the formation of:

Machine cell MC-2 = {Molding machine 3, Molding machine 4, Molding machine 5, Molding machine 6}

Part group PG-2 = {Reflector 1, Bezel 2, Inner Lens 2, Reflex Lens, Outer Lens, Inner Lens 1, Housing}

Molding machines within manufacturing cell 2 are not considered for subsequent steps. At this moment, all the molding machines (machines of *sequence order* 1) have been assigned to machine cells. For this reason, the next step proceeds to cluster hard-coating chambers (machines of *sequence order* 2).

Step 7. Repeat process starting from Step 1.

Step 1. Begin with the incidence matrix taking into consideration the **2** *sequence order* machines only. In this case, hard-coating chambers.

Machine cell 1

Machine cell 2

Sequence Order	Machine\Part	Reflector 2	Trim Ring	Light Guide	Bracket	Bezel 1	Reflector 1	Outer lens	Bezel 2	Inner Lens 1	Inner Lens 2	Reflex Lens	Housing
1	Molding machine 1	A	A	A	B								
	Molding machine 2	B	B	B	A	A	B						
	Molding machine 3					B	A		A		B	B	
	Molding machine 4							B	B	B	A	A	
	Molding machine 5							A		A			B
	Molding machine 6												A
2	Hard-coating chamber 1		A			A	B						
	Hard-coating chamber 2		B			B	A	B					
	Hard-coating chamber 3							A					
3	Metallizing machine 1	B	A			A			A			B	
	Metallizing machine 2	A	B			B	B		B		B	A	
	Metallizing machine 3						A				A		

Figure 3.10: Machines of sequence order 2 (within red frame)

Iteration 3

Step 2. Calculate a vector e_m which counts the number of entries (A=2, B=1) in the incidence matrix for each machine (row) and find the maximum of the elements of vector e_m. In this case, hard-coating chambers 1 and 2 have $\max(e_m) = 5$. Hard-coating chamber 1 is selected since it has more A-entries than hard-coating chamber 2. This hard-coating chamber 1 is the first element of the machine cell 3.

$$e_m: [5\ 5\ 2]$$
$$\max(e_m) = 5$$

Sequence Order	Machine\Part	Reflector 2	Trim Ring	Light Guide	Bracket	Bezel 1	Reflector 1	Outer lens	Bezel 2	Inner Lens 1	Inner Lens 2	Reflex Lens	Housing	em
1														
2	Hard-coating chamber 1		A			A	B							5
	Hard-coating chamber 2		B			B	A	B						5
	Hard-coating chamber 3							A						2

Figure 3.11: Computations of number of entries A-B of each machine

Step 3. Calculate the *percentage of parts shared* (P_{pm}) between the hard-coating chamber 1 and all other machines of *sequence order* 2.

hard-coating chamber	**1**	**2**	**3**
P_{pm}		4/5	0/2

Step 4. Select the machine with more than 50 % *of parts shared* ($P_{pm} \geq 0.5$). In this case, only hard-coating chamber 2 has $P_{pm} = 4/5 = 0.8 \geq 0.5$. Hence, hard-coating chamber 2 is added to machine cell 3.

Sequence Order	Machine\Part	Reflector 2	Trim Ring	Light Guide	Bracket	Bezel 1	Reflector 1	Outer lens	Bezel 2	Inner Lens 1	Inner Lens 2	Reflex Lens	Housing
1													
2	Hard-coating chamber 1		A			A	B						
	Hard-coating chamber 2		B			B	A	B					
	Hard-coating chamber 3							A					

Figure 3.12: Hard-coating chamber 2 with a $P_{pm} \geq 0.5$ with respect to hard-coating chamber 1

Step 5. Repeat process starting from Step 3.

Step 3. The *percentage of parts shared* (P_{pm}) between the hard-coating chamber 2 and all other machines of *sequence order* 2 is calculated. Subsequently, the 'cumulative' *percentage of parts shared* (P_{pm}) between the hard-coating chamber 1-and-2 and all other machines of *sequence order* 2 is calculated.

hard-coating chamber	1	2	3
Ppm between chamber 2 and others			2/2
Ppm between chambers 1-and-2 and others (Cumulative *Ppm*)			2/2

Step 4. Select the hard-coating chamber 3 which has more than 50 % *of parts shared* ($P_{pm} = 2/2 = 1 \geq 0.5$) and add it to machine cell 3.

Sequence Order	Machine\Part	Reflector 2	Trim Ring	Light Guide	Bracket	Bezel 1	Reflector 1	Outer lens	Bezel 2	Inner Lens 1	Inner Lens 2	Reflex Lens	Housing
1													
2	Hard-coating chamber 1		A			A	B						
	Hard-coating chamber 2		B			B	A	B					
	Hard-coating chamber 3							A					

Figure 3.13: Hard-coating chamber 3 with a $P_{pm} \geq 0.5$ with respect to chambers 1-and-2

Step 5. No change takes places by repeating step 3 and therefore the manufacturing cell 3 is closed.

Step 6. Rearrange the selected machines (hard-coating chambers 1, 2 and 3) within the closed manufacturing cell 3 with their corresponding parts in the top left most part of the incidence matrix as best as possible. Only parts (columns) with A-intersections must be included in the target cell.

Machine cell 1

Machine cell 2

Sequence Order	Machine\Part	Reflector 2	Light Guide	Bracket	Trim Ring	Bezel 1	Reflector 1	Outer lens	Bezel 2	Inner Lens 1	Inner Lens 2	Reflex Lens	Housing
	Molding machine 1	A	A	B	A								
	Molding machine 2	B	B	A	B	A	B						
1	Molding machine 3					B	A		A		B	B	
	Molding machine 4							B	B	B	A	A	
	Molding machine 5							A		A			B
	Molding machine 6												A
	Hard-coating chamber 1				A	A	B						
2	Hard-coating chamber 2				B	B	A	B					
	Hard-coating chamber 3							A					

Machine cell 3

Figure 3.14: Machine cells of sequence orders 1 and 2

End of Iteration 3 results in the formation of:

Machine cell MC-3 = {Hard-coating chamber 1, Hard-coating chamber 2, Hard-coating chamber 3}

Part group PG-3 = {Trim Ring, Bezel 1, Reflector 1, Outer Lens}

Now, all the hard-coating chambers (machines of *sequence order* 2) have been assigned to a machine cell. For this reason the next step proceeds to cluster metallizing machines (machines of *sequence order* 3).

Step 7. Repeat process starting from Step 1.

Step 1. Begin with the incidence matrix taking into consideration the **3** *sequence order* machines only. In this case, metallizing machines.

Sequence Order	Machine\Part	Reflector 2	Light Guide	Bracket	Trim Ring	Bezel 1	Reflector 1	Outer lens	Bezel 2	Inner Lens 1	Inner Lens 2	Reflex Lens	Housing
1	Molding machine 1	A	A	B	A								
	Molding machine 2	B	B	A	B	A	B						
	Molding machine 3					B	A		A		B	B	
	Molding machine 4							B	B	B	A	A	
	Molding machine 5							A		A			B
	Molding machine 6												A
2	Hard-coating chamber 1				A	A	B						
	Hard-coating chamber 2				B	B	A	B					
	Hard-coating chamber 3							A					
3	Metallizing machine 1	B			A	A			A			B	
	Metallizing machine 2	A			B	B	B		B		B	A	
	Metallizing machine 3						A				A		

Figure 3.15: Machines of sequence order 3

Iteration 4

<u>Step 2</u>. Calculate a vector e_m which counts the number of entries (A=2, B=1) in the incidence matrix for each machine (row) and find the maximum of the elements of vector e_m. In this case, metallizing machine 2 has $\max(e_m) = 9$. This machine is the first element of the machine cell 4.

$$e_m: [8\ 9\ 4]$$
$$\max(e_m) = 9$$

Sequence Order	Machine\Part	Reflector 2	Trim Ring	Light Guide	Bracket	Bezel 1	Reflector 1	Outer lens	Bezel 2	Inner Lens 1	Inner Lens 2	Reflex Lens	Housing	e_m
1														
2														
3	Metallizing machine 1	B			A	A			A			B		8
	Metallizing machine 2	A			B	B	B		B		B	A		9
	Metallizing machine 3						A				A			4

Figure 3.16 Computation of number of entries A-B for each machine

Step 3. Calculate the *percentage of parts shared* (P_{pm}) between the metallizing machine 2 and all other machines of *sequence order* 3.

Metallizing machine	**1**	**2**	**3**
P_{pm}	8/8		4/4

Step 4. Select the machines with more than 50 % *of parts shared* ($P_{pm} \geq 0.5$). In this case, both metallizing machines 1 and 3 have $P_{pm} = 1 \geq 0.5$. Hence, these two machines are added to machine cell 4.

Sequence Order	Machine\Part	Reflector 2	Trim Ring	Light Guide	Bracket	Bezel 1	Reflector 1	Outer lens	Bezel 2	Inner Lens 1	Inner Lens 2	Reflex Lens	Housing
1 2													
3	Metallizing machine 1	B	A			A			A			B	
	Metallizing machine 2	A	B			B	B		B		B	A	
	Metallizing machine 3						A				A		

Figure 3.17: Addition of metallizing machines 1 and 3 to machine cell 4

Step 5. No change takes places by repeating step 3 and therefore the manufacturing cell 4 is closed.

Step 6. Rearrange the selected machines (metallizing machines 1, 2 and 3) within the closed manufacturing cell 4 with their corresponding parts in the top left most part of the incidence matrix as best as possible.

Machine cell 1
Machine cell 2
Machine cell 3
Machine cell 4

Sequence Order	Machine\Part	Light Guide	Bracket	Reflector 2	Trim Ring	Bezel 1	Reflector 1	Outer lens	Bezel 2	Reflex Lens	Inner Lens 2	Inner Lens 1	Housing
1	Molding machine 1	A	B	A	A								
	Molding machine 2	B	A	B	B	A	B						
	Molding machine 3					B	A		A	B	B		
	Molding machine 4							B	B	A	A	B	
	Molding machine 5							A				A	B
	Molding machine 6												A
2	Hard-coating chamber 1				A	A	B						
	Hard-coating chamber 2				B	B	A	B					
	Hard-coating chamber 3							A					
3	Metallizing machine 1			B	A	A			A	B			
	Metallizing machine 2			A	B	B	B		B	A	B		
	Metallizing machine 3						A				A		

Figure 3.18: Final rearranged incidence matrix

End of Iteration 4 results in the formation of:

Machine cell MC-4 = {Metallizing machine 1, Metallizing machine 2, Metallizing machine 3}

Part group PG-4 = {Reflector 2, Trim Ring, Bezel 1, Reflector 1, Bezel 2, Reflex Lens, Inner Lens 2}

Finally, all the machines from all the sequence orders have been assigned to machine cells.

Step 7. STOP.

Figure 3.18 shows the final rearranged part-machine matrix after conducting the proposed cell formation algorithm. Evidently, the obtained clusters (machine cells 1, 2, 3, and 4) do not form a block diagonal array as in the existing methods. Truly, the proposed cell formation method works and classify elements in a different way. However, the essence of Group

Technology is still honored: To divide the manufacturing system into smaller and thus more-manageable subsystems. Figure 3.19 below displays the physical layout of the respective incidence matrix.

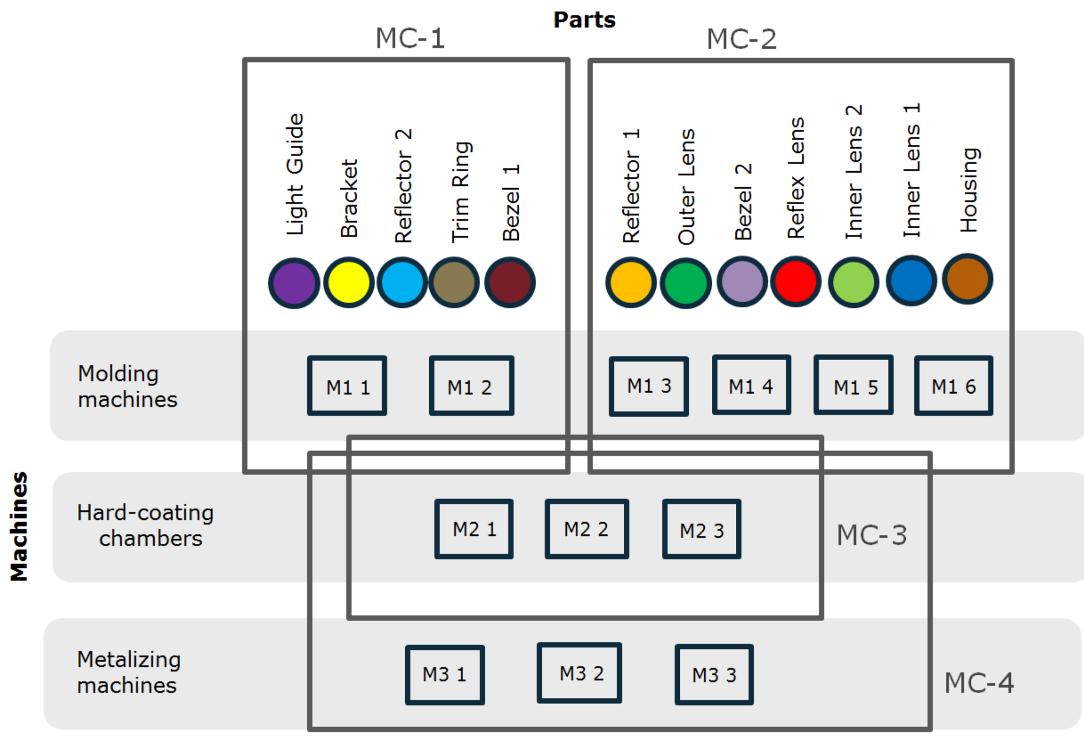


Figure 3.19: Physical layout of clustered matrix

Additionally, the concept of "part family" is applied in a different manner. Part families are generated based on their process requirements. Oppositely, machine cells are created according to their features similarities. This way parts can be grouped according to their required processes with no necessity of duplicating equipment and with less complex intercellular transportation. Figure 3.20 identifies the part families using this philosophy.

		PF-1		PF-2	PF-3		PF-4	PF-5	PF-6			PF-7	
Sequence Order	Machine\Part	Light Guide	Bracket	Reflector 2	Trim Ring	Bezel 1	Reflector 1	Outer lens	Bezel 2	Reflex Lens	Inner Lens 2	Inner Lens 1	Housing
1	Molding machine 1	A	B	A	A								
	Molding machine 2	B	A	B	B	A	B						
	Molding machine 3					B	A		A	B	B		
	Molding machine 4							B	B	A	A	B	
	Molding machine 5							A				A	B
	Molding machine 6												A
2	Hard-coating chamber 1				A	A	B						
	Hard-coating chamber 2				B	B	A	B					
	Hard-coating chamber 3							A					
3	Metallizing machine 1			B	A	A			A	B			
	Metallizing machine 2			A	B	B	B		B	A	B		
	Metallizing machine 3						A				A		

Figure 3.20: Formed part families based on process requirements

Part families PF-1 and PF-7, for example, require to be processed by molding machines only. This means the parts included in these families are only processed by machines of sequence order 1 before they are finished. Yet, the molding machines of PF-1 and PF-7 are different (machine cells 1 and 2). On the other hand, part Families PF-3 and PF-4 have to visit all 3 sequence order machines (molding, hard-coating, and metallizing machines) to be completed. This means the parts within these families are more complex and need more processes to be manufactured. Shortly, the 12 parts of the target facility are grouped into 7 part families and the 12 machines are grouped into 4 machine cells.

Dissimilar to the traditional mode used to identify the parts in a factory, the proposed part families are intended to digitally catalog all the parts.

Frequently, the source of a defect in a plastic component has to be tracked in order to be corrected. This action is not always simple considering the long chain of processes preceding the final inspection.

3.1.2 Example 2

A further example is conducted in this section using an incidence matrix with 14 parts and 13 machines. Again, the process path is divided in 3 sequence orders. The steps to solve this example have been omitted but the original incidence matrix and its result are shown below:

Sequence order	Machine\Part	Outer lens	Bezel 1	Bezel 2	Bracket	Trim Ring 1	Trim Ring 2	Reflex Lens	Inner Lens	Reflector 1	Reflector 2	Reflector 3	Inner Optics	Cover	Housing
1	Molding machine 1				A	B	B							B	
	Molding machine 2		A	B	B	A	A		B				A	A	
	Molding machine 3		B					A	A						
	Molding machine 4			A						A	A	B	B		
	Molding machine 5	A						B		B		A			
	Molding machine 6	B									B				B
	Molding machine 7														A
2	Hard-coating chamber 1	A		B						A					
	Hard-coating chamber 2	B		A						B					
3	Metalizing machine 1			B		A								A	
	Metalizing machine 2		A	A		B	A								
	Metalizing machine 3		B				B			A				B	
	Metalizing machine 4									B					

Figure 3.21 Unarranged part-machine matrix

Sequence order	Machine\Part	Inner Optics	Bracket	Inner Lens	Reflex Lens	Trim Ring 1	Cover	Bezel 1	Trim Ring 2	Bezel 2	Reflector 1	Outer lens	Reflector 2	Reflector 3	Housing
1	Molding machine 2	A	B	B		A	A	A	A	B					
	Molding machine 1		A			B	B		B						
	Molding machine 3			A	A			B							
	Molding machine 4	B								A	A		A	B	
	Molding machine 5				B						B	A		A	
	Molding machine 6											B	B		B
	Molding machine 7														A
2	Hard-coating chamber 1									B	A	A			
	Hard-coating chamber 2									A	B	B			
3	Metalizing machine 1					A	A			B					
	Metalizing machine 2					B		A	A	A					
	Metalizing machine 3						B	B	B		A				
	Metalizing machine 4										B				

Figure 3.22: Final rearranged part-machine matrix

Here, the application of the proposed cell formation method leads the formation of 5 part families and 4 machine cells.

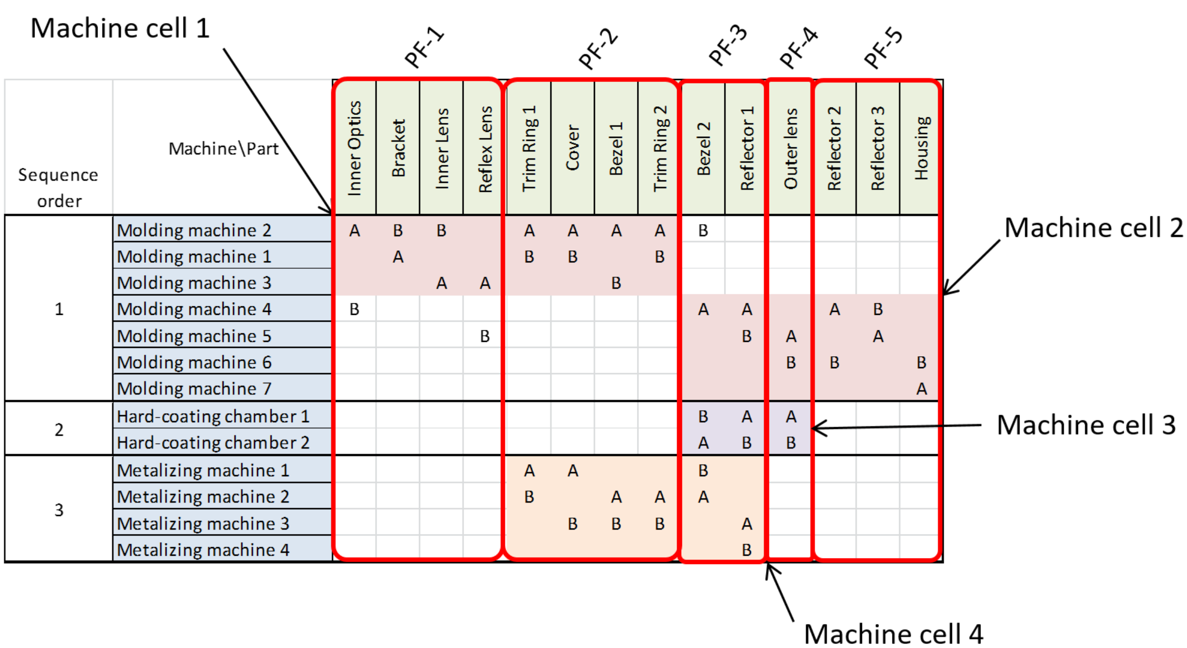


Figure 3.23: Formed part families based on process requirements

3.2 Performance measurement

Every change implemented in a manufacturing setting has to be assessed and the formation of cells is not the exception. There are several measures of performance used to evaluate the formed groups in the cell formation algorithms, each of them varies depending on the data considered. However, the two most popular and useful measures are yet grouping efficiency η and grouping efficacy τ. [19] Their objective is to compare the quality of the obtained solutions by different methods based on an absolute scale.

3.2.1 Grouping Efficiency η

Grouping efficiency was first proposed by Chandrasekaran and Rajagopalan in 1986. It is computed as a weighted average dependent on the two efficiencies η_1 and η_2:

$$\eta = w\eta_1 + (1 - w)\eta_2$$

where,

$$\eta_1 = \frac{\text{Number of 1s in the diagonal blocks}}{\text{Total number of elements (1s and 0s) in the diagonal blocks}}$$

$$\eta_2 = \frac{\text{Number of 0s in the off-diagonal blocks}}{\text{Total number of elements (1s and 0s) in the off-diagonal blocks}}$$

Basically, function η_1 accounts for the packing density inside the formed cells and function η_2 for the inter cellular moves. The weighting factor w ranges from 0 to 1 and it varies relatively to the matrix size. A value of 0.5 is normally recommended.

Next, the grouping efficiency for the partitions obtained in Figure 3.18 from the Example 1 is computed (see Appendix III). Here, the values A and B from the proposed part machine matrix are considered equally as 1s in order to compute the efficiency.

$$\eta = (0.5)\ (0.6197) + (1 - 0.5)\ (0.9726) = 0.796$$

Likewise, the grouping efficiency of the groupings from Figure 3.22 from the Example 2 is also computed.

$$\eta = (0.5)\ (0.5513) + (1 - 0.5)\ (0.9711) = 0.7613$$

Grouping efficiencies for both results show to be relatively high. For a bigger matrix, increasing the *w* factor leads to a larger efficiency.

3.2.2 Grouping Efficacy τ

In 1990, Kumar and Chandrasekaran proposed grouping efficacy to overcome the discriminating influence present in the grouping efficiency.

$$\Gamma = \frac{1 - \psi}{1 - \varphi}$$

where,

$$\psi = \frac{\text{Number of exclusive elements}}{\text{Total number of operations}}$$

$$\varphi = \frac{\text{Number of 0s (voids) in blocks}}{\text{Total number of operations}}$$

Contrary to the grouping efficiency, grouping efficacy is not affected by the size of the matrix (no *w* factor).

The grouping efficacy for the groupings obtained in Figure 3.18 from the Example 1 is:

$$\Gamma = 0.6027$$

Similarly, Example 2 shown in Figure 3.22 is:

$$\Gamma = 0.5301$$

The computation of grouping efficacies indicates a poorer performance. However, it has to be considered that the existence of voids in the solution will always be circumstance if more than two machines are grouped together. This is because every part has a maximum of two machines to select and thus a cluster with more than two machines cannot be completely ‘filled’. Additional parameters like distance between machines, processing times or costs should be considered to properly evaluate the performance of the results.

Chapter 4: Case Study

4.1 Description

This section presents a real scenario on which 33 parts and 26 machines have to grouped into a more organized layout.

Sequence Order	Machine \ Part	Reflector A1	Reflector A2	Housing A	Outer Lens A	Trim Ring A	Bezel A	Inner Bezel A	Outer Bracket A	Reflector B	Housing B	Outer Lens B	Inner Lens B	Inner Bezel B	Trim Ring C	Housing C	Outer Lens C	Inner Bezel C1	Inner Bezel C2	Outer Bezel C	Bracket C	Reflector D1	Reflector D2	Housing D	Outer Lens D	Bezel D	Inner Lens D	Light Guide D	Cover D	Reflector E	Housing E	Lens E	Bezel E	Cover Frame E
1	Molding M1	A					A																A							B				
	Molding M2	B																				B	B										A	
	Molding M3		A				B			A											A	A								A			B	
	Molding M4		B			A			B	B					B											B								
	Molding M5					B			A												B					A								
	Molding M6												B														A	B						
	Molding M7												A		A													A				A		
	Molding M8				A																				A		B					B		
	Molding M9											A					B								B									
	Molding M10				B							B		B			A												B					
	Molding M11													A				B	A															B
	Molding M12							B										A	B	B									A					A
	Molding M13							A												A														
	Molding M14			B												A															A			
	Molding M15			A							A													B							B			
	Molding M16										B					B								A										
2	Coating C1	A	B																															
	CoatinG C2	B	A							A												A	B							B				
	Coating C3				B					B		B					A						A		A					A				
	Coating C4				A							A					B					B			B									
3	Metallizing C1					A									A	B															A			
	Metallizing C2	B				B				B					B	A						B	A			A				B	B			
	Metallizing C3	A	A							A				B				B	A			A	B							A				
	Metallizing C4		B					A						A				A								B								
	Metallizing C5						A	B											B														A	
	Metallizing C6						B																										B	

Figure 4.1: Part-machine matrix of an actual manufacturing case

The colors of parts represent different lamp models. Therefore, this case illustrates a facility that builds 5 different lamp assemblies. Subsequently, it is conducted the proposed methodology to the given scenario. Results are shown in Figure 4.2 below:

`	Machine \ Part	Bracket C	Bezel E	Bezel A	Reflector A1	Reflector A2	Reflector D1	Reflector B	Reflector E	Reflector D2	Inner Bezel A	Inner Bezel C2	Inner Bezel C1	Inner Bezel B	Cover D	Cover Frame E	Outer Bezel C	Inner Lens B	Light Guide D	Lens E	Inner Lens D	Trim Ring C	Trim Ring A	Bezel D	Outer Bracket A	Housing C	Housing E	Housing A	Housing B	Housing D	Outer Lens A	Outer Lens D	Outer Lens B	Outer Lens C	em
1	Molding M3	A	B	B		A	A	A	A																										12
	Molding M2		A		B		B			B																									5
	Molding M1			A	A				B	A																									7
	Molding M12										B	B	A		A	A	B																		9
	Molding M13										A						A																		4
	Molding M11											A	B	A		B																			6
	Molding M7																	A	A	A		A													8
	Molding M6																	B	B		A														4
	Molding M4					B		B														B	A	B	B										7
	Molding M5	B																					B	A	A										6
	Molding M15																										B	A	A	B					6
	Molding M16																									B			B	A					4
	Molding M14																									A	A	B							5
	Molding M8																			B	B										A	A			6
	Molding M10													B	B																B		B	A	6
	Molding M9																															B	A	B	4
2	Coating C3							B	A	A																					B	A	B	A	11
	Coating C4						B																								A	B	A	B	7
	CoatinG C2				B	A	A	A	B	B																									9
	Coating C1				A	B																													3
3	Metallizing C3				A	A	A	A	A	B		A	B	B																					15
	Metallizing C4					B					A		A	A																					8
	Metallizing C2				B		B	B	B	A												B	B	A		A	B								13
	Metallizing C1																					A	A			B	A								7
	Metallizing C5		A	A							B	B																							6
	Metallizing C6		B	B																															2

Figure 4.2: Clusters obtained after conducting the proposed cell formation method

Clearly, 7 molding machine cells, 1 coating chamber cell, and 2 metallizing machine cells are formed. Blue curved lines indicate union between the connected boxes (cells). Next, the obtained part families are determined in Figure 4.3:

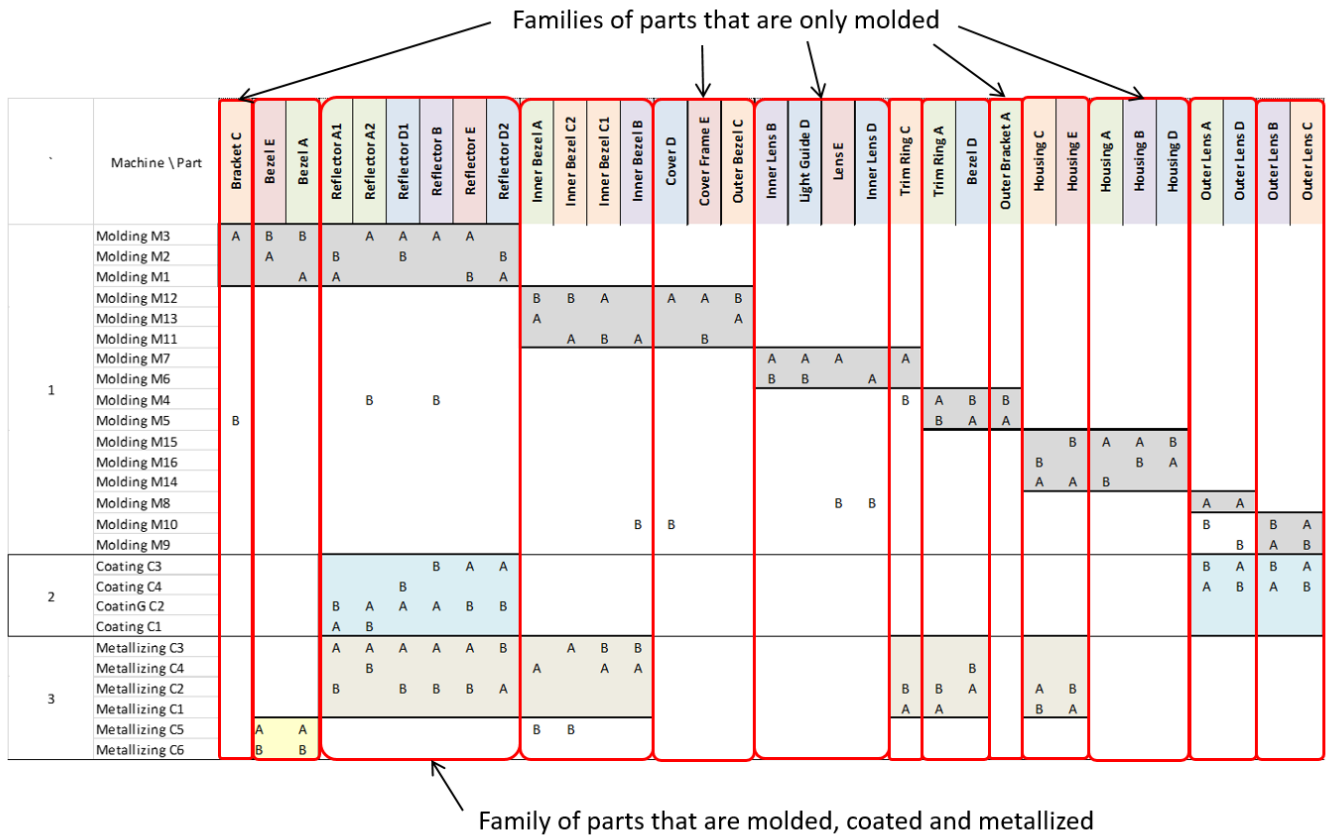


Figure 4.3: Part families based on process requirements

The proposed cell formation algorithm demonstrated to perform properly in a bigger part-machine matrix.

There were found 13 part families which allow a better understanding of the feature categories. There is, for instance, only one family of parts which requires the three types of machines (molding, coating and metallizing). Special attention has to be spent into these components since they are more complex to build and thus are more prone to quality defects. On the other hand, there are 5 part families that need to be molded only. These are less complicated in terms of manufacturability. As a result, the well-defined part families ease the error tracking processes.

There are obtained 10 machines cells that permit an improved management of the resources and equipment. With these groupings of machines, managers are able to effectively assign people as responsible of different areas. Moreover, the maintenance of equipment is also enhanced due to the physical proximity of machines with similar features.

The computation of efficiency and efficacy leads to the values $\eta = 0.777$ and $\Gamma = 0.55$, respectively. As it was stated at the end of Section 3, however, additional parameters such as distance, cost, processing time or number of operators have to be considered in order to quantify and evaluate the efficiency of the result.

4.2 Other Applications

The advantages of the described algorithm can also be applied to other similar cases involving sequential processes (that is, the order of processes is predefined and cannot be modified) with alternative machines A & B. In the home appliances industry, for example, domestic washers and dryers are built with metal panels which have to be created out of a steel sheet. These components are normally stamped, bended, and then coated with a type of anti-corrosion paint. Thus, the entire process can be improved by means of the proposed cell formation algorithm.

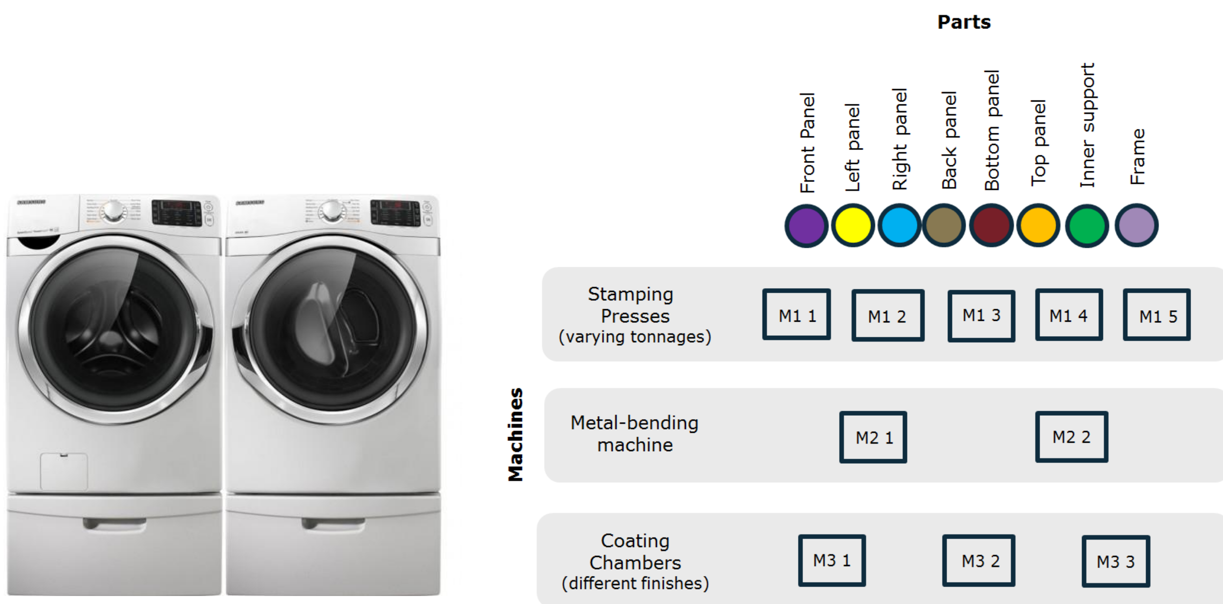


Figure 4.4: Home appliances industry with sequential processes and alternative machine selection

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Chapter 5: Conclusion

5.1 Summary

The manufacturing systems, from the automotive lighting industry or any similar, highly rely on the manipulation of data to make production possible. It is important to identify efficient methods to organize the information and obtain the maximum benefits of it. It has been proven that the high complexity of a manufacturing facility triggers different problems, especially in the planning process. It becomes difficult to achieve a lean environment without a classification of parts and machines into groups. Truthfully, a big room for improvement has been found in the automotive lighting industry. With a great number of plant resources to organize including components and equipment, it is urgent to generate both part families and machine cells. However, none of the existing cell formation methods have demonstrated to effectively resolve this issue. For this reason, a new clustering method is proposed to comply with the requirements of this area. Its results exhibit a new, more practical and efficient way to classify the elements through the part-machine matrix formulation. Undoubtedly the transportation between stations and the setup procedures are reduced when this methodology is applied. Furthermore, the proposed part family definition eases not only the part-to-machine assignment task but it also permits an enhanced tracking of the source of defects on parts. Clearly, the nature of the new technique allows a less error prone performance compared to the current methods and it leads to feasible solutions.

5.2 Future Work

A true guarantee that the new cellular manufacturing arrangement will outperform the traditional schemes will only be possible through its application. Careful attention has to be spent while establishing the cells and how the machines and parts are assigned to each one. Thus, the consent and feedback from the end users will determine whether this proposed method is convenient or not.

In addition, processing and set up times, measured distances, costs and number of workers have to be taken into account in order to quantify and efficiently evaluate the obtained results. The existing measures of performance (grouping efficiency and efficacy) cannot be adapted to the proposed algorithm due to its clustering nature. This process of valuation, however, will vary according to each company's expectations.

Finally, the proposed methodology has to be adapted into a worthwhile and practical software. By creating a computerized tool based on this algorithm it will be possible to improve and facilitate the management of the manufacturing resources.

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Appendix I – Computation of SLCA similarity coefficients

Machine Pair	Similarity coefficient calculation
M1 M2	1 / (1 + 2) = 1 / 3 = 0.333
M1 M3	0 / 4 = 0
M1 M4	2 / (2 + 1) = 2 / 3 = 0.666
M1 M5	0 / 5 = 0
M2 M3	0 / 4 = 0
M2 M4	2 / (2 + 1) = 2 / 3 = 0.666
M2 M5	0 / 5 = 0
M3 M4	0 / 5 = 0
M3 M5	2 / (2 + 1) = 2 / 3 = 0.666
M4 M5	0 / 6 = 0

Table 6.1 Similarity coefficients for example matrix

Machine Pair	Similarity coefficient calculation
Mol 1 Mol 2	4 / 6 = 0.666
Mol 1 Mol 3	0 / 9 = 0
Mol 1 Mol 4	0 / 8 = 0
Mol 1 Mol 5	0 / 7 = 0
Mol 1 Mol 6	0 / 5 = 0
Mol 1 Coa 1	1 /6 = 0.1666
Mol 1 Coa 2	1 / 7 = 0.143
Mol 1 Coa 3	0 / 5 = 0
Mol 1 Met 1	2 / 7 = 0.286
Mol 1 Met 2	2 /9 = 0.222
Mol 1 Met 3	0 / 6 = 0

Table 6.2: Similarity coefficient between Molding machine 1 and other equipment

Machine Pair	Similarity coefficient calculation
Mol 2 Mol 3	2 / 9 = 0.222
Mol 2 Mol 4	0 / 11 = 0
Mol 2 Mol 5	0 / 9 = 0
Mol 2 Mol 6	0 / 7 = 0
Mol 2 Coa 1	3 / 6 = 0.5
Mol 2 Coa 2	3 /7 = 0.429
Mol 2 Coa 3	0 / 7 = 0
Mol 2 Met 1	3 / 8 = 0.375
Mol 2 Met 2	4 / 9 = 0.444
Mol 2 Met 3	1 / 8 = 0.125

Table 6.3: Similarity coefficient between Molding machine 2 and other equipment

Machine Pair	Similarity coefficient calculation
Mol 3 Mol 4	3 / 7 = 0.429
Mol 3 Mol 5	0 / 8 = 0
Mol 3 Mol 6	0 / 6 = 0
Mol 3 Coa 1	2 / 6 = 0.333
Mol 3 Coa 2	2 / 7 = 0.286
Mol 3 Coa 3	0 / 6 = 0
Mol 3 Met 1	3 / 7 = 0.429
Mol 3 Met 2	5 / 7 = 0.714
Mol 3 Met 3	2 / 5 = 0.4

Table 6.4: Similarity coefficient between Molding machine 3 and other equipment

Machine Pair	Similarity coefficient calculation
Mol 4 Mol 5	2 / 6 = 0.333
Mol 4 Mol 6	0 / 6 = 0
Mol 4 Coa 1	0 / 8 = 0
Mol 4 Coa 2	1 / 8 = 0.125
Mol 4 Coa 3	1 / 5 = 0.2
Mol 4 Met 1	2 / 8 = 0.25
Mol 4 Met 2	3 / 9 = 0.333
Mol 4 Met 3	1 / 6 = 0.166

Table 6.5: Similarity coefficient between Molding machine 4 and other equipment

Machine Pair	Similarity coefficient calculation
Mol 5 Mol 6	1 / 3 = 0.333
Mol 5 Coa 1	0 / 6 = 0
Mol 5 Coa 2	1 / 6 = 0.166
Mol 5 Coa 3	1 / 3 = 0333
Mol 5 Met 1	0 / 8 = 0
Mol 5 Met 2	0 / 10 = 0
Mol 5 Met 3	0 / 5 = 0

Table 6.6: Similarity coefficient between Molding machine 5 and other equipment

Machine Pair	Similarity coefficient calculation
Mol 6 Coa 1	0 / 4 = 0
Mol 6 Coa 2	0 / 5 = 0
Mol 6 Coa 3	0 / 2 = 0
Mol 6 Met 1	0 / 6 = 0
Mol 6 Met 2	0 / 8 = 0
Mol 3 Met 3	0 / 3 = 0

Table 6.7: Similarity coefficient between Molding machine 6 and other equipment

Machine Pair	Similarity coefficient calculation
Coa 1 Coa 2	3 / 4 = 0.75
Coa 1 Coa 3	0 / 4 = 0
Coa 1 Met 1	2 / 6 = 0.333
Coa 1 Met 2	3 / 7 = 0.429
Coa 1 Met 3	1 / 4 = 0.25

Table 6.8: Similarity coefficient between Hard-coating machine 1 and other equipment

Machine Pair	Similarity coefficient calculation
Coa 2 Coa 3	1 / 4 = 0.25
Coa 2 Met 1	2 / 7 = 0.286
Coa 2 Met 2	3 / 8 = 0.375
Coa 2 Met 3	1 /5 = 0.2

Table 6.9: Similarity coefficient between Hard-coating machine 2 and other equipment

Machine Pair	Similarity coefficient calculation
Coa 3 Met 1	0 / 6 = 0
Coa 3 Met 2	0 / 8 = 0
Coa 3 Met 3	0 / 3 = 0

Table 6.10: Similarity coefficient between Hard-coating machine 3 and other equipment

Machine Pair	Similarity coefficient calculation
Met 1 Met 2	5 / 7 = 0.714
Met 1 Met 3	0 / 7 = 0

Table 6.11: Similarity coefficient between Metallizing machine 1 and other equipment

Machine Pair	Similarity coefficient calculation
Met 2 Met 3	2 / 7 = 0.286

Table 6.12: Similarity coefficient between Metallizing machine 2 and other equipment

Appendix II – Computation of SLCA similarity coefficients using proposed part-machine matrix

		Machines										
		Mol 1	Mol 2	Mol 3	Mol 4	Mol 5	Mol 6	Coa 1-Coa 2	Coa 3	Met 1	Met 2	Met 3
Machines	Mol 1	0	0.666	0	0	0	0	0.166	0	0.666	0.222	0
	Mol 2		0	0.222	0	0	0	0.5	0	0.375	0.444	0.125
	Mol 3			0	0.429	0	0	0.333	0	0.429	0.714	0.4
	Mol 4				0	0.333	0	0.125	0.2	0.25	0.333	0.166
	Mol 5					0	0.333	0.166	0.333	0	0	0
	Mol 6						0	0	0	0	0	0
	Coa 1-Coa 2							0	0.25	0.333	0.429	0.25
	Coa 3								0	0	0	0
	Met 1									0	0.714	0
	Met 2										0	0.286
	Met 3											0

Figure 6.13: First grouping iteration

		Machines									
		Mol 1	Mol 2	Mol 3-Met2	Mol 4	Mol 5	Mol 6	Coa 1-Coa 2	Coa 3	Met 1	Met 3
Machines	Mol 1	0	0.666	0	0	0	0	0.166	0	0.666	0
	Mol 2		0	0.222	0	0	0	0.5	0	0.375	0.125
	Mol 3-Met 2			0	0.429	0	0	0.429	0	0.714	0.4
	Mol 4				0	0.333	0	0.125	0.2	0.25	0.166
	Mol 5					0	0.333	0.166	0.333	0	0
	Mol 6						0	0	0	0	0
	Coa 1-Coa 2							0	0.25	0.333	0.25
	Coa 3								0	0	0
	Met 1									0	0
	Met 3										0

Figure 6.14: Second grouping iteration

	Machines									
		Mol 1	**Mol 2**	**Mol 3-Met2-Met1**	**Mol 4**	**Mol 5**	**Mol 6**	**Coa 1-Coa 2**	**Coa 3**	**Met 3**
Machines	**Mol 1**	0	0.666	0.666	0	0	0	0.166	0	0
	Mol 2		0	0.375	0	0	0	0.5	0	0.125
	Mol 3-Met 2-Met 1			0	0.429	0	0	0.429	0	0.4
	Mol 4				0	0.333	0	0.125	0.2	0.166
	Mol 5					0	0.333	0.166	0.333	0
	Mol 6						0	0	0	0
	Coa 1-Coa 2							0	0.25	0.25
	Coa 3								0	0
	Met 3									0

Figure 6.15: Third grouping iteration

	Machines								
		Mol 1-Mol 2	**Mol 3-Met2-Met1**	**Mol 4**	**Mol 5**	**Mol 6**	**Coa 1-Coa 2**	**Coa 3**	**Met 3**
Machines	**Mol 1-Mol 2**	0	0.666	0	0	0	0.5	0	0.125
	Mol 3-Met 2-Met 1		0	0.429	0	0	0.429	0	0.4
	Mol 4			0	0.333	0	0.125	0.2	0.166
	Mol 5				0	0.333	0.166	0.333	0
	Mol 6					0	0	0	0
	Coa 1-Coa 2						0	0.25	0.25
	Coa 3							0	0
	Met 3								0

Figure 6.16: Fourth grouping iteration

Machines		Machines						
		Mol 1-Mol 2-Mol 3-Met2-Met1	Mol 4	Mol 5	Mol 6	Coa 1-Coa 2	Coa 3	Met 3
Machines	Mol 1-Mol 2-Mol 3-Met 2-Met 1	0	0	0	0	0.5	0	0.125
	Mol 4		0	0.333	0	0.125	0.2	0.166
	Mol 5			0	0.333	0.166	0.333	0
	Mol 6				0	0	0	0
	Coa 1-Coa 2					0	0.25	0.25
	Coa 3						0	0
	Met 3							0

Figure 6.17: Fifth grouping iteration

Machines		Machines					
		Mol 1-Mol 2-Mol 3-Met2-Met1-Coa 1-Coa 2	Mol 4	Mol 5	Mol 6	Coa 3	Met 3
Machines	Mol 1-Mol 2-Mol 3-Met 2-Met 1-Coa 1-Coa 2	0	0.125	0.166	0	0.25	0.25
	Mol 4		0	0.333	0	0.2	0.166
	Mol 5			0	0.333	0.333	0
	Mol 6				0	0	0
	Coa 3					0	0
	Met 3						0

Figure 6.18: Sixth grouping iteration

	Machines					
		Mol 1-Mol 2-Mol 3-Met2-Met1-Coa 1-Coa 2	Mol 4-Mol 5	Mol 6	Coa 3	Met 3
Machines	Mol 1-Mol 2-Mol 3-Met 2-Met 1-Coa 1-Coa 2	0	0.166	0	0.25	0.25
	Mol 4-Mol 5		0	0.333	0.333	0.166
	Mol 6			0	0	0
	Coa 3				0	0
	Met 3					0

Figure 6.19: Seventh grouping iteration

	Machines				
		Mol 1-Mol 2-Mol 3-Met2-Met1-Coa 1-Coa 2	Mol 4-Mol 5-Mol 6	Coa 3	Met 3
Machines	Mol 1-Mol 2-Mol 3-Met 2-Met 1-Coa 1-Coa 2	0	0.166	0.25	0.25
	Mol 4-Mol 5-Mol 6		0	0.333	0.166
	Coa 3			0	0
	Met 3				0

Figure 6.20: Eight grouping iteration

		Machines		
		Mol 1-Mol 2-Mol 3-Met2-Met1-Coa 1-Coa 2	Mol 4-Mol 5-Mol 6-Coa 3	Met 3
Machines	Mol 1-Mol 2-Mol 3-Met 2-Met 1-Coa 1-Coa 2	0	0.166	0.25
	Mol 4-Mol 5-Mol 6-Coa 3		0	0.166
	Met 3			0

Figure 6.21: Ninth grouping iteration

		Machines	
		Mol 1-Mol 2-Mol 3-Met2-Met1-Coa 1-Coa 2-Met 3	Mol 4-Mol 5-Mol 6-Coa 3
Machines	Mol 1-Mol 2-Mol 3-Met 2-Met 1-Coa 1-Coa 2-Met 3	0	0.166
	Mol 4-Mol 5-Mol 6-Coa 3		0

6.22: Tenth grouping iteration

Appendix III – Computation of efficiency and efficacy

Example 1:

Number of A's and B's in the blocks

$$\eta_1 = \frac{44}{71} = 0.6197$$

Total number of elements (A, B and 0's) in the diagonal blocks

Number of 0's in the off-diagonal blocks

$$\eta_2 = \frac{71}{73} = 0.9726$$

Total number of elements (A, B and 0's) in the off-diagonal blocks

Example 2:

Number of A's and B's in the blocks

$$\eta_1 = \frac{43}{78} = 0.5513$$

Total number of elements (A, B and 0's) in the diagonal blocks

Number of 0's in the off-diagonal blocks

$$\eta_2 = \frac{101}{104} = 0.9711$$

Total number of elements (A, B and 0's) in the off-diagonal blocks

Efficacy:

$$\Gamma = \frac{1 - \psi}{1 - \varphi}$$

Grouping Efficacy Example 1

$$\Gamma = \frac{46 - 2}{46 + 27} = 0.6027$$

Grouping Efficacy Example 2

$$\Gamma = \frac{46 - 3}{46 + 35} = 0.5301$$

Case Study:

Efficiency

$$\eta = (0.5)\ (0.5714) + (1 - 0.5)\ (0.9835) = 0.777$$

Efficacy

$$\Gamma = 110 / 200 = 0.55$$

Vita

Victor Loya was born in Ciudad Juarez, Mexico, across the United States border from El Paso, Texas. He is the first son of two of Victor Loya and Marisela Garnica. He completed all his academic education in Ciudad Juarez before attending college and in the fall of 2008 he was accepted in the program of Mechanical Engineering from the University of Texas at El Paso. He acquired his bachelor of science degree in the spring of 2013 and during this same year he started to work for Electrolux Home Appliances. Starting 2014, he enrolled in the master's program of Manufacturing Engineering at UTEP and a few months later he decided to pursue a career of his own interest in the automotive industry as a Design Engineer in Automotive Lighting, a Fiat Chrysler Automobiles subsidiary.

Contact: victor.mlg@hotmail.com