A research into the suitability of manufacturing cells under highly varied product mix.

This paper presents the report of the BSC graduation assignment at Company X.

Orkide Nur Kara
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Author	Orkide Nur Kara s1506137 o.n.kara@student.utwente.nl
Bachelor program	Industrial Engineering & Management
Graduation commitee	Dr. Ir. A. Al Hanbali Faculty of Behavioural, Management and Social Sciences Department Industrial Engineering and Business Information Systems Dr. D. Demirtas Faculty of Behavioral Management and Social Sciences Department Industrial Engineering and Business Information Systems
Company X	Drs. X

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Management summary

Company X would like to have a method to be able to quantitatively analyze if there's a business case for creating production cells in the factory. The company currently operates in a job shop based manufacturing environment in which similar machines are grouped into functional departments. This means that the parts move from department to department through the manufacturing process.
The company currently does not have any production cells, neither have they identified products which together have a 'common' routing. Because of the highly varied product mix and the lack of an overview of common routings, there are many production flows that cause a lot of traffic between departments. Company X would like to know if there is a business case to create cells in order to cut back on routing delays and costs. Therefore, the research question discussed in this thesis is identified as:

Which (sub)routings are more suitable for cellular manufacturing than for functional manufacturing?

Research approach
In order to evaluate a business case for this, we identified the common routings in the highly varied product mix based on historical production data. Thereafter, these routings are clustered into routing families by means of the discrete clustering method and the similarity coefficient algorithm. Finally, the results of the clustering methods are used to identify the routings that are suitable for cellular manufacturing.

Routing mix analysis
The first step in converting a work area into a manufacturing cell is to assess the current work area conditions. Since Company X's product mix and thereby the routing fluctuates over time and is highly diversified, the routing mix of the company has been investigated. A routing-frequency analysis has been used to assess the current routing mix of the company. By means of the Pareto analysis the most frequently performed operations and thereafter the most common routings in the factory are identified.

Clustering methods
The literature describes several methods for cell formation, including a machine part grouping analysis and a similarity coefficient based approach. We used the Production Flow Analysis as a framework. We first performed a factory flow analysis, in which we analyzed the departmental flows and created a basic flow chart for the flows within the factory. Second, we performed group analysis with the discrete clustering method so that we grouped routings into routing families to create cells. We validated the results of the discrete clustering technique by performing the similarity coefficient method.

Results
The clustering methods, discrete clustering technique and the similarity coefficient algorithm result in the same three cells. The first cell contains three cutting machines, three bending machines and two stainless steel welding machines. The second cell contains TIG/MAG welding machines, grinding machine and the painting machine. The third cell contains degreasing machine. Based on the three clusters found with the clustering analyzes, we checked if moving a machine to another cluster reduces the departmental flows.

Conclusion and recommendation
The implementation of the three cells results in 32.4% decrease in departmental flows. This percentage is due to routings performed in the first and the second cell. The decrease in travel time is equal to 38.4% per year. Based on the decrease in departmental flows and thereby the travel time we recommend to place the stainless steel welding machine in the sheet metal center and to place the TIG/MAG steel welding machines and the grinding machine in the painting department.

Preface

This report is the result of my internship at Company X as part of my bachelor thesis in Industrial Engineering & Management. The purpose of the study was to investigate the suitability of manufacturing cells for the production environment of Company X. The three-month internship was the first time in my study in which I have applied the theory into practice. This was a new and very educational experience and therefore I would like to thank some people who have accompanied me in this process.

First of all, I would like to thank Company X for the opportunity they gave me. Not only was I allowed to work on a very interesting and exciting topic, they also gave me the opportunity to work in and experience a challenging environment. Furthermore, the research I carried out was of relevance to the entire company, so everybody was very interested in what I was doing.

I want to thank my supervisors Ahmad Al Hanbali and Derya Demirtas for their valuable insight and feedback on my work. I would especially like to thank Jasper for his excellent guidance and the way he has supported me in achieving this great result. I would also like to thank other employees who were always willing to make time for my questions and helped me this way in the collection of the necessary information.

Finally, I would like to thank my friends and family for the continuous support and the interest they have shown in my research.

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Definitions

Cell	= also called a production cell or a manufacturing cell, which is an arrangement of resources in a manufacturing environment to improve the speed and cost of the manufacturing process by improving production flows and eliminating waste.
Operation	= a manufacturing step/ production step that is a part of the routing. A company has many operations to convert a part into a product.
Pareto Analysis	= also called 20/80 analysis, which is a quantitative method to find the 20% of routings that contribute to the 80% of all routings in the factory.
Part	= anything that is counted in inventory, which can be purchased from a vendor or manufactured. A part is not necessarily a product, as it can be a semi-finished product that needs to be processed further.
PFA	= Production Flow Analysis, a cell formation method introduced by Burbridge (1971).
Product	= anything that is being sold to the customer.
Product mix	=is the set of all product lines and items that a company offers for sale.
Routing	= the exact sequence of necessary production steps in order to produce a part/product. A routing exists of the sequence of operations needed to manufacture a part/product.
Routing mix	= all different routings in the factory. Routings differ from each other on the basis of the necessary operations and/or the sequence of these manufacturing steps.
SCA	= similarity coefficient algorithm, which is a method to create part families and thereby cells. In this thesis, SCA refers to the Jaccard similarity coefficient that we use to create routing families.
SLP	= Systematic Layout Planning, a method for layout planning that had been proposed by Richard Muther (1961).
(Sub)routing	= a part of the whole routing of a product, which consists of a few manufacturing steps performed consecutively in order to manufacture the product.

Chapter 1: Introduction

This chapter introduces the main points of the bachelor assignment. It starts with the identification of the core problem from a problem cluster, with a motivation of the choice for the core problem. Further on, the stages of the research approach with deliverables at each stage are defined to explain the direction of the bachelor project. Finally, the research scope clearly defines the limitations of the research taking into consideration the time available.

1.1 The company

The research assignment will be performed at Company X, which is a sheet metal supplier who produces a continuous flow of sheet products, frames and assemblies. The production facility is located at a plant where approximately 100 people are working.
Company X specializes in engineering and producing high-quality specialized sheet material for the Original Equipment Manufacturers (OEM), so it does not produce its own products. The products are customer specific, either designed by the customer itself or engineered by company's engineering department.

1.2 Problem identification

Problem cluster

Company X is a supplier and therefore does not manufacture its own products. The organization maintains a make to order strategy, meaning that the production only starts if there is an order. The company doesn't produce its own products, but it manufactures it for OEM. Collaboration during the entire product life cycle is important, starting at product development and extending to the required logistical services. As such, the company has a diversified product mix, where a few products are the same. Each part in their database has its own default routing in the default part data. This routing dictates in which order operations need to be performed. Because of the highly varied product mix and the absence of an overview of products with the same production sequence, there are many routings within the production facility. This causes a lot of traffic of parts between the departments.

The problem cluster in figure 1.1 presents all problems Company X is currently facing. The red boxes indicate the possible core problems, that are responsible for the costs (green marked). The purpose of a problem cluster is to get insight in all problems of a company and find the causes of these problems. The problems that are not triggered by another problem, or simply do not have a cause, are considered as a possible core problem. Only core problems can be handled in order to fix the problems in the company. In our case, three possible core problems can be defined:

1) No research is being done about a tool.
2) Grouping of similar machines in departments.
3) Physical production layout.

The first core problem says that the company hasn’t done any research about the methods and software tools that quantitatively analyze the routings within the factory. The company's demand fluctuates in time and so does the routings. Because of the fluctuating product mix, and thereby the fluctuating routing a tool that can identify the predominant routings is very desirable for the company.
The second and the third core problem refer to the layout of the factory. The factory owns a functional layout, which means that there are departments in which similar machines are grouped together. All departments have their own area in the production facility. In short, the second core problem indicates the organizational structure of the factory, while the third core problem points to the physical layout.

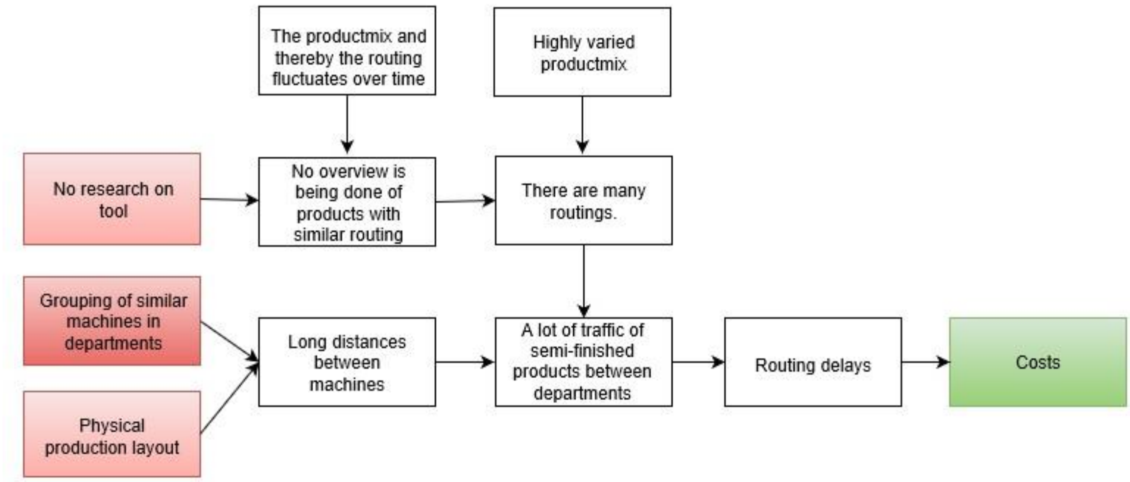

Figure 1.1 Problem cluster of Company X

Problem statement

The problem is the functionally oriented layout of the production facility. This functional manufacturing system refers to a facility design in which all similar machines or personnel with similar function are grouped together. The factory is arranged as a functional layout with a grouping of common process equipment, as opposed to being laid out for process flow. The result of a factory layout based on grouping common equipment is that products must flow from department to department through the manufacturing process. The result may be dramatic in production scheduling and control as well as excessively long queue times.

Relevance of the problem

A lot of traffic of parts occurs within the factory, as the parts need to be routed between departments. The second core problem is chosen as the definitive problem, which is being handled in this project. We chose this second problem, because it's connected with the first possible core problem: "No research is being done about a tool". This possible core problem will be solved, while dealing with the real core problem, as we first need to identify the common production routings in order to solve the problem. To be able to do this we will need a tool that can extract predominant routings in a database of million entries. A tool is needed, because of the product mix, and thereby routing, fluctuates significantly over time. After that, we will be able to identify which routings are suitable for being processed in production cells, rather than being routed over functional departments.

Research objective and research questions

The objective of the research is to find out whether production cells might be an option for company's (sub)routings. Cell layout is an attempt to bring some order to the complexity of product flows in the factory. The suitability of production cells will be examined based on the identified predominant routings. If it's an option, routings that are suitable for being processed in production cells, rather than being routed over functional departments will be investigated.

1.3 Research question and sub questions

Research question: Which (sub)routings are more suitable for cellular manufacturing than for functional manufacturing?

Sub questions:

1. **What does the production process look like?**
   a. How does the production process start?

b. How is the routing of a product being determined?
c. What do the production departments look like?

2. **What has been written in the academic literature regarding the problem Company X is facing?**
   a. How can the presented problem be analyzed or has been analyzed before?
   b. Which methods are available for analyzing/extracting predominant routings?
   c. Which methods suit my problem?
   d. What is known about cellular manufacturing?
   e. Which clustering methods can be used for cell formation?
   f. Which conditions regarding the product mix need to be met when designing a production cell?
   g. How can you identify which routings are suitable for production cells and which for functional layout, when there's a varied product mix?
   h. What factors are important in deciding which routings should be processed in a production cell and which should have a routing over departments?
3. **What is the current routing mix of Company X and what are the common (sub)routings?**
   a. How many different routings can be determined?
   b. What is the frequency of the routings in the mix?
   c. Which common (sub)routings are available?
4. **What do the results of the chosen clustering methods say about using manufacturing cells?**
   a. Which routing families can be created with the clustering methods?
   b. Are production cells an option for (a subset of) company's routing mix?
   c. Which (sub)routings are suitable for being processed in a cellular production and which machines should be grouped together in cells?

1.4 Research approach

The research question is an action problem and the knowledge problems are mentioned in the sub questions. The knowledge problems exist because there is a lack of knowledge and therefore some information needs to be gained. These knowledge problems have to be solved one by one in order to solve the action problem. By sequentially dealing with these knowledge problems, we come closer to the solution of the action problem. Five stages can be defined to arrive at the intended solution.
1) Analyze the current situation. The bachelor thesis starts with the analysis of the current production process that clarifies how the routing of products are being determined and how the production actually starts. Thereafter, a literature review is being conducted to gather information about the ways to solve the action problem Company X is facing. Based on the results of the literature review, we will choose the most appropriate method for analyzing the common routings in the production order data and the most appropriate method to cluster the routings into families and thereby create cells.
2) Analyze the production order data stored in the ERP system. Analyzing the production order data is necessary for performing the Pareto analysis and the Production Flow Analysis. Information about the production orders such as the routing of the products are retrieved from the ERP system.
3) Extract the common routings. By means of the first Pareto analysis the most frequently performed operations are identified. The second Pareto analysis reveals the predominant routings which only exist of the operations found with the first Pareto analysis.
4) Cluster the routings. The routings found with the Pareto analyzes are being used in the clustering analysis. The clustering methods reveal which routing families can be created and how these families can be assigned to cells. This stage involves the evaluation of the clustered families and the review whether production cells might be an option for company's routing mix or not.

5) Classify routings into cellular vs. functional layout. After evaluation of the results, a conclusion can be drawn about the suitability of manufacturing cells for the production environment of Company X and the routings that are suitable for being processed in cells are confirmed.

Deliverables
Three deliverables can be identified:
1) Identification of the clustering method(s).
2) Identification of the predominant routings in the factory.
3) Conclusion about the feasibility of the cellular layout based on the clustering results.

Scope of research
The realization of a production cell depends on many factors such as: parts that can be processed in the cell, space to locate a cell, the machines in which the parts can be handled, the workers that can be assigned to the respective machines and the investment needed to design a cell. This research is about finding out whether a production cell can be realized given the highly varied product mix. This study will give an advice on the basis of the detected routings that are clustered in the families.

Inclusion

The project concerns the development of a method to analyze the common routings in a highly varied product mix, based on the production order data from the ERP database. Based on the found common routings, the feasibility of production cells will be investigated. So the project should conclude whether production cells can be used for some (sub)routings or not.

Exclusion

Outside the scope of this research are the cost and the investment in a production cell and the design of the production cell. The project does not conclude if it's more profitable to use production cells, than routing over functional departments. Other facility layouts including product layout and fixed position layout are also outside the scope of this research. So the market on new technology or alternatives, other than cellular manufacturing, won't be studied. Some research topics that are beyond of this project, but can be investigated as an extension of this project are related to the cost and the investment in the production cell and the design of the production cell. Some "nice to know" questions related to the design of the production cell are:
-Should the company design a U/O production cell to the identified routings?
-Are there any constraints on using the existing machines?
-Which operators can be assigned to the machines in the cell?

Next questions concern the cost and investment in the project:
-Will there be extra costs involved in the investment in machines and redesign of the production cell?
-In terms of cost, is it better to use production cells for the identified (sub)routings?

Chapter 2: Research design

This chapter motivates the development of the research design and the conceptual framework of the research in which literature of representative scientific and professional resources has been integrated. The first section presents the research method in which the approach for solving the knowledge problems is explained and the variables that are investigated in the project are clarified. The second section presents the data collection and analysis methods for each sub question. In the third section, we chose a theoretical perspective to define the main constructs and to develop a theoretical framework, related to the knowledge problems, which are mentioned in the sub questions.

2.1 Research method

2.1.1 Research approach

The purpose of this research is to describe the routings that can be realized in a cellular manufacturing system. The part of the research in which literature review is conducted, a method is chosen and the routings that are eligible for cellular manufacturing are identified, can be described as a descriptive research. Data stored in the ERP database will by means of a method quantitatively analyzed. The quantitative analysis of the production order data will reveal the predominant routings. Based on the identified routings and the studied conditions, a conclusion will be drawn about the suitability of manufacturing cells.

The first step in converting a work area into a manufacturing cell is to assess the current work area conditions. This means that the current product mix should be identified. Since Company X's product mix and thereby the routing fluctuates over time and is highly diversified, the routing mix of the company is being investigated. A routing-frequency analysis can be used to identify the predominant routings. The second step is the production flow analysis. The common (sub)routings found with the routing-frequency analysis should be broken down into a number of part sets or families. The grouping process involves identifying routings with similarities in manufacturing characteristics, and grouping them into families. Cell formation methods can be used to group routings into families.

The part routing analysis answers the next knowledge questions about the routing mix of the company, which are mentioned in sub question 3:

1) How many different (sub)routings can be determined?

2) What is the frequency of the routings in the mix?

3. Which common (sub)routings are available?

Production flow analysis and the cell formation methods answer the questions about grouping of routings into routing families, which are mentioned in sub question 4.

4) How can the (sub)routings be classified into routing families?

5) Which routing families can be created with the clustering methods?

6)Are production cells an option for (a subset of) Company X's routing mix?

The knowledge questions mentioned above are typical for a descriptive and quantitative research. The results of the part routing analysis and the production flow analysis make the decision for the suitable layout much easier. The volume-variety characteristics of the operation narrows the choice down to one layout option: cellular manufacturing or functional layout. So the volume-variety analysis indicates which products are suitable for the different production layouts. Products that have a low volume-mixed variety combination are suitable for cellular manufacturing, while products that have low volume-high variety combination are eligible for functional layout.

2.1.2 Operationalization of key variables

The relation between the product mix and the facility layout becomes clear during the project. Literature review includes a search for factors that are important in the layout decision process. These factors should help classify products into those suitable for functional layout and those suitable for cellular layout. These factors include the volume and the variety of products.

Problem statement: To what extent does the product mix determine the layout design?
Variables: number of different (sub)routings, the frequency of the (sub)routings, the created routing families, the number of these routing families and the suitable layout.

2.1.3 Limitations of research design

The ERP database is fully loaded with the history production data. Data about the orders belonging to 2015 is being used for the assessment of the current routing mix. Further on, all departments and all routing processes in 2015 is being used in the routing-frequency analysis.

2.2 Data collection methods

Research question	Analysis method	Data collection
1a. How does the production process start?	Analysis of the current situation and observation	-Interview engineers -ERP database -Analysis parts -Analysis production -Analysis departments -Analysis planning
1b. How is the routing of a product being determined?	Analysis of the current situation and observation	-Interview pre-production department
1c. What do the production departments look like?	Analysis of the current situation and observation	-Analysis production -Analysis departments -Interview foreman of each production department -Analysis of the floor plan
2a. How can the problem presented be analyzed or has been analyzed before?	Literature review	-Articles about facility layouts and cellular manufacturing -Books about production management and cellular layout -Critical reviews about cells
2b. Which methods are available for analyzing/extracting predominant routings in a database of millions of entries?	Literature review	-Books about business research methods and production management -Articles about analysis of varied product mix and functional layout -Scientific articles about research methods
2c. Which methods suit my problem?	Discussion with thesis supervisor	-Literature review results

2d. What is known about cellular manufacturing?	Literature review	-Books about facility layout & design and cellular manufacturing -Articles about facility layout & design and cellular manufacturing -Critical reviews about production cells
2e. Which clustering methods can be used for cell formation?	Literature review	- Books about facility layout & design and cellular manufacturing -Articles about facility layout & design and cellular manufacturing
2f. Which conditions regarding the product mix need to be met when designing a production cell?	Literature review	-Articles about production cells -Critical reviews about cellular manufacturing - Books about cellular manufacturing and operations management
2g. How can you identify which routings are suitable for production cells and which for functional layout, when there's a varied product mix?	Literature review	-Books about production management and operations management -Articles about production management and operations management -Critical reviews about production cells
2h. What factors are important in deciding which routings should be processed in a production cell and which should have a routing over departments?	Literature review and analysis of the current situation	-Books about facility layout & design and operations management -Articles about facility layout & design and production cells
3a. How many different routings can be determined?	Results by applying Pareto analysis	Applying Pareto analysis to extract common routings.
3b. What is the frequency of the routings in the mix?	Results by applying Pareto analysis	Applying Pareto analysis to extract common routings.
3c. Which common (sub)routings are available?	Analysis of the current situation	Applying Pareto analysis to extract common routings.
4a. Which routing families can be created with the clustering methods?	Results of PFA and clustering analyzes	-Applying production flow analysis and clustering analyzes.
4b. Are production cells an option for (a subset of) Company X's routing mix?	Evaluation of the results	- Applying production flow analysis and clustering analyzes.
4c. Which (sub)routings are suitable for being processed in a cellular production and which machines should be grouped together in cells?	Evaluation of the results	- Applying production flow analysis and clustering analyzes.

2.3 Theoretical perspective and model

2.3.1 Explaining choice of theoretical perspective

Based on the gained knowledge from the literature and the results from the clustering methods, the suitability of production cells for Company X's products will be evaluated according to the operations management (OM) perspective. Flow analysis is being done, because it plays an important role in deciding the layout. A flow analysis concentrates on some quantitative measure of movement between departments or activities. Operations management perspective is being used to minimize the complexity of material flow within the factory. Manufacturing cells is an attempt to bring some order to the complexity of flow which is currently operating under a functional layout. Since the layout is designed to facilitate the flow of the product, from raw material to the finished product, the main concern is the flow of materials. A lot of factors affect the flow pattern. The factors include the number of parts in product, number of operations on each part, sequence of operations on each part, number of subassemblies and number of units to be produced.

Brief description of this theoretical perspective

Operations management is the activity of managing the resources that create and deliver services and products. The operations function is the part of the organization that is responsible for this activity. Operations managers are responsible for the design of the operation and its processes and the design of its products. The OM topic covered in this research assignment is the layout and the flow of transformed resources (materials).

2.3.2 Description of the theoretical model based on literature review

The layout of an operation or process means how transforming resources are positioned relative to each other and how various tasks are allocated to these transforming resources. Together, these two decisions dictate the pattern of flow for transformed resources as they progress through the production process (Slack et al. (2013)). To a large extent the objectives of any layout depend on the strategic objectives of the process. Generally, layout should minimize the length of flow for materials through the operation and preferably make the flow clear. The importance of flow to an operation will depend on its volume and variety characteristics. Figure 2.1 presents the theoretical model that shows the relationship between a facility layout and the volume-variety characteristics. According to this model, flow is not a major issue, when volume is very low and variety is relatively high. With higher volume and lower variety, flow becomes an issue. When the variety of products or services reduces to the point where a distinct category with similar requirements becomes evident, but variety is not small, cell layout could become appropriate. Thus, the volume-variety characteristics of the production process will narrow the choice for the layout.

Clear definition of main concepts and variables

In almost all aspects of the industry there is a disproportionate relationship between elements. For example, in typical situations we find that 20% of the output is spread over 70% of the products. This relative proportion is the basis of the product-mix problems. Investigation of the relationships between elements is called volume-variety analysis, which is the basis for deciding which layout arrangement to use – production line, job-shop or a combination.

2.4 Types of layout

2.4.1 Different layouts

In Slack et al. (2013), different types of facility layout are introduced. These are as follows:
<u>Fixed position layout:</u> layout in which the position of a product is located such that it remains largely

stationary, while transforming resources are moved to and from it.
Process layout: layout where similar resources or processes are located together (also called functional layout).
Cell layout: layout in which transforming resources are located with a common purpose such as processing the same types of product together in a cell.
Product layout: layout in which transforming resources are located in a sequence defined by the processing needs of a product.

The figure below shows the process layouts that are appropriate for different volume-variety combinations. The variety of products concerns the similarity or difference between products that are produced. Volume refers to the amount of products produced.

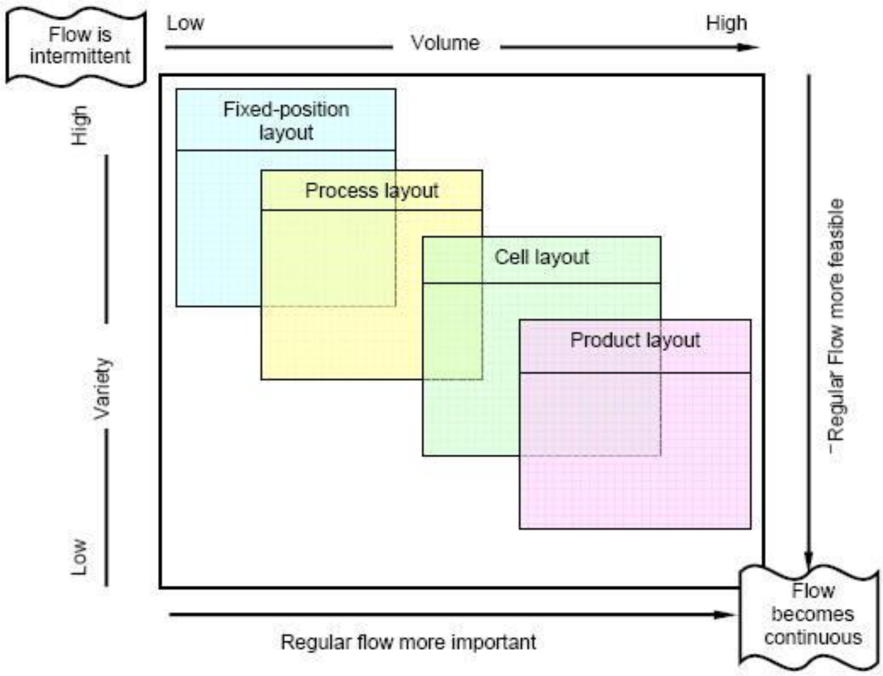

Figure 2.1 Relation between a layout and a volume-variety (Slack et al. (2013))

2.4.2 Processes

The facility layout is related to the manufacturing process type. A process can be defines as a continuous sequence of work tasks, generally carried out in a particular department, which completes a particular major stage in the conversion of materials into products. Different process types imply different volume-variety characteristics for the process. The different processes are defined as next:
Jobbing processes: processes that deal with high variety and low volumes, in which each product has to share the operation's resources with many others. There may be some repetition of flow and activities. A job shop comprises of general purpose machines arranged into different departments. Characteristics of a job-shop production system are the following:

1. High variety and low volume of each product.
2. Use of general purpose machines and facilities.
3. Highly skilled operators who can take up each job as a challenge because of uniqueness.
4. Large inventory of materials, tools, parts.

5. Detailed planning is essential for sequencing the requirements of each product, capacities for each work center and order priorities.

Batch processes: processes that produce more than one product. The variety of the products can vary from low to high. Each batch has its own process route. Characteristics of a batch production system are the following:

1. Production runs are shorter.
2. Plant and machinery are flexible.
3. Plant and machinery set up is used for the production of item in a batch and change of set up is required for processing the next batch.
4. Manufacturing lead time and cost are lower as compared to job order production.

Mass processes: processes which produce items in high volume and relatively low variety. Characteristics of a mass production are the following:

1. Standardization of product and process sequence.
2. Dedicated special purpose machines having higher production capacities and output rates.
3. Large volume of products.
4. Shorter cycle time of production.

Continuous production: processes that are high-volume and low-variety; usually products made on a continuous process are produced in an endless flow. Production facilities are arranged as per the sequence of production operations from the first operations to the finished product. The items are made to flow through the sequence of operations through material handling devices such as conveyors, transfer devices, etc. Characteristics of a continuous production are the following:

1. Dedicated plant and equipment with zero flexibility.
2. Material handling is fully automated.
3. Process follows a predetermined sequence of operations.
4. Component materials cannot be readily identified with final product.
5. Planning and scheduling is a routine action.

2.5 Company X's process characteristics

Company X currently owns a functional layout. This process oriented layout has certain advantages, including flexibility with regard to a changing product mix. The layout imposes no dedication of machines to parts, as the machines are grouped into functional departments. This allows the company to produce a wide variety of parts in small lot sizes.

The internal manufacturing structure of Company X is based on the job shop. Their products are wide variety and their production volumes are very small. Functional layout is implemented to handle the complexity of the production flows. Activities being performed in the cutting department can be characterized as batch processes. There are two machines in the cutting department, where only the CNC combi machine performs 90% of the work. This machine can perform laser- and punching activities to cut out material from the metal. All cutting jobs are performed in batches to minimize the waste in materials. The rest of the activities performed in the factory are jobbing processes. Therefore, Company X's internal manufacturing system can be characterized as a job shop.

Chapter 3: Production process

This chapter answers the first sub question: "*What does the production process look like?" The first section describes how an order is being released and the necessary inputs for the production order process. The second section explains how the routing of products are determined and which departments are involved in this process. The last section presents the categorization of production departments based on the main operations in the factory.*

3.1 Production order process

3.1.1 Types of orders

As mentioned earlier, the company maintains a make to order strategy, meaning the production process only starts when there is an order from a customer. In that sense, a pull strategy is utilized for order release. The company uses MRP to generate production schedules. Currently, two types of manufacturing orders can be distinguished: initial orders and repeat orders.

Repeat order: this type of order can be handled without an approval by the sales-, pre-production- and engineering department and is used for either the framework contracts, repeat orders from a customer or sales forecast. In case of a framework contract the company may decide to manufacture some parts upfront, awaiting final assembly. This process is called the customer order decoupling point, as the demand can be forecasted. After this customer decoupling point, the process can be described as a pull process.

Initial order: this type of order is generated when the sales department enters a client order in the ERP system. In case of a sales offer for a product that has not been produced before, the pre-production department determines the routings, required resources and associated capacity requirements (processing times). Based on the available resources, the planner checks whether it is possible to deliver the products on by the client proposed date or not. If that is not possible, an alternative date is being proposed by the planner. After the date agreement, the ERP generated production order is getting released, required documents are printed and sent to the work floor. The production starts with the printed production orders. These documents go to the departments where the parts are manufactured. The barcode on the production order is scanned at the start and the end of the associated machining process so that the required processing time is maintained and administered. The scheduled orders, backorders and the available time for the then going operation is visible on the screen. In each production department, a screen is available in which the production can be tracked.

3.1.2 Inputs

Two inputs can be defined in the production process: the production planning (which is made by means of MRP) and the production order. The production order exists of the routing of the article, which refers to the production steps that need to be followed in order to finish the product. For every production order, a bill of materials (BOM) is generated specifying required components and materials, a standard routing which dictates the required processing steps and a calculation of required production time. All operations have a work card number.

3.1.3 Software

Company X uses an ERP system from software Company B. A production order is generated, when a specified number of an article needs to be ready on a given date for use or delivery. Every production order is linked with a unique production order number, just like every article is linked with an article number. The ERP system checks the requirements for all articles. If an article is already in stock, then no start up advice is being made. If the article is out of stock, then the ERP system controls the type of the article. There are two types of articles: a manufacturing article and a purchase article. A production order is only generated when the article can be manufactured and therefore is a manufacturing article. If it concerns a purchase article, then a purchasing order is created of the required materials. The final step in the production order creation process is checking which materials the recently made production orders need. The engineering department is responsible for converting the initial client order into a production order. The engineering team enters the data necessary for completing the production order, such as the bill of materials, production steps and the processing time of the article.

3.2 Part routing process

3.2.1 Routing based on the type of order

The product routing refers to the sequence of the production steps necessary to manufacture a product. Muther (1961) defines the routing as: "The process, its operations, and their sequence." Because the company manufactures highly customized products, there are many routings.

The possibility of varying the sequence of operations is largely dictated by the nature of the process, and only minor variations are normally possible. As an example of a routing problem, it might be possible to drill a hole in a shaft before or after finish turning its outside diameter. In making the choice one would consider the effect on handling costs and whether, by drilling before turning, the burs produced by drilling would be removed, making it unnecessary to have an additional operation to remove burrs.
In case of the choice of work centers for operations, there is sometimes a greater freedom of choice. There may be several machines which could be used to do a particular welding or drilling operation. Two factors exist which will affect the selection: the cost of the operation and the balance of capacity. The cost factor will influence the choice towards the selection of machine on which operating costs are lowest.
All in all, the decisions made in routing are closely related to those involved in the choice of material form and in the choice of plant.

Dependent on the type of order, the process before the routing determination proceeds in a different way.
Repeat order: the engineering and pre-production department are not responsible for any work and therefore they are not involved in the routing process. The routing of a product is already stored in the ERP system. Thus, these repeat orders can be directly planned with little supplement from engineering and pre-production department. The identification of purchase parts and manufacture parts are determined on the basis of knowledge and experience of the pre-production department.
Initial order: these orders can be new orders or modified orders. Routing is determined on the basis of the documents received. Documents can be received from the engineering department of Company X or from the client itself. These documents include bill of materials, drawings made in Solidworks and additional information regarding the surface treatment. On the basis of these documents and the knowledge and experience of the pre-production department, the routing is defined in the calculation system from Company C.

3.2.2 Software

Calculation system

Company X uses a calculation system from Company C that is developed for customer-order-driven manufacturing in the sheet metal industry. With this program an offer can quickly and accurately be made. The calculation system makes calculations of processing times based on technology regulations and technology data. Calculation methods and data technology are available for the common routings. These methods and data can easily be modified for a particular situation. Equipment, operations, technology data, calculation methods and standard times can easily be changed or added. The existing tables can be imported.

ERP system

The ERP system from Company B is used to control the production. It is used to capture the data, such as routing, materials and definition of operations. This data is stored in this ERP system so that it can be used for repeat orders. No new routings are defined for repeat orders. Right after the routing is determined with the calculation program from Company C, an export file is created to transfer the information to the ERP system. The routing of all production orders are stored in the ERP system of the company. The parts and the products are stored as "articles" in the ERP System.

3.3 Production departments

Company X has several departments in which people and machines are grouped together according to their function. The factory has a functional layout, meaning all similar machines are grouped into departments. The business office in which people work to facilitate the production process, is functionally oriented just like the factory. The internal manufacturing structure is based on the job shop. Their products are wide variety and their production volumes are very small. Functional layout is implemented to handle the complexity of the production flows.

3.3.1 Departments in the business office

In this project, we restrict us to the business office and the factory. The business office exists of the sales-, engineering- , pre-production- and the planning department. The sales and the planning department are omitted here, since they are not included in the scope of the project.

Engineering department

The engineering team is responsible for the product design. They are responsible for converting the client order into a product by drawings made in Solidworks. The order type determines the production process. As mentioned earlier, there are two types of orders. Before the order is brought to another department, the order type is being checked. If it is a repeat order, then the order goes after planning directly to the work floor. Customers who want something new, work together with the engineering team to define the product dimensions and specifications. Then, the pre-production department determines the routing on basis of the drawings made by engineers and the customer.
The figure 3.1 shows the processing steps in the business office to complete an initial order. The engineering and the pre-production phase is omitted, if the order is an repeat order.

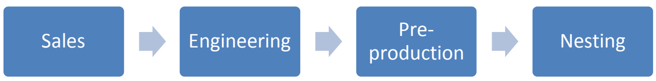

Figure 3.1 Processing steps for an initial order.

Normally, an initial order is generated as follows:
1) The sales department enters a client order in the ERP system.
2) The engineers make the product drawings, possibly in cooperation with the customer.
3) The pre-production team identifies the manufacturing parts and purchasing parts and determines the routing and the materials, so that the production order can be planned and executed.

Pre-production department

The responsibilities of the pre-production department start with receiving the drawings of products and the bill of materials needed for manufacturing. Dependent on the type of the order, Company X receives drawings of the client itself or from the engineering department of Company X. Repeat orders directly go to the work floor, while new or changed orders first pass by the engineering department. The engineering team makes the necessary drawings of the products and prepares a bill of materials (BOM). On the basis of the drawings and BOM, the pre-production engineers can identify from previous knowledge and experience the routing of the parts by means of the calculation tool. Also the parts that need to be bought to manufacture a product is determined by the work engineers. After the routing is defined in this program, the information (materials, processing times, routing) for every article number is manually transferred to the ERP system by the pre-production department.

3.3.2 Departments in the factory

The products are manufactured in a process based factory, in which five production departments can be distinguished on the basis of the following main processes: bending, cutting, welding, painting, and assembling. The next departments can be distinguished in the factory:

Assembling department
Bending department
CNC Cutting department
Painting department
Stainless steel welding department
Steel welding department

Assembling department
Assembling is the last converging process step in the factory. Here all subassemblies are assembled into one final product. There is one main operation in this department: assembling. This process is a handcraft, as no machines are needed.

Bending department
Operations like bending, drilling and punching are being mostly done in the bending department. The cutting department and the bending department are in the same location, as shown in the floor map in figure 3.2. Some bending machines are located in the "assembling projects" department which is next to the sheet metal center. There is a negligible distance and an easy access between these departments, so that these two departments can be seen as a one big department where cutting and bending operations are being performed. Recently, the spot welding machines, normally located in the welding department, are moved to the “assembling projects” department.

CNC Cutting department
Together with the bending department, the cutting department forms the sheet metal center. At the cutting department all parts required to manufacture a finished product are cut out of sheet metal, with the exception of purchase parts. The parts are processed in the CNC laser cutter. The parts first pass the cutting department, as this process should happen before other operations like bending and welding. So manufacturing starts for most of the products with cutting.

Painting department
The products are being power coated in the painting department. There is one painting robot and one degreasing machine available and two sprayers that can be operated by workers. Operations like painting and degreasing are being mainly performed.

Stainless steel welding department
The stainless steel welding department is separated from the steel welding department to avoid any contact between stainless steel and metal particles. One of the most frequently used machines in this

department is the stainless steel welding machine. The most often performed operations are steel welding and stainless grinding.

Steel welding department

Welding is one of the converging process steps, where multiple parts are welded to form a subassembly. The welding department is physically divided into two regions. The first area is the entrance of the factory, while the other area is opposite the paint shop. There are many TIG/ MAG machines which are unequally spread over the two areas. Grinding machines are placed in the first area. Spot welding, welding and grinding are the most frequently performed operations in the steel welding department.

Chapter 4: Literature Review

The literature review answers the second sub question: "What has been written in the academic literature regarding the problem Company X is facing?" This chapter contains the necessary information that gives direction to the research. The chapter starts with a brief introduction about the general approach to layout problems in the literature and continues with the explanation of quantitative methods for the product mix analysis . The third and fourth section describe the cellular manufacturing system and how a process based layout can be turned into a cellular layout. The end of this chapter provides information about the suitability of the layouts under different manufacturing processes and finally concludes with the chosen methods for both product mix analysis and cell formation.

4.1 Approach to layout problems

Many articles and books have been written about layout problems. Many consulted resources suggest to start with a product mix analysis to change or improve an existing layout. One of the effective methods for layout planning was proposed by Muther (1961) which is called systematic layout planning (SLP). Muther (1961) argues that the product quantity analysis (also called volume-variety analysis) is the prevalent factor in deciding the most appropriate layout for a factory. The SLP introduces an approach in which steps can be used sequentially to develop a new layout. The first step of the systematic layout planning is the assessment of the product mix of a company. The second step is the material flow analysis which refers to a quantitative analysis of part moves between departments.

4.2 Quantitative methods for product mix analysis

Product mix analysis should be conducted to find the common routings within the factory. The methods which can be used to quantitatively analyze the most common routings are as follows:

Pareto Analysis

In order to study and simplify production flows in a manufacturing facility, the first step is to identify and separate the significant from the insignificant routings, thereby; focusing the routings contributing to the dominant flows. Routing Mix segmentation can be done using P-Q Analysis which is also known as a Pareto Analysis and (ii) P-Q-$ Analysis which is a bi-criteria extension of the P-Q Analysis that takes into account the cost factor. By using either of these two techniques, dominant routings can be quickly identified using an 80-20 rule. Depending upon the criterion to choose, either Production Quantity Alone or both Production Quantity and Revenue, the 80-20 rule seeks the sample of products that contributes 80% of total Quantity using P-Q Analysis, or 80% of both Quantity and Revenue using P-Q-$ analysis. P-Q Analysis identifies at most three product segments (High, Medium and Low Volume) in the product mix of a job shop. Whereas, P-Q-$ Analysis could identify up to four different segments in the same product mix. The product mix segmentation described above can be very helpful when working with very large datasets.

From-To chart

The most popular method of analyzing flow is to use charts and diagrams. Different methods are suitable for different production volumes. Francis and White (1974) stated that the method of analyzing material flow is dependent on the production volume for the product. Referring to the P-Q chart, the high volume products are candidates for a product layout. Therefore, the assembly chart, operation process chart and flow process chart are used to analyze the flow of materials for the high volume items. When there are several high- and medium- volume products to be produced, the multiproduct process chart is used to examine the interrelationships between products. The from-to chart is used in conjunction with functional layout analysis. Consequently, it is used to analyze the material flow for the low volume- products (Francis and White (1974)).

Since Company X's factory layout is process-oriented with low volume products, a from-to chart can be used to analyze the routing. From-to charts are descriptive models. As such, the construction of a from-to chart does not directly result in the solution of a layout problem. Rather, the from-to chart is a convenient means of reducing a large volume of data into a workable form. By performing this quantitative analysis, the departments having large volumes of item movement can be identified and a layout design in which these departments are located near one another can be developed.

4.3 Cellular Manufacturing

The cellular layout is intended to combine the advantages of both functional layout and process layout. As explained earlier, the functional layout offers flexibility in processing products and a process layout makes a linear flow of products possible. A cellular layout is supposed to inherit the advantages of a functional layout manufacturing a large variety of parts and a product layout dedicated to mass production of one product (in case of cells —one family of products).

A cellular manufacturing system suggests (Goldengorin et al. 2013) that parts that need similar operations and resources should be grouped into product families such that each family is processed within an smaller size manufacturing subsystem—a cell. This means that every cell belongs to one part family and every identified part family can be dedicated to one cell. In this case, the number of part families is equal to the number of cells. Machines in a cellular manufacturing system are grouped in such a way that the physical distance between machines in a cell is small and each cell contains all machines required to process the parts in the corresponding part family. A cellular manufacturing system reduces the complexity of flow by separating the flows but also preserves a certain degree of flexibility as part families are usually robust to changes in the product mix.

Group Technology

Cellular manufacturing is a modern manufacturing system incorporating group technology principles. Group Technology philosophy offers a systems approach to the reorganization of traditional complex job shop and flow shop-manufacturing systems into cellular manufacturing systems. Shunk (1985) provides a good working definition of Group Technology:

"...a disciplined approach to identify things such as parts, processes, equipment, tools, people or customer needs by their attributes, analyzing those attributes looking for similarities between and among the things; grouping the things into fatuities according to similarities; and finally increasing the efficiency and effectiveness of managing the things by taking advantage of the similarities."

Group technology is a technique for identifying and bringing together related or similar components in a production process in order to take advantage of their similarities. Similarities can be based on the geometry, production sequence and function. Family of parts is the process of grouping work pieces into logical families so that they can be produced by the same group of machines, tooling and people.
Cell formation suggests grouping machines into manufacturing cells and parts into the product families such that each family is processed in one cell. It is not necessary for every component to pass to each machine, but the machines within the cell should ideally be capable of carrying out all the operations required in the family. Group technology is used in batch and jobbing production.

Production flow analysis

Production flow analysis (PFA) is a method that is been used to transform a functional layout into a product-oriented layout. It is a technique for planning the change to Group Technology in existing batch and jobbing production factories. This technique examines the product requirements and process grouping simultaneously to allocate tasks and machines to cells in a cellular layout.

When applied to a single factory, the classic framework for manual implementation of PFA consists of four stages, each stage achieving material flow reduction for a progressively reducing portion of the factory:
1)Factory flow analysis: plans the division of the factory into major groups or departments each of which completes all the parts it makes, and it plans a simple unidirectional flow system joining these departments.
2) Group analysis: uses matrix resolution to divide each department in turn into groups, each of which completes all the parts it makes. Providing that one starts with departments which complete parts, GA can, inside certain limits of group size, and with very few exceptional parts, always find groups which complete parts, with no backflow, no crossflow (between groups) and no need to buy any additional equipment.
3) Line analysis: analyses the flow of materials between the machines in each group to find the information needed for plant layout.
4) Tooling analysis: the final technique returns to matrix resolution-in this case matrices of parts and the tools they use. It studies each machine in each group in turn, in order to find "tooling families" of parts which can all be made on the machine with the same set of tools at the same setup and also to find the sequence of loading which will minimize setup times.
Factory flow analysis and group analysis are the main techniques used to find groups and families.

Suitability of the layouts
A manufacturing cell is supposed to handle all parts in one part family. The choice for the layout depends on the manufacturing process type. The layout type is often the physical translation of one type of process. Volume variation characteristics determine the type of process, but there is often overlap between process types in certain volume variation combinations. The relationship and overlap are shown in Figure 4.1. From an operations management perspective, batch processes are the most suitable process types for the cellular layout.

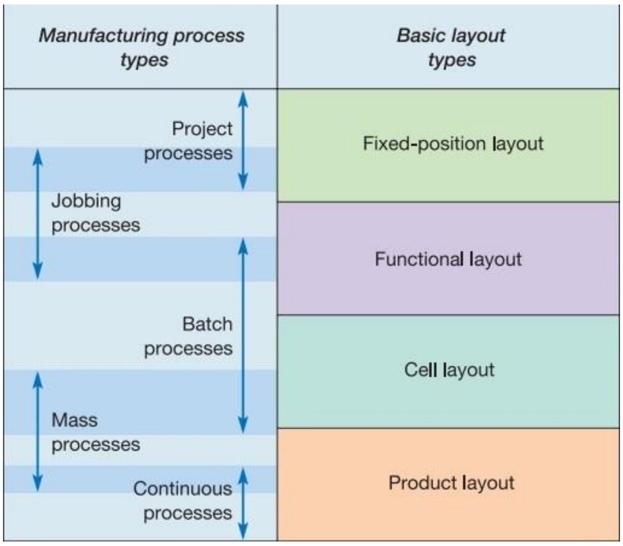

Figure 4.1 The relationship between process types and basic layout types (Slack et al. (2013))

According to Leonides (1991) a functional layout is suitable when the volume of production for any one of product is not sufficient to create a dedicated production line for any one item. This type of layout is appropriate when a large variety of low volume items are manufactured by a shop. Functional layouts generally involve more disorganized flow compared to a product layout. Backtracking and crossing of flows is common. The average overall distance travelled between machines is also high. Because the flow pattern is more disordered and likely to change from day to day, the use of flexible path material handling equipment is most advised. When it comes to path flexibility, industrial vehicles are most prominent. The commonly used industrial vehicles on shop floors today are AGVs, lift trucks and hand trucks.

By means of Group Technology products/parts that require similar manufacturing characteristics are identified and grouped together into a product/part family. If the production volume for a family is large, a product layout can be created to produce that family. Likewise, where a product layout is not justified for a family, a cellular layout is created. Within the cell, machines may be arranged either according to a product or process layout. The attractive feature of group technology from material handling point of view is based on the assumption that by grouping similar products into the same family, the combined production volume of the family may be large enough to justify the use of a product layout in the cell.

The use of volume-variety chart is a method to identify the most appropriate layout for the given manufacturing situation. A volume-variety chart is a histogram of annual production volume by types arranged in a decreasing order of the annual volumes. The height of each block represents the annual volume of production for the corresponding product. The histogram is partitioned into three regions identified respectively as high volume, median volume, and low volume production. All three regions may not be available in all manufacturing situations. The high volume items are produced according to product layouts. Low volume items are produced using a process layout. The intermediate volume items may be produced under product layout, cellular layout or process layout depending on whether product groupings can be formed. The difficulty in using the Volume-Variety is the lack of specificity of what constitutes a large volume, intermediate volume, and low volume. A number that constitutes a large volume production in one industry may become a low volume in another. Therefore, any classification into large, medium, or low volume production must recognize the work contents of the parts.

4.4 Approaches to cell formation

Production-oriented techniques for cell formation

At the highest level, the methods for part family/machine cell formation can be classified as design-oriented or production-oriented. Design-oriented approaches group parts into families based on similar design features. Production-oriented techniques aggregate parts requiring similar processing. The production oriented techniques for cell formation are listed below:

Production Flow Analysis

As described earlier, one of the most successful approaches for designing a layout for high-mix low-volume production facilities is production flow analysis, introduced by Burbridge (1971). It's objective is to provide a method of transforming a process oriented layout to a product oriented layout. This analysis enables the researcher to identify parts with similar manufacturing characteristics and eventually group these parts into part families.

Production Flow Analysis and Simplification Toolkit (PFAST)

PFAST, developed by Irani et al. (1999), extends the manual methods of the production flow analysis to enable the study of production flows in complex high-mix-low-volume environments when the manual methods of PFA cannot be used. Using PFA, complex material flows resulting from process oriented layouts, or functional layouts, are converted into more organized and efficient flows via transformation to product oriented layouts, which are either cellular or flowline layouts. However, this approach is only suitable when the complexity of the production flow is not too high and the product mix clearly contains product families. When the complexity is very high and product families are unclear as of most high-mix-low-volume facilities and job shops, traditional manual PFA can be difficult to apply.

Array based clustering methods

This approach is based upon a production flow analysis which uses routing sheet or process plans. A common feature of this approach is that it sequentially rearranges columns and rows of the machine/part matrix according to an index until diagonal blocks are generated. It operates on a 0-1 machine-part matrix performing a series of column and row manipulations trying to produce small-clustered blocks along the diagonal of the matrix. The machine-part incidence matrix, A, consists of elements aij = 1 if part j requires processing on machine i otherwise aij = 0. Methods of this type have received much attention because of their simplicity. Examples of popular array based clustering methods include direct clustering technique, rank order clustering and bond energy algorithm. Kamrani et al. (1995) analyzed that common criticisms of the array based clustering methods are that (1) identification of exclusive groups in a block diagram sometimes requires subjective judgment; (2) most methods consider only binary routing information and neglect other important cost and operational factors; and (3) in most cases, bottleneck machines must be removed before any machine/part groups can be identified dearly.

Statistical clustering algorithms

Statistical cluster algorithms have been used quite often in the decomposition of manufacturing cells. In particular, use of hierarchical clustering methods such as the single and the complete linkage methods has been studied extensively. This approach requires a calculation of similarity coefficients between each pair of parts or machines. It involves finding a measure of similarity between two machines, tools, design features etc. and using this data to form part families and machine groups. Parts or machines with close similarity coefficients are arranged in the same group. Kamrani et al. (1995) stated that several problems associated with this approach remain to be solved. They pointed out that the selection of clustering criteria and performance measure and the determination of the number of part families are the common problems that can be encountered with the statistical clustering algorithms.

Mathematical programming and heuristic approaches.

Numerous studies of cell formation have been conducted that employ mathematical programming and heuristics to improve clustering effectiveness. These approaches are flexible enough to incorporate most objective functions and constraints in a precise format. Kamrani et al. (1995) believed that mathematical programming and heuristic approaches consider the problem only in a static sense for purely stable manufacturing environments. Additionally, none of the methods considers uncertainty or vagueness, both of which normally are presented in the information required by the models.

Fuzzy clustering and modeling approaches

Most early cell formation research assumes that the information used for cell formation, such as production cost, demand, and processing time, is certain and that the objectives and constraints considered can be formulated precisely. This early research also assumes that each part can belong to only one part family, yet parts may exist whose membership is much less evident. Only a few researchers have addressed the issues of vagueness and uncertainty in the cell formation problem. Fuzzy modeling and clustering approaches may provide a solution in such cases. For instance, a fuzzy c-mean clustering method was used in to form part families (or machine cells) such that a part (or machine) could belong to more than one family (or cell), with different degrees of membership.

4.5 Conclusion

The detailed design of a cellular layout is difficult, partly because the idea of a cell is itself a compromise between process and product layout. To simplify the task, it is useful to concentrate on either the process or the product aspects of cell layout (Slack et al. (2013)). If we choose to concentrate on processes, we could use cluster analysis to find which processes group naturally together. This involves examining each type of process and asking which other types of processes a product or part using that process is also likely to need. In this research we choose to focus on the processes, so that we can use cluster analysis to group (sub)routings into families.

Choice for the cell formation method

First of all, it is important to note that this thesis is a research about finding out if cellular manufacturing is suitable for the manufacturing environment of Company X. As such, only a conclusion will be drawn about the suitability of production cells. Other types of layout are outside the scope of this project and therefore the method of analysis should only test the feasibility of manufacturing cells based on the routings. Given the time available, the next conditions are devised that a method needs to fulfill:
1)Come with a clear conclusion about the use of cellular layout for the different routings.
2)Being able to do an analysis based on the routings (production-oriented technique).
3)Identify the common (sub)routings.
Based on the conditions above, the method that we choose to identify the common (sub)routings and to finally discover whether production cells is possible or not, is production flow analysis introduced by Burbridge (1971). The production flow analysis is a systematic approach, which is divided in clear phases. This analysis is basically the first step to discover whether group technology, or in this case cellular manufacturing, can be introduced to a manufacturing company or not. Production flow analysis can be used in this research, because this method only focuses on the suitability of manufacturing cells in Company X.
Moreover, we are only concerned about the production steps and not the design characteristics of the parts in the factory of Company X. PFA is concerned solely with methods of manufacture, and does not consider the design features or shape of the components. Furthermore, the PFA is a method that is suitable for changing a process oriented layout to a product oriented layout. It is especially devised for planning the change to Group Technology in existing batch and jobbing production facilities, what makes it very suitable for low volume- high variety manufacturing environments. Given that Company X currently has a job shop based manufacturing system, production flow analysis is a good methodology to switch to cellular layout.

The cluster approaches

Designing a manufacturing cell consists of the following procedures: grouping similar parts into part families following their processing requirements, and grouping heterogeneous machines into manufacturing cells and subsequently designating part families to cells. We use Production Flow Analysis as the basis approach, meaning we start with analyzing departmental flows (factory flow analysis) and then use a clustering method to group (sub)routings into families (group analysis). Two clustering methods for routings are being used in this analysis:

- Discrete clustering technique (array based clustering method)
- Similarity coefficient algorithm (statistical clustering algorithm)

The group analysis phase of the production flow analysis is being performed by using the direct clustering technique, which can easily be performed with Excel. First, a machine-routing matrix is constructed, in which each row represents a routing and each column in the matrix represents a machine. The matrix is then being sorted according to the algorithm into blocks, where the each final block represents a cell. The similarity coefficient algorithm is being performed to validate the clustering results of the DCA. This approach involves finding a measure of similarity between two machines. This data is then being used to form routing families and thereby machine groups.

Chapter 5: Part Routing Analysis

This chapter answers the third sub question: "What is the current routing mix of Company X and what are the common (sub)routings?" This chapter presents the sample of routings that is being used in the Production Flow Analysis. Two Pareto analyses are being conducted to first find the sample of operations that are most frequently performed and second to reveal the most common routings that are being used in the clustering analyzes.

5.1 Operations analysis

As mentioned before, all products, parts and sub-assemblies are stored in the ERP system by means of an article number. Because different parts use different combinations of processes in different sequences, a process organization always produces very complex material flow systems. In this thesis, production order data stored in the ERP system belonging to 2015 is used for analysis purposes. This data contains information of products that have been produced in 2015. Data taken from ERP system consists of:

- Production order ID
- Operation ID
- Machine Usage Frequency (calculated)

All operations are stored in the ERP system by means of a unique code. An operation refers here to any production step in the factory that is a part of a routing. Every operation can only be carried out by one machine type, except the CNC combi machine in the cutting department that can perform three different operations.

After the analysis of data stored in the ERP system the next information regarding the operations is obtained:

- 109 different operations
- 21036 production orders that have been made in 2015

45/109 operations are outsourced and can therefore be omitted in the analysis. 30/109 operations are not performed by machines in the factory, e.g. they are done by workers, which therefore can be omitted. Some programming operations are omitted, which are not relevant in this analysis. Another operation that can be omitted is lead bonding, which is being performed in a secluded location by only certain workers. This means the remaining 34/109 operations are taken into account. So 34 operations can be found in the ERP system, in which three operations belong to the combi machine in the cutting department. All other operations are linked to one machine.

Based on the main operations, six departments can be distinguished which are summarized below together with the number of operations belonging to each department. The number of operations decreases, given that not every operation is being performed by a machine. There are a few operations that are only carried out by the workers in the respective department; no machines are available for these operations. Assembling operations performed in the assembling department are mainly performed by workers where only small equipment is required. The last column lists per department the number of operations that is being performed by a machine, probably in presence of a worker.

Department name	Department Code	# of operations	# of operations on a machine
Cutting	W030	10	10
Bending	W040	9	9
Stainless Welding	W060	5	4
Welding	W070	5	4
Painting	W090	4	2
Assembling	W100	1	0
		∑34	∑29

In order to reduce the problem into a manageable size, a Pareto analysis is being conducted. The Pareto analysis of the operations in the factory of Company X presents the 20% of the operations that contributes to the 80% of the production orders.

Figure 5.1 shows the trend of the cumulative percentage of machine usage frequency of 29 operations. The usage frequency of a machine is measured in percentages of different production orders machined on the machine. In the scope of this thesis, a class operations that consist of 80% of the machine usage are used. Other operations are ignored. There are 13 operations having usage of first 80 % of the machines. 9 operations use 15 % of the machine usage. The rest, 7 operations, consist of 5 % of the machine usage. In brief, 13 operations are identified that are being performed frequently on a machine and simultaneously contribute to 80% (of the routing) of the production orders. The figure shows that the operation W041 appears in 17889 production orders of all orders made in 2015. That is equal to (17889/21036) 85,0% of the production orders in 2015.

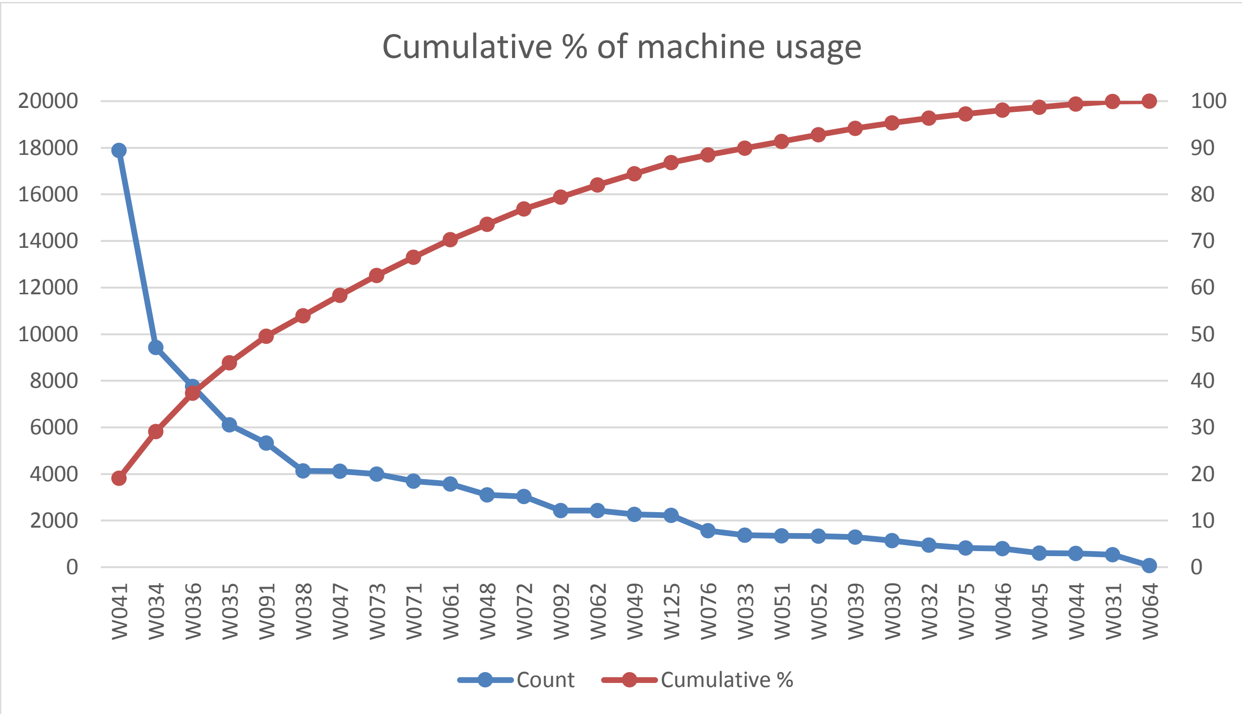

Figure 5.1 Pareto Chart of operations sorted by percentage of machine usage frequency

5.2 Routing analysis

This section presents the routings that are taken into account for the Production Flow analysis with the discrete clustering technique and the similarity coefficient algorithm. As it is mentioned in chapter four, the (sub)routings that result from the Pareto analysis are being used for the clustering. The routing refers here to the sequence of the necessary production steps in order to produce a part/product. Production Flow Analysis can be applied to either all the routes in the company, or to a random sample. The sample greatly reduces the time required for analysis and therefore a Pareto analysis is being conducted to find a sample of routings. This routing analysis is being performed on the basis of the found operations, described in the previous section.

Normally a product-quantity, or in this case a part-quantity, should be performed to create a sample, so that not all parts are being used in the PFA. The product-mix of Company X, and thereby the routing fluctuates over time, that's why a routing-frequency is being used, instead of a part-quantity. The routing-frequency analysis shows the occurrence frequency of the (sub)routings in production orders made in 2015. The frequency is a better indicator for the upcoming orders than the quantity per production order.

In this project we choose to focus on the process aspects of a cellular layout, meaning the exact sequence of the production steps are not important. The idea here is that parts can quickly move between machines in the cell, regardless of the order in which to perform the production steps. The routing analysis is being done taking into account that production steps appear consecutively in the routing. Figure 5.2 presents the first four most frequently occurring (sub)routings. Because the data consisted of a huge number of routings, only the first four of all (sub)routings are visible in the chart below. On basis of this Pareto analysis, it can be concluded that there are 49 (sub)routings that contribute to 80% of the production orders. A list of these (sub)routings is added to Appendix B.

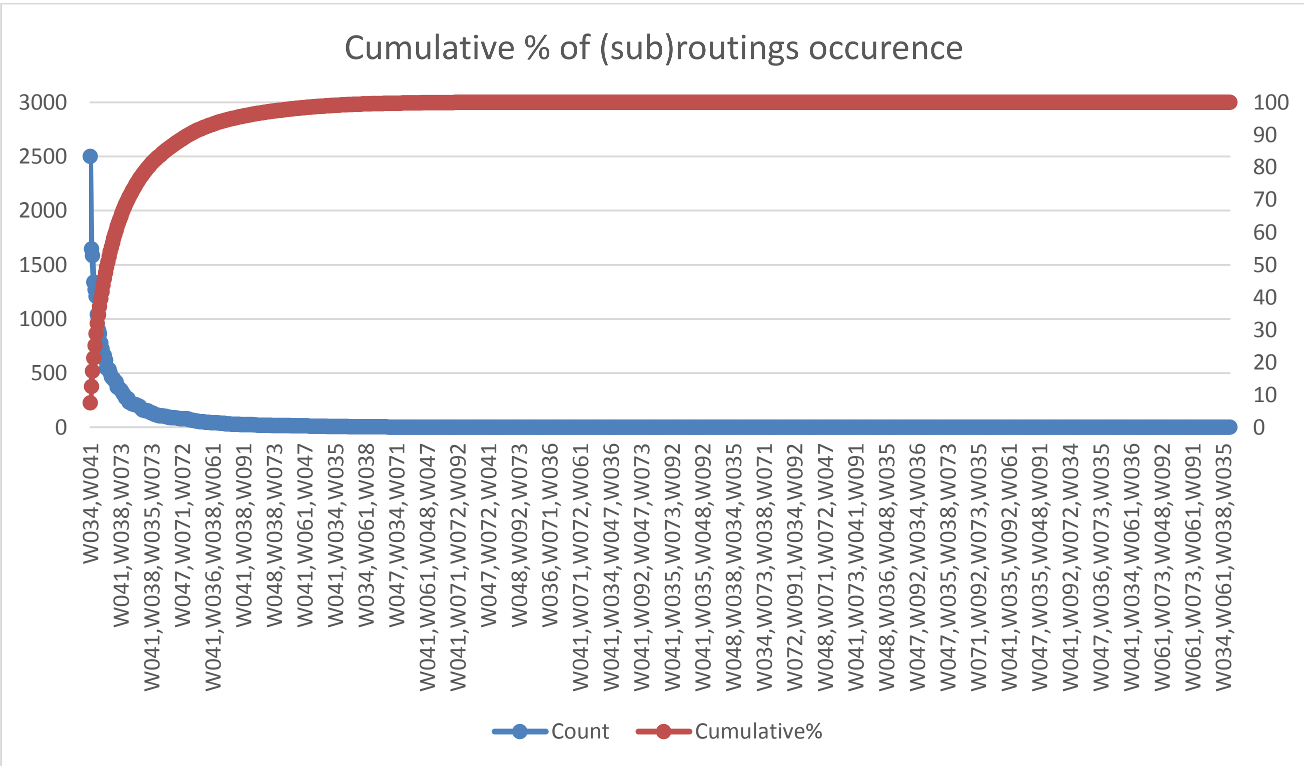

Figure 5.2 Pareto Chart of (sub)routings sorted by percentage of occurrence

Chapter 6: Results of the Clustering analyzes

This chapter answers the fourth sub question: "What do the results of the chosen clustering methods say about using manufacturing cells?" The first section presents the results of the production flow analysis which consists of the factory flow analysis and the group analysis with the direct clustering technique. The second section shows the results of the similarity coefficient algorithm, which validate the results found with the Production Flow Analysis.

6.1 Results of the Factory Flow Analysis

In a sheet metal type industry, a basic flow chart generally shows the routes covered by, say, 85% of the components processed (Burbridge (1971)). The purpose of factory flow analysis is to find the remaining 15% of exceptional component routes, classify them, and then try to modify as many as possible so that they fit the basic flow chart. All simplification is concerned with the elimination of unnecessary variety, and factory flow analysis is concerned with reducing the number of unnecessary interdepartmental routes, in order to simplify the flow system. For Factory Flow Analysis it is only necessary to know the series of departments visited by each (sub)routing. Based on the Pareto analysis of the most common (sub)routings, described in the previous chapter, the flow chart of the main flows in 2015 is constructed. This flow chart is added to Appendix C. Based on the practical insight, all routings that are practically not possible are detected and eliminated from the routing list. The exceptions are all complex routings which do not fit the basic flow chart. A (sub)routing is an exception if in fact this order of production cannot be performed. These exceptions are recognized by a very low occurrence frequency compared to the other (sub)routings. An example of a eliminated routing consists of the operations painting and bending performed consecutively. Practically, this sequence of production steps is not possible, because the paint on the part gets off immediately after bending. Another example is the (sub)routing: bending, cutting. Here, the order of operations is not realistic, since the part that has been cut, can break down during bending.

The flow chart in the Appendix is simplified by eliminating routings that can be considered as an exception. The simplified chart that arises from eliminating exceptions is given in figure 6.1. This flow chart shows that production orders mostly start with a cutting operation, if that is needed and end with a welding or painting operation.

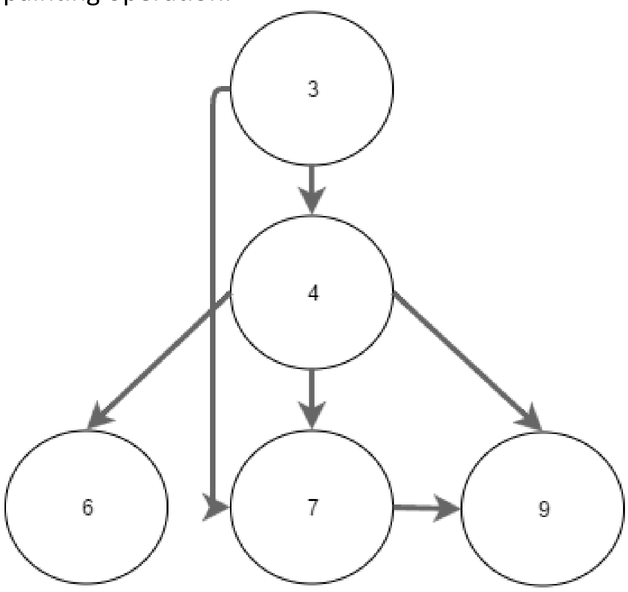

Figure 6.1 Simplified basic flow chart

The departments are given with the following numbers:

- 3 = Cutting department
- 4= Bending department
- 6= Stainless steel welding department
- 7= Steel welding department
- 9= Painting department

6.2 Results of the Group Analysis

The second phase of the Production Flow Analysis is the group analysis which is performed with the discrete clustering technique. By means of the direct clustering technique three cells are created.
The first cell contains the following machines:

1. CNC combi machine
2. CNC laser trumph machine
3. Deburring machine
4. Bending machines
5. Pemserter machines
6. Assembling bending machines
7. Stainless steel welding machine
8. Stainless steel spot welding machine

The second cell contains the following machines:

1. TIG/MAG welding machines
2. Grinding machines
3. Painting machine

The third cell contains one machine:

1. Degreasing machine

The first cell contains the machines that are currently placed together in the sheet metal center, because the bending department and the cutting department are in the same location. Based on this clustering technique, it can be concluded that the machines in the bending and the cutting department should be located next to each other in the sheet metal center.
The second cell exists of the machines of the steel welding and the painting department. The MIG/TIG machines are currently spread over two locations: welding department (entrance) and the welding department opposite the painting department while the painting machine is located in the painting department. This cell can ideally be placed in the painting department, as the painting machine can hardly be moved. Currently, there is not enough space in the painting department, but we assume here that Company X makes space for this cell.
The third cell consists of only one machine, the degreasing machine which is currently placed in the painting department.

Assuming that the locations of these cells are determined as described above, we can find out if any reduction in flows between departments can be perceived. Table E.2 in the Appendix shows that a decrease of 32.4% in departmental flows can be achieved after implementing cells in given locations. The decrease in departmental flows is calculated with the 100 most occurring routings in 2015.

The clustering with the PFA shows still some inefficiencies, because two cutting machines (CNC combi and CNC trumph) and two bending machines (bending machine and pemserter) appear in almost all routings in the matrix and thereby in all cells. There is only one machine available of both cutting machines. There are currently four bending machines available that can be moved to the three cells. We ignore the possibility of moving bending machines to all cells, because it won't be very efficient. Almost all orders starts with a cutting operation, that is why it is not efficient to distribute these bending machines over the three cells. The parts must be first cut in the first cell, and then be moved to the second or the third cell in order to be processed further. We can say this on the basis of the practical insight and the experience of the expert in the company, but can also prove it with numbers calculated on the basis of information retrieved from production order data in the ERP system. These calculations are based on the routing-frequency analysis of 2015, given in table B.2 in the Appendix. The table below gives the percentage of the probabilities that a cutting operation can be performed before a specific (sub)routing. The W03% in the first column refers to any cutting operation in the first cell that should be performed before the rest of the given subsequent operations. The third column presents the percentages of the probabilities that any cutting operation is being performed before a routing, while the last column indicates the probability of a cutting operation being performed by a cutting machine in the first cell before a routing.

(sub)routing (codes)	(sub)routing (names)	Probability in %	Probability in %
W03%-W041-W061	Cutting-bending-stainless steel welding	80.9	72.1
W03%-W041-W071	Cutting-bending-steel welding	46.1	41.2
W03%-W041-W072	Cutting-bending-grinding	0	0
W03%-W041-W073	Cutting-bending-spot welding	90.7	84.7
W03%-W041-W091	Cutting-bending-painting	98.3	92.1
W03%-W041-W092	Cutting-bending-degreasing	93.8	78.2

These results prove that it is not better to place one of the four bending machines in the second or the third cell, because in most cases the routings that are processed in the second and the third cell are preceded by a cutting operation in the first cell. This means that part routings that are similar to one of the routings in the second or the third cell initially need to visit the first cell. Furthermore, the operation performed by the pemserter machine (W047) also shows inefficiencies. This operation appears in the routings of the second and the third cell. Since there are two pemserter machines available, it is possible to place one of these machines in the second or the third cell. Calculations (table E.3 in the Appendix) show that the decrease in departmental flows is equal to 34.2% given that one of the pemserter machines is placed in the first cell and the other one is placed in the second cell so that the cell [W047,W071,W072,W091] is created. This percentage is due to the routings [W047,W071] and the [W047,W071,W072]. The table below gives the percentages of the probabilities that a cutting operation can be performed before these (sub)routings. The W0% in the first column refers to any operation in the first cell that should be performed before the next operations in the routing. The results prove that the implementation of the cell [W047,W071,W072,W091] is not a better option despite the 34.2% decrease in departmental flows, because these routings are with a probability of 100% preceded by an operation in the first cell.

(sub)routing (codes)	(sub)routing (names)	Probability in %	Probability in %
W0%-W047-W071	W0%-pemserter-steel welding	100	100
W0%-W047-W071-W072	W0%-pemserter-steel welding-grinding	100	100
W0%-W047-W092	W0%-pemserter-degreasing	84.2	84.2

The decrease in departmental flows is equal to 34.9% if one of the pemserter machines is placed in the first cell and the other one is placed in the third cell, thereby creating the cell [W047-W092]. This decrease is due to the routing [W047-W092]. The probability that an operation from the first cell is performed before the routing [W047-W092] is equal to 84.2%. This means that parts that have the (sub)routing [W047-W092] in their routing initially need to visit the first cell in 84.2% of the cases. Despite the greater decrease in departmental flows (34.9%), creating the cell [W047-W092] brings little improvement [table E.4].

6.3 Results of the Similarity Coefficient Algorithm

The results of the similarity coefficient algorithm has been summarized in a dendogram. The table below shows the numbers used for machines with the similarity coefficient algorithm.

NUMBER OF THE MACHINE	MACHINE NAME	NUMBER OF THE MACHINE	MACHINE NAME
1	Degreasing machine	**7**	Assembling bending machine
2	Painting machine	**8**	Pemserter machine
3	Grinding machine	**9**	Bending machine
4	TIG/MAG welding machine	**10**	Deburring machine
5	Stainless steel spot welding machine	**11**	CNC laser trumph
6	Stainless steel welding machine	**12**	CNC combi machine

The dendogram in figure 6.2 shows that the number of cells depends on the desired similarity between machines. The aim of the similarity coefficient algorithm is to minimize the number of the cells. This brings us to a similarity of 15% between the machine pairs and the creation of the same three cells:

First cell: - CNC laser combi, CNC laser trumph, deburring machine, bending machines, pemserter machine, assembling bending machines, spot welding machines and stainless steel welding machines

Second cell: - grinding machine, painting machine and TIG/MAG machines

Third cell: - degreasing machine

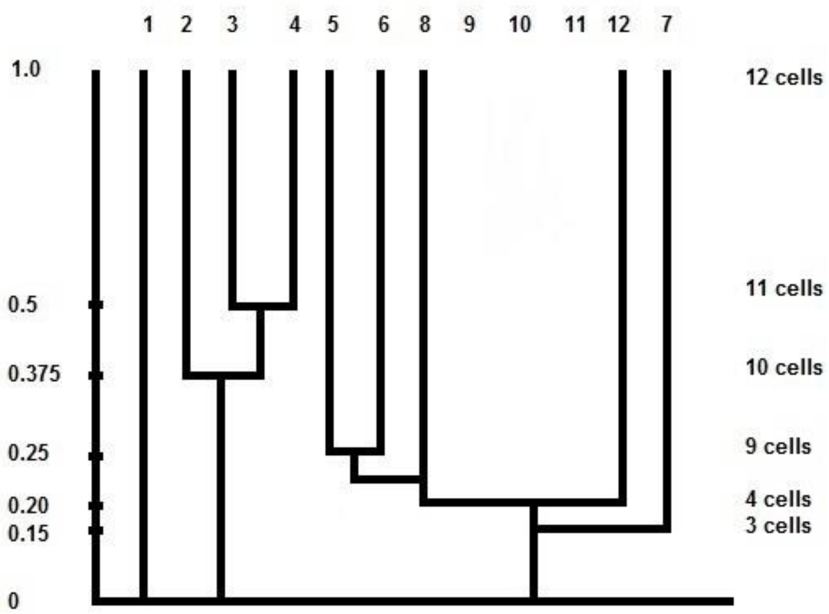

Figure 6.2 Dendogram of the results of the similarity coefficient algorithm

7. Conclusion, recommendation and future research

This chapter answers the research question: "Which (sub)routings are more suitable for cellular manufacturing than for functional manufacturing?"

7.1 Conclusion

The objective of this research is to analyze if there is a business case to create cells in Company X.
The conclusion is based on some assumptions about the location. We assumed that the first cell is located in the sheet metal center and the second cell is located in the painting department.

First of all, it can be concluded that it is possible to create cells in Company X. The similarity coefficient algorithm and the direct clustering technique result in the same three cells. By using the similarity coefficient algorithm we validated the results of the direct clustering technique. Since the two different clustering methods result in the same cells, we can say that the clustering that results from these two methods is a good clustering.

The proposed facility layout that results from the three cells does not differ too much from the current layout. The changes between the factory layout with the three cells and the current facility layout is summarized below:
1) Seven machines in the first cell are currently placed in the same location. Only the stainless steel welding machine is placed in the stainless steel welding department.
2) The welding machines and the grinding machine in the second cell are currently located next to each other in the welding department. The painting machine is set down in the painting department. The degreasing machine is located in the painting department.

We quantitatively proved that the decrease in departmental flows is equal to 32.4% in case the three cells are created in Company X. This percentage is due to five routings. The table below, which is derived from table E.2 in the Appendix, presents the routings that actually cause the decrease in flows between departments. We can see that 57.3% of the decrease in flows is due to the (sub)routings in the second cell. By creating the second cell the decrease in flows is equal to 1441 part moves that is equal to 57.3% of all moves. The other three (sub)routings belong to the first cell and cause 42.7% of the decrease of all departmental moves.

(Sub)routing	# of orders in 2015	# of flows before cell	# of flows after cell	per year before cell	per year after cell
W072,W091	779	1	0	779	0
W072,W091,W071	662	1	0	662	0
Sum				1441	
					0.573
W041,W061	544	1	0	544	0
W061,W073	309	1	0	309	0
W041,W038,W061	219	1	0	219	0
Sum				1072	
					0.427

7.2 Recommendation

This thesis gives a recommendation about implementing cells based on the routings. The use of manufacturing cells can be recommended to the production department of Company X.
Based on what is found with the clustering analyzes, we can say that Company X should create the first and the second cell. The table in the previous section proves that the decrease in departmental flows is due to the creation of the first cell containing cutting, bending and stainless steel welding machines and the second cell containing the steel welding machines, the grinding machine and the paint shop. We quantitatively proved that placing the stainless steel welding machine next to the machines in the sheet metal center contributes to 42.7% of the total decrease (32.4%) in departmental moves. The moving of the steel welding machines in the painting department contributes to the 57.3% of the total decrease (32.4%). The decrease in distance between machines after implementing cells in the given locations is equal to 42.6% and the decrease in travel time is equal to 38.4% (see Table E.6 in the Appendix).
We can recommend to place the stainless steel welding machine in the sheet metal center where other bending and cutting machines are currently located. Furthermore, we can recommend to create the second cell which consists of the TIG/MAG welding machines, the grinding machine and the painting shop. The (sub)routings suitable for being processed in the first and the second cell are added to Appendix F.

The painting machine and the degreasing machine are almost not movable and currently there is not enough space to place the welding machines next to the painting machine in the painting department. If Company X decides not to make space free for the welding machines, then there is an alternative option. The company can decide to locate the welding machines in the welding department opposite the paint shop. The distance between this location and the painting department is approximately 50 meters. This means that the parts still need to be moved from the welding department to the paint shop, but the distance and thereby the travel time would still be reduced. The decrease in departmental flows is in this case equal to 22.4%. The decrease in travel time would be 37.8% [table E.6 in Appendix].

7.3 Future research

This research is about finding out whether cellular manufacturing can be introduced in the company based on the production flows within the factory. That is why this analysis makes a recommendation based on the routings. Based on the routings, we can recommend to create cells within the factory. There are other factors that might influence the suitability of manufacturing cells. It is possible that it is not beneficial for Company X to create cells because of some other factors like space requirements. For sure there are other layouts that can be investigated as well. The hybrid of the functional layout and the cellular layout can be suitable for the company. Therefore, it is good to develop layout alternatives. Some nice to know research areas that might affect the decision to create cells are the following: space requirements, layout alternatives and the cost and investment in the cells.

References

Anon., n.d. *Benefits from Lean and Cellular Manufacturing.* [Online]
Available at: http://www.strategosinc.com/lean_benefits.htm
[Accessed 16 March 2016].

Goldengorin, B., Krushinsky, D. & Pardalos, P. M., 2013. *Cell formation in industrial engineering.* s.l.:Springer.

Heragu, S. S., 2008. *Facilities design.* s.l.:CRC Press.

Inman, R. A., n.d. *Cellular Manufacturing.* [Online]
Available at: http://www.referenceforbusiness.com/management/Bun-Comp/Cellular-Manufacturing.html
[Accessed 28 March 2016].

Kamrani, A. K., Parsaei, H. R. & Liles, D. H., 1995. *Planning, design and analysis of cellular manufacturing systems.* s.l.:Newnes.

Khaewsukkho, S., 2008. *New approaches for design of high-mix low-volume facilities,* Columbus: The Ohio State University .

Leonides, C. T., 1991. *Manufacturing and Automation Systems: Techniques and Technologies: Advances in Theory and Applications, Part 2 of 5.* first ed. San Diego: Academic Press .

Muther, R., 1961. *Systematic Layout Plannning.* first ed. Boston: Industrial Education Institute.

Shunk, D. L., 1985. *GROUP TECHNOLOGY PROVIDES ORGANIZED APPROACH TO REALIZING BENEFITS OF CIMS.* 4th ed. s.l.:s.n.

Slack, N., Brandon-Jones, A. & Johnston, R., 2013. *Operations Management.* 7th ed. Harlow: Pearson Education Limited.

Suttle, R., n.d. *What Is a Product Mix?.* [Online]
Available at: http://smallbusiness.chron.com/product-mix-639.html
[Accessed 18 March 2016].

Tompkins, J. A., White, J. A., Bozer, Y. A. & Tanchoco, J. M. A., 2010. *Facilities Planning.* fourth ed. s.l.:John Wiley & Sons.

White, J. A. & Francis, R. L., 1974. *Facility layout & Location.* 1st ed. New Jersey: Prentice-Hall.

Intern Resources:

KAM Archive

ERP system

Appendix A: Machines per department

The table A.1 below lists the machines that are currently placed in each department. The fourth column shows how many identical machines are available of each machine type.

Department	Operation	Machine name	Number
Cutting	W034,W035	CNC combi machine	1
	W036	CNC laser trumph	1
	W038	Deburring machine	1
Bending	W041	Bending machine	4
	W047	Pemserter machine	2
	W048	Assembling bending machines (4 machines)	3 + 2 + 2 + 1
	W073	Stainless steel spot welding	2
Stainless steel welding	W061	Stainless steel welding machine	5
Steel welding	W071	TIG/MAG welding machine	12 (6 TIG & 6 MAG machines)
	W072	Grinding machine	6
Painting	W091	Painting machine	1
	W092	Degreasing machine	1

Appendix B: Pareto Analyses

The (sub)routings in 2015 are quantitatively analyzed. This analysis reveals the most common routings in which the operations are performed consecutively. Table B.1 below presents the 20% of the operations that contribute to the 80% of all routings which appear in the production orders in 2015.

Operation	Count	Cumulative count	Cumulative %
W041	17889	17889	19,05
W034	9432	27321	29,10
W036	7759	35080	37,36
W035	6103	41183	43,86
W091	5331	46514	49,54
W038	4130	50644	53,94
W047	4113	54757	58,32
W073	3998	58755	62,58
W071	3692	62447	66,51
W061	3573	66020	70,31
W048	3096	69116	73,61
W072	3035	72151	76,84
W092	2436	74587	79,44
W062	2430	77017	82,03
W049	2261	79278	84,44
W125	2223	81501	86,80
W076	1559	83060	88,46
W033	1370	84430	89,92
W051	1343	85773	91,35
W052	1329	87102	92,77
W039	1286	88388	94,14
W030	1143	89531	95,36
W032	946	90477	96,36
W075	824	91301	97,24
W046	795	92096	98,09
W045	601	92697	98,73
W044	593	93290	99,36
W031	529	93819	99,92
W064	73	93892	100,00

Table B.2 presents the 20% of the (sub)routings that contribute to the 80% of all production orders in 2015.

	Routing	Count	Cumulative Count	Cumulative%
1	W036,W041	2499	2499	7,12
2	W034,W041	1789	4288	12,22
3	W041,W047	1645	5933	16,91
4	W071,W072	1583	7516	21,42
5	W038,W041	1439	8955	25,53

6	W035,W041	1272	10227	29,15
7	W041,W073	1209	11436	32,60
8	W041,W092	1040	12476	35,56
9	W041,W071	896	13372	38,12
10	W041,W048	863	14235	40,58
11	W072,W091	779	15014	42,80
12	W041,W071,W072	721	15735	44,85
13	W035,W038	677	16412	46,78
14	W071,W072,W091	662	17074	48,67
15	W034,W038	617	17691	50,43
16	W041,W061	544	18235	51,98
17	W036,W038	541	18776	53,52
18	W036,W041,W092	531	19307	55,04
19	W041,W071,W072,W091	504	19811	56,47
20	W035,W038,W041	464	20275	57,79
21	W034,W038,W041	449	20724	59,07
22	W035,W041,W047	447	21171	60,35
23	W036,W048	427	21598	61,57
24	W041,W091	418	22016	62,76
25	W036,W041,W047	369	22385	63,81
26	W034,W041,W047	364	22749	64,85
27	W036,W038,W041	355	23104	65,86
28	W038,W041,W073	343	23447	66,84
29	W041,W047,W071	330	23777	67,78
30	W061,W073	309	24086	68,66
31	W041,W047,W071,W072	292	24378	69,49
32	W036,W041,W073	272	24650	70,27
33	W073,W071	267	24917	71,03
34	W034,W041,W073	265	25182	71,78
35	W034,W041,W092	230	25412	72,44
36	W047,W092	229	25641	73,09
37	W038,W041,W061	219	25860	73,72
38	W041,W092,W047	214	26074	74,33
39	W036,W041,W048	213	26287	74,93
40	W034,W047	208	26495	75,53
41	W035,W047	207	26702	76,12
42	W041,W073,W061	202	26904	76,69
43	W041,W073,W071	195	27099	77,25
44	W036,W041,W091	192	27291	77,79
45	W038,W048	179	27470	78,30
46	W034,W048	164	27634	78,77
47	W035,W048	158	27792	79,22
48	W038,W041,W048	157	27949	79,67
49	W034,W073	152	28101	80,10

Appendix C: Factory flow analysis

This annex presents the results of the factory flow analysis which consists of the routing-frequency analysis and the basic flow chart. The routing-frequency analysis reveals the departmental moves within the factory.

Table C.1 presents a list of the departmental moves in the factory. The number of visits between departments is added, while the order of the moves has not been taking into account. This table is derived from the results of the routing-frequency analysis. The routing 3 indicates the number of moves in the cutting department, so it refers to interdepartmental moves.

ROUTING	FREQUENCY
3-4	8479
4	2508
4-7	2105
7	1850
3	1835
4-9	1687
4-3-4	1550
3-4-3	1268
4-3-9	953
7-4-7	916
3-4-7	880
7-9	779
7-9-7	662
4-6	544
4-7-7-9	504
4-4-7	330
4-4-7-7	292
3-4-6	219
4-4-9	214
4-6-7	202
3-7	152

Table C.2 presents a list of the departmental moves in the factory, where the order of the departments in the routing does count and where exceptions are eliminated. For example, routing 3-4 indicates a routing that starts in department 3 and goes to department 4.

ROUTING	FREQUENCY
3-4	8382
4	2508
4-7	1885
7	1850
3	1835
4-9	1657
3-4-9	953
7-9	777
3-4-7	722
4-6	543
4-7-9	504
3-4-6	219

3-7	121

Figure C.1 presents the flow chart that is based on the number of visits between departments given in table C.1. This chart presents the routings that are considered as an exception which are indicated by black arrows.

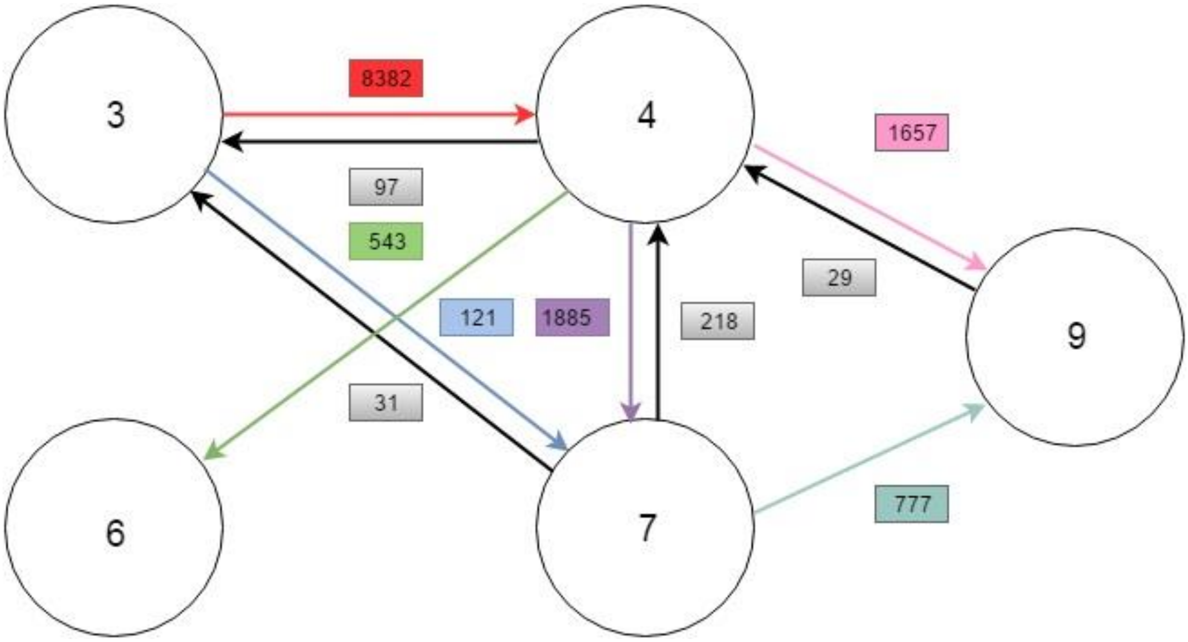

Figure C.1 The flow chart with marked exceptions

Figure C.2 presents the basic flow chart (without exceptions).

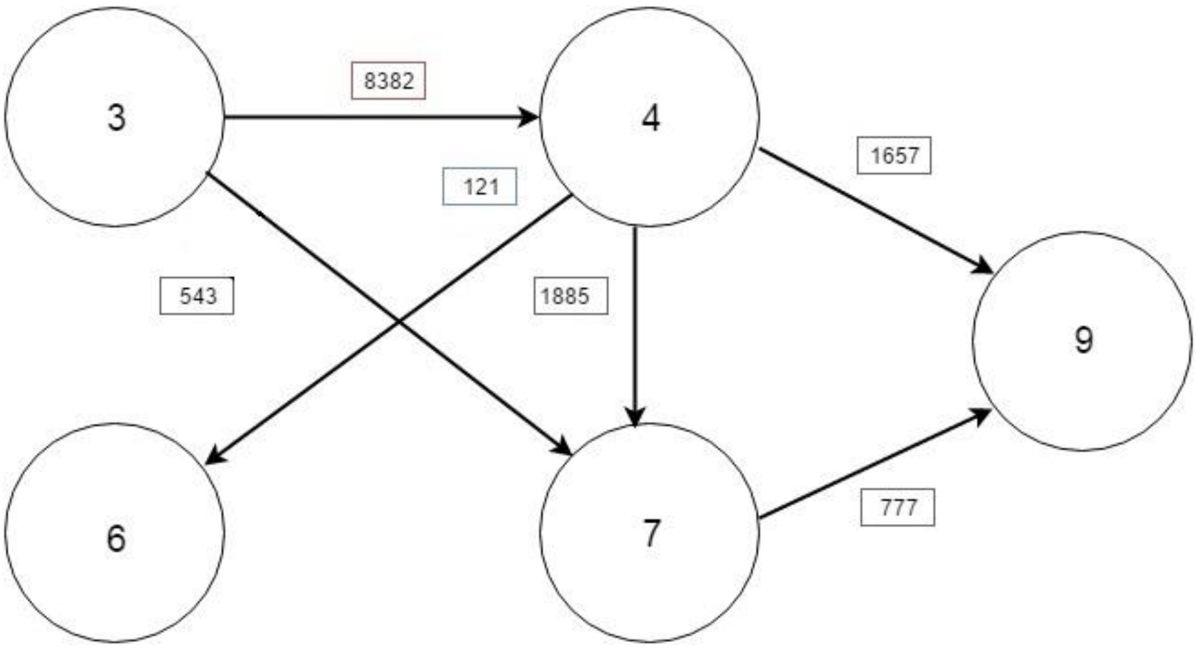

Figure C.2 The basic flow chart

Appendix D: Action plan for the clustering methods

This annex presents the roadmap to create machine cells with the chosen clustering methods. First, the approach of the production flow analysis with the discrete clustering technique is being explained and then the steps needed to cluster with the similarity coefficient algorithm.

Production flow Analysis (PFA) with Discrete Clustering Technique

For Factory Flow Analysis it is only necessary to know the series of departments visited by each (sub)routing. The clustering is being performed in the second phase of the PFA: Group Analysis. For Group Analysis it is necessary to know which machines are visited by each (sub)routing. The Direct Clustering Algorithm is being used to find groups of (sub)routings.

The roadmap to cluster (sub)routings into families and thereby create cells for Company X consists of two phases: creating 1) machine-routing matrix and 2) families. First, a machine-routing matrix is constructed, by following the steps below:

1. Make a list of all (sub)routings.
2. Enter these (sub)routings in any order in the first column in an Excel sheet.
3. Make a list of all machines types needed to make the (sub)routings.
4. Enter the machines in any order in the row. Enter all machine types only once.
5. Enter in the matrix, emerged from the steps 2 and 4, which machines are needed for each (sub)routing in the matrix.

From now on, the direct clustering algorithm is being used to create routing families. Tompkins et al. (2010) provides a good action plan for the discrete clustering technique:

6. Sum the 1s in each column and in each row of the machine-routing matrix. Order the rows in descending order of the number of 1s in rows, and order the columns in ascending order of the number of 1s in each.
7. Beginning with the first row of the (sub)routings of the matrix, shift to the left of the matrix all columns having a 1 in the first row. Continue the process row by row until no further opportunity exists for shifting columns.
8. Column by column, beginning with the leftmost column, shift rows upward when opportunities exist to form blocks of 1.
9. Form the cells.

Similarity Coefficient Algorithm

The idea is to measure similarity between machine pairs. The similarity coefficient we use in the analysis is the Jaccard similarity coefficient. The Jaccard similarity coefficient between a pair of machines can be defined as the number of part types that visit both machines, divided by the number of part types that visit at least one machine. The following is assumed before the start of the calculation.

Let a_{ki} = {1, if routing k requires machine i

0, otherwise}

Let n= number of routings (49 routings in our case).

Let s_{ij}= similarity coefficient between machines i and j.

$s_{ij} = \frac{\sum_{k=1}^{n} aki*akj}{\sum_{k=1}^{n}(aki+akj-akiakj)} = \frac{\#\ parts\ visit\ both\ machines\ i\ and\ j}{\#\ parts\ that\ visit\ at\ least\ one\ of\ i\ and\ j}$

Heragu (2008) describes the similarity coefficient algorithm as following:

1. Start with each machine in a different cell. This means that we have 12 machines, and therefore 12 cells in the beginning.
2. List all possible pairwise combinations of different cells. Calculate the a_{ki} for every pair of machines.
3. Compute the s_{ij} value for each pair.
4. Choose a certain threshold for the s_{ij} and check which machine pairs meet the threshold.
5. Combine machine pairs whose s_{ij} value is equal or above the threshold in a cell.
6. Go back to step #2.

Algorithm notes:

- Determining the SC values:
  - For machine pairs: use s_{ij} equation
  - For cell pairs: determine SC value for each machine in first cell with each machine in second cell and use the largest value.
- In each subsequent iteration, use a lower threshold value.

Appendix E: Grouping analysis

This annex presents the results found with the clustering analyzes. It presents the three cells that are created with the discrete clustering technique and the similarity coefficient algorithm. The tables added to this annex present the percentage of decrease in departmental flows after implementing specific cells.

Figure E.1 Machine-routing matrix which shows the cells that are created by means of the direct clustering technique.

	92	**91**	**72**	**71**	**73**	**61**	**48**	**47**	**41**	**38**	**36**	**34,35**	**SUM**
41,92,47	1							1	1				3
47,92	1							1					2
41,36,92	1								1		1		3
41,34,92	1								1			1	3
41,92	1								1				2
41,71,72,91		1	1	1					1				4
72,91,71		1	1	1									3
72,91		1	1										2
41,36,91		1							1		1		3
41,91		1							1				2
41,71,72,47			1	1				1	1				4
41,71,72			1	1					1				3
71,72			1	1									2
41,71,47				1				1	1				3
41,71				1					1				2
71,73				1	1								2
41,73,61					1	1			1				3
41,73,71					1	1			1				3
61,73					1	1							2
41,38,73					1				1	1			3
41,36,73					1				1		1		3
41,34,73					1				1			1	3
41,73					1				1				2
34,73					1							1	2
41,38,61						1			1	1			3
41,61						1			1				2
41,38,48							1		1	1			3
41,36,48							1		1		1		3
41,48							1		1				2
38,48							1			1			2
36,48							1				1		2
34,48							1					1	2
35,48							1					1	2

41,36,47								1	1		1		3
41,35,47								1	1			1	3
41,34,47								1	1			1	3
41,47								1	1				2
34,47								1				1	2
35,47								1				1	2
41,36,38									1	1	1		3
41,38,35									1	1		1	3
41,34,38									1	1		1	3
38,41									1	1			2
36,41									1		1		2
34,41									1			1	2
35,41									1			1	2
35,38										1		1	2
34,38										1		1	2
36,38										1		1	2
SUM	5	5	6	8	9	5	7	10	32	11	7	16	

Table E.2 presents the number of departmental moves before and after implementing three cells that results from the clustering methods.

(SUB)ROUTİNG	# OF ORDERS İN 2015	# OF FLOWS BEFORE CELL	# OF FLOWS AFTER CELL	PER YEAR BEFORE CELLS	PER YEAR AFTER CELLS
W036,W041	2499	0	0	0	0
W034,W041	1789	0	0	0	0
W041,W047	1645	0	0	0	0
W071,W072	1583	0	0	0	0
W038,W041	1439	0	0	0	0
W035,W041	1272	0	0	0	0
W041,W073	1209	0	0	0	0
W041,W092	1040	1	1	1040	1040
W041,W071	896	1	1	896	896
W041,W048	863	0	0	0	0
W072,W091	779	1	0	779	0
W041,W071,W072	721	1	1	721	721
W035,W038	677	0	0	0	0
W072,W091,W071	662	1	0	662	0
W034,W038	617	0	0	0	0
W041,W061	544	1	0	544	0
W036,W038	541	0	0	0	0
W036,W041,W092	531	1	1	531	531
W041,W071,W072, W091	504	2	1	1008	504
W041,W038,W035	464	0	0	0	0

W041,W034,W038	449	0	0	0	0
W041,W035,W047	447	0	0	0	0
W036,W048	427	0	0	0	0
W041,W091	418	1	1	418	418
W041,W036,W047	369	0	0	0	0
W041,W034,W047	364	0	0	0	0
W041,W036,W038	355	0	0	0	0
W041,W071,W047	330	1	1	330	330
W061,W073	309	1	0	309	0
W038,W041,W073	304	0	0	0	0
W041,W071,W072, W047	292	1	1	292	292
W041,W036,W073	272	0	0	0	0
W071,W073	267	1	1	267	267
W041,W034,W073	265	0	0	0	0
W041,W034,W092	230	1	1	230	230
W047,W092	229	1	1	229	229
W041,W038,W061	219	1	0	219	0
W041,W092,W047	214	1	1	214	214
W041,W036,W048	213	0	0	0	0
W034,W047	208	0	0	0	0
W035,W047	207	0	0	0	0
W041,W036,W091	192	1	1	192	192
W038,W048	179	0	0	0	0
W041,W073,W071	175	1	1	175	175
W034,W048	164	0	0	0	0
W035,W048	158	0	0	0	0
W041,W038,W048	157	0	0	0	0
W034,W073	152	0	0	0	0
W041,W034,W071	152	1	1	152	152
W041,W073,W061	151	1	0	151	0
W036,W047	151	0	0	0	0
W038,W073	137	0	0	0	0
W041,W038,W035, W073	134	0	0	0	0
W041,W071,W072, W073	131	1	1	131	131
W041,W035,W073	122	0	0	0	0
W041,W071,W072, W034	119	1	1	119	119
W038,W041,W073, W061	115	1	0	115	0
W041,W034,W048	114	0	0	0	0
W041,W036,W071	112	1	1	112	112
W071,W091	106	1	1	106	106
W048,W092	104	1	1	104	104

W034,W041,W047, W071	104	1	1	104	104
W047,W048	103	0	0	0	0
W041,W034,W038, W073	103	0	0	0	0
W036,W073	101	0	0	0	0
W041,W071,W048	100	1	1	100	100
W041,W035,W047, W071	96	1	1	96	96
W048,W061	94	1	0	94	0
W041,W073,W048	90	0	0	0	0
W035,W041,W047	88	0	0	0	0
W041,W034,W038, W061	88	1	0	88	0
W047,W071	86	1	1	86	86
W041,W038,W047	86	0	0	0	0
W041,W035,W048	85	0	0	0	0
W041,W071,W072, W035	85	1	1	85	85
W041,W071,W072, W036	84	1	1	84	84
W035,W038,W041, W061	79	1	0	79	0
W048,W073	78	0	0	0	0
W041,W061,W048	78	1	0	78	0
W034,W091	77	1	1	77	77
W036,W041,W047, W071	77	1	1	77	77
W041,W034,W091	76	1	1	76	76
W041,W035,W061	76	1	0	76	0
W036,W038,W041, W073	72	0	0	0	0
W041,W092,W048	70	1	1	70	70
W048,W036,W038	68	0	0	0	0
W047,W073	65	0	0	0	0
W041,W036,W092, W047	64	1	1	64	64
W072,W073	63	1	1	63	63
W071,W092	60	1	1	60	60
W047,W071,W072	58	1	1	58	58
W041,W073,W047	58	0	0	0	0
W036,W041,W073, W071	57	1	1	57	57
W041,W034,W038, W048	53	0	0	0	0
W048,W038,W034	52	0	0	0	0
W041,W038,W035, W048	52	0	0	0	0

W041,W034,W061	51	1	0	51	0
W048,W038,W035	50	0	0	0	0
W041,W061,W073	50	1	0	50	0
SUM	32365	50	35	11719	7920
%DECREASE			-0.30		-0.324

Table E.3 presents the decrease in departmental flows in case three cells are created in which one of the the pemserter machines is placed in the first cell and the other one is placed in the second cell. The decrease in flows is mainly due to the (sub)routings that are marked with a yellow color.

(SUB)ROUTİNG	# OF ORDERS İN 2015	# OF FLOWS BEFORE CELL	# OF FLOWS AFTER CELL	PER YEAR BEFORE CELLS	PER YEAR AFTER CELLS
W036,W041	2499	0	0	0	0
W034,W041	1789	0	0	0	0
W041,W047	1645	0	0	0	0
W071,W072	1583	0	0	0	0
W038,W041	1439	0	0	0	0
W035,W041	1272	0	0	0	0
W041,W073	1209	0	0	0	0
W041,W092	1040	1	1	1040	1040
W041,W071	896	1	1	896	896
W041,W048	863	0	0	0	0
W072,W091	779	1	0	779	0
W041,W071,W072	721	1	1	721	721
W035,W038	677	0	0	0	0
W072,W091,W071	662	1	0	662	0
W034,W038	617	0	0	0	0
W041,W061	544	1	0	544	0
W036,W038	541	0	0	0	0
W036,W041,W092	531	1	1	531	531
W041,W071,W072, W091	504	2	1	1008	504
W041,W038,W035	464	0	0	0	0
W041,W034,W038	449	0	0	0	0
W041,W035,W047	447	0	0	0	0
W036,W048	427	0	0	0	0
W041,W091	418	1	1	418	418
W041,W036,W047	369	0	0	0	0
W041,W034,W047	364	0	0	0	0
W041,W036,W038	355	0	0	0	0
W041,W071,W047	330	1	1	330	330
W061,W073	309	1	0	309	0
W038,W041,W073	304	0	0	0	0
W041,W071,W072, W047	292	1	1	292	292

W041,W036,W073	272	0	0	0	0
W071,W073	267	1	1	267	267
W041,W034,W073	265	0	0	0	0
W041,W034,W092	230	1	1	230	230
W047,W092	229	1	1	229	229
W041,W038,W061	219	1	0	219	0
W041,W092,W047	214	1	1	214	214
W041,W036,W048	213	0	0	0	0
W034,W047	208	0	0	0	0
W035,W047	207	0	0	0	0
W041,W036,W091	192	1	1	192	192
W038,W048	179	0	0	0	0
W041,W073,W071	175	1	1	175	175
W034,W048	164	0	0	0	0
W035,W048	158	0	0	0	0
W041,W038,W048	157	0	0	0	0
W034,W073	152	0	0	0	0
W041,W034,W071	152	1	1	152	152
W041,W073,W061	151	1	0	151	0
W036,W047	151	0	0	0	0
W038,W073	137	0	0	0	0
W041,W038,W035, W073	134	0	0	0	0
W041,W071,W072, W073	131	1	1	131	131
W041,W035,W073	122	0	0	0	0
W041,W071,W072, W034	119	1	1	119	119
W038,W041,W073, W061	115	1	0	115	0
W041,W034,W048	114	0	0	0	0
W041,W036,W071	112	1	1	112	112
W071,W091	106	1	1	106	106
W048,W092	104	1	1	104	104
W034,W041,W047, W071	104	1	1	104	104
W047,W048	103	0	0	0	0
W041,W034,W038, W073	103	0	0	0	0
W036,W073	101	0	0	0	0
W041,W071,W048	100	1	1	100	100
W041,W035,W047, W071	96	1	1	96	96
W048,W061	94	1	0	94	0
W041,W073,W048	90	0	0	0	0
W035,W041,W047	88	0	0	0	0
W041,W034,W038,	88	1	0	88	0

W061					
W047,W071	86	1	0	86	0
W041,W038,W047	86	0	0	0	0
W041,W035,W048	85	0	0	0	0
W041,W071,W072, W035	85	1	1	85	85
W041,W071,W072, W036	84	1	1	84	84
W035,W038,W041, W061	79	1	0	79	0
W048,W073	78	0	0	0	0
W041,W061,W048	78	1	0	78	0
W034,W091	77	1	1	77	77
W036,W041,W047, W071	77	1	1	77	77
W041,W034,W091	76	1	1	76	76
W041,W035,W061	76	1	0	76	0
W036,W038,W041, W073	72	0	0	0	0
W041,W092,W048	70	1	1	70	70
W048,W036,W038	68	0	0	0	0
W047,W073	65	0	0	0	0
W041,W036,W092, W047	64	1	1	64	64
W072,W073	63	1	1	63	63
W071,W092	60	1	0	60	0
W047,W071,W072	58	1	0	58	0
W041,W073,W047	58	0	0	0	0
W036,W041,W073, W071	57	1	1	57	57
W041,W034,W038, W048	53	0	0	0	0
W048,W038,W034	52	0	0	0	0
W041,W038,W035, W048	52	0	0	0	0
W041,W034,W061	51	1	0	51	0
W048,W038,W035	50	0	0	0	0
W041,W061,W073	50	1	0	50	0
SUM	32365	50	32	11719	7716
%DECREASE			-0.36		-0.342

Table E.4 presents the decrease in departmental flows in case three cells are created in which one of the the pemserter machines is placed in the first cell and the other one is placed in the third cell. The decrease in flows is mainly due to the (sub)routing that is marked with a yellow color.

(SUB)ROUTİNG	# OF ORDERS İN 2015	# OF FLOWS BEFORE CELL	# OF FLOWS AFTER CELL	PER YEAR BEFORE CELLS	PER YEAR AFTER CELLS

W036,W041	2499	0	0	0	0
W034,W041	1789	0	0	0	0
W041,W047	1645	0	0	0	0
W071,W072	1583	0	0	0	0
W038,W041	1439	0	0	0	0
W035,W041	1272	0	0	0	0
W041,W073	1209	0	0	0	0
W041,W092	1040	1	1	1040	1040
W041,W071	896	1	1	896	896
W041,W048	863	0	0	0	0
W072,W091	779	1	0	779	0
W041,W071,W072	721	1	1	721	721
W035,W038	677	0	0	0	0
W072,W091,W071	662	1	0	662	0
W034,W038	617	0	0	0	0
W041,W061	544	1	0	544	0
W036,W038	541	0	0	0	0
W036,W041,W092	531	1	1	531	531
W041,W071,W072, W091	504	2	1	1008	504
W041,W038,W035	464	0	0	0	0
W041,W034,W038	449	0	0	0	0
W041,W035,W047	447	0	0	0	0
W036,W048	427	0	0	0	0
W041,W091	418	1	1	418	418
W041,W036,W047	369	0	0	0	0
W041,W034,W047	364	0	0	0	0
W041,W036,W038	355	0	0	0	0
W041,W071,W047	330	1	1	330	330
W061,W073	309	1	0	309	0
W038,W041,W073	304	0	0	0	0
W041,W071,W072, W047	292	1	1	292	292
W041,W036,W073	272	0	0	0	0
W071,W073	267	1	1	267	267
W041,W034,W073	265	0	0	0	0
W041,W034,W092	230	1	1	230	230
W047,W092	229	1	0	229	0
W041,W038,W061	219	1	0	219	0
W041,W092,W047	214	1	1	214	214
W041,W036,W048	213	0	0	0	0
W034,W047	208	0	0	0	0
W035,W047	207	0	0	0	0
W041,W036,W091	192	1	1	192	192
W038,W048	179	0	0	0	0
W041,W073,W071	175	1	1	175	175

W034,W048	164	0	0	0	0
W035,W048	158	0	0	0	0
W041,W038,W048	157	0	0	0	0
W034,W073	152	0	0	0	0
W041,W034,W071	152	1	1	152	152
W041,W073,W061	151	1	0	151	0
W036,W047	151	0	0	0	0
W038,W073	137	0	0	0	0
W041,W038,W035, W073	134	0	0	0	0
W041,W071,W072, W073	131	1	1	131	131
W041,W035,W073	122	0	0	0	0
W041,W071,W072, W034	119	1	1	119	119
W038,W041,W073, W061	115	1	0	115	0
W041,W034,W048	114	0	0	0	0
W041,W036,W071	112	1	1	112	112
W071,W091	106	1	1	106	106
W048,W092	104	1	1	104	104
W034,W041,W047, W071	104	1	1	104	104
W047,W048	103	0	0	0	0
W041,W034,W038, W073	103	0	0	0	0
W036,W073	101	0	0	0	0
W041,W071,W048	100	1	1	100	100
W041,W035,W047, W071	96	1	1	96	96
W048,W061	94	1	0	94	0
W041,W073,W048	90	0	0	0	0
W035,W041,W047	88	0	0	0	0
W041,W034,W038, W061	88	1	0	88	0
W047,W071	86	1	1	86	86
W041,W038,W047	86	0	0	0	0
W041,W035,W048	85	0	0	0	0
W041,W071,W072, W035	85	1	1	85	85
W041,W071,W072, W036	84	1	1	84	84
W035,W038,W041, W061	79	1	0	79	0
W048,W073	78	0	0	0	0
W041,W061,W048	78	1	0	78	0
W034,W091	77	1	1	77	77
W036,W041,W047,	77	1	1	77	77

W071					
W041,W034,W091	76	1	1	76	76
W041,W035,W061	76	1	0	76	0
W036,W038,W041, W073	72	0	0	0	0
W041,W092,W048	70	1	1	70	70
W048,W036,W038	68	0	0	0	0
W047,W073	65	0	0	0	0
W041,W036,W092, W047	64	1	1	64	64
W072,W073	63	1	1	63	63
W071,W092	60	1	0	60	0
W047,W071,W072	58	1	1	58	58
W041,W073,W047	58	0	0	0	0
W036,W041,W073, W071	57	1	1	57	57
W041,W034,W038, W048	53	0	0	0	0
W048,W038,W034	52	0	0	0	0
W041,W038,W035, W048	52	0	0	0	0
W041,W034,W061	51	1	0	51	0
W048,W038,W035	50	0	0	0	0
W041,W061,W073	50	1	0	50	0
SUM	32365	50	33	11719	7631
%DECREASE			-0.34		-0.349

Table E.5 presents the decrease in departmental flows in case the steel welding machines and the grinding machine (W071,W072) cannot be placed in the painting department but are moved to the welding department opposite the painting shop.

(SUB)ROUTİNG	# OF ORDERS İN 2015	# OF FLOWS BEFORE CELL	# OF FLOWS AFTER CELL	PER YEAR BEFORE CELLS	PER YEAR AFTER CELLS
W036,W041	2499	0	0	0	0
W034,W041	1789	0	0	0	0
W041,W047	1645	0	0	0	0
W071,W072	1583	0	0	0	0
W038,W041	1439	0	0	0	0
W035,W041	1272	0	0	0	0
W041,W073	1209	0	0	0	0
W041,W092	1040	1	1	1040	1040
W041,W071	896	1	1	896	896
W041,W048	863	0	0	0	0
W072,W091	779	1	0	779	0
W041,W071,W072	721	1	1	721	721

W035,W038	677	0	0	0	0
W072,W091,W071	662	1	1	662	662
W034,W038	617	0	0	0	0
W041,W061	544	1	0	544	0
W036,W038	541	0	0	0	0
W036,W041,W092	531	1	1	531	531
W041,W071,W072, W091	504	2	2	1008	1008
W041,W038,W035	464	0	0	0	0
W041,W034,W038	449	0	0	0	0
W041,W035,W047	447	0	0	0	0
W036,W048	427	0	0	0	0
W041,W091	418	1	1	418	418
W041,W036,W047	369	0	0	0	0
W041,W034,W047	364	0	0	0	0
W041,W036,W038	355	0	0	0	0
W041,W071,W047	330	1	1	330	330
W061,W073	309	1	0	309	0
W038,W041,W073	304	0	0	0	0
W041,W071,W072, W047	292	1	1	292	292
W041,W036,W073	272	0	0	0	0
W071,W073	267	1	1	267	267
W041,W034,W073	265	0	0	0	0
W041,W034,W092	230	1	1	230	230
W047,W092	229	1	0	229	0
W041,W038,W061	219	1	0	219	0
W041,W092,W047	214	1	1	214	214
W041,W036,W048	213	0	0	0	0
W034,W047	208	0	0	0	0
W035,W047	207	0	0	0	0
W041,W036,W091	192	1	1	192	192
W038,W048	179	0	0	0	0
W041,W073,W071	175	1	1	175	175
W034,W048	164	0	0	0	0
W035,W048	158	0	0	0	0
W041,W038,W048	157	0	0	0	0
W034,W073	152	0	0	0	0
W041,W034,W071	152	1	1	152	152
W041,W073,W061	151	1	0	151	0
W036,W047	151	0	0	0	0
W038,W073	137	0	0	0	0
W041,W038,W035, W073	134	0	0	0	0
W041,W071,W072, W073	131	1	1	131	131

W041,W035,W073	122	0	0	0	0
W041,W071,W072, W034	119	1	1	119	119
W038,W041,W073, W061	115	1	0	115	0
W041,W034,W048	114	0	0	0	0
W041,W036,W071	112	1	1	112	112
W071,W091	106	1	1	106	106
W048,W092	104	1	1	104	104
W034,W041,W047, W071	104	1	1	104	104
W047,W048	103	0	0	0	0
W041,W034,W038, W073	103	0	0	0	0
W036,W073	101	0	0	0	0
W041,W071,W048	100	1	1	100	100
W041,W035,W047, W071	96	1	1	96	96
W048,W061	94	1	0	94	0
W041,W073,W048	90	0	0	0	0
W035,W041,W047	88	0	0	0	0
W041,W034,W038, W061	88	1	0	88	0
W047,W071	86	1	1	86	86
W041,W038,W047	86	0	0	0	0
W041,W035,W048	85	0	0	0	0
W041,W071,W072, W035	85	1	1	85	85
W041,W071,W072, W036	84	1	1	84	84
W035,W038,W041, W061	79	1	0	79	0
W048,W073	78	0	0	0	0
W041,W061,W048	78	1	0	78	0
W034,W091	77	1	1	77	77
W036,W041,W047, W071	77	1	1	77	77
W041,W034,W091	76	1	1	76	76
W041,W035,W061	76	1	0	76	0
W036,W038,W041, W073	72	0	0	0	0
W041,W092,W048	70	1	1	70	70
W048,W036,W038	68	0	0	0	0
W047,W073	65	0	0	0	0
W041,W036,W092, W047	64	1	1	64	64
W072,W073	63	1	1	63	63
W071,W092	60	1	0	60	0

W047,W071,W072	58	1	1	58	58
W041,W073,W047	58	0	0	0	0
W036,W041,W073, W071	57	1	1	57	57
W041,W034,W038, W048	53	0	0	0	0
W048,W038,W034	52	0	0	0	0
W041,W038,W035, W048	52	0	0	0	0
W041,W034,W061	51	1	0	51	0
W048,W038,W035	50	0	0	0	0
W041,W061,W073	50	1	0	50	0
SUM	32365	50	33	11719	7631
%DECREASE			-0.26		-0.224

Table E.6 presents the decrease in travel time per year in case the three cells that result from the clustering analyzes are implemented. The last column indicates the percentage decrease in travel time in case the steel welding machines and the grinding machine that are part of the second cell, are placed in the welding department opposite the painting shop. This means that only the first cell and the third cell are implemented.

(SUB)ROUTİNG	# OF ORDERS İN 2015	DİSTANCE BEFORE CELLS	DISTANCE AFTER CELLS	TRAVEL TIME BEFORE CELLS PER YEAR (SEC.)	TRAVEL TIME AFTER CELLS (1,2,3) PER YEAR (SEC.)	TRAVEL TIME AFTER CELLS (1,3) PER YEAR
W036,W041	2499	0	0	0	0	0
W034,W041	1789	0	0	0	0	0
W041,W047	1645	0	0	0	0	0
W071,W072	1583	0	0	0	0	0
W038,W041	1439	0	0	0	0	0
W035,W041	1272	0	0	0	0	0
W041,W073	1209	0	0	0	0	0
W041,W092	1040	350	350	187200	187200	187200
W041,W071	896	500	350	230272	161280	161280
W041,W048	863	0	0	0	0	0
W072,W091	779	150	0	59983	0	0
W041,W071,W072	721	500	350	185297	129780	129780
W035,W038	677	0	0	0	0	0
W072,W091,W071	662	150	0	50974	0	0
W034,W038	617	0	0	0	0	0
W041,W061	544	400	0	112064	0	0
W036,W038	541	0	0	0	0	0

W036,W041,W092	531	350	350	95580	95580	95580
W041,W071,W072,W091	504	650	350	168336	90720	103824
W041,W038,W035	464	0	0	0	0	0
W041,W034,W038	449	0	0	0	0	0
W041,W035,W047	447	0	0	0	0	0
W036,W048	427	0	0	0	0	0
W041,W091	418	350	350	75240	75240	75240
W041,W036,W047	369	0	0	0	0	0
W041,W034,W047	364	0	0	0	0	0
W041,W036,W038	355	0	0	0	0	0
W038,W041,W073	304	0	0	0	0	0
W041,W071,W047	330	500	350	84810	59400	59400
W061,W073	309	270	0	42951	0	0
W041,W071,W072,W047	292	500	350	75044	52560	52560
W041,W036,W073	272	0	0	0	0	0
W071,W073	267	500	350	68619	48060	48060
W041,W034,W073	265	0	0	0	0	0
W041,W034,W092	230	350	350	41400	41400	41400
W047,W092	229	350	350	41220	41220	41220
W041,W038,W061	219	400	0	45114	0	0
W041,W092,W047	214	350	350	38520	38520	38520
W041,W036,W048	213	0	0	0	0	0
W034,W047	208	0	0	0	0	0
W035,W047	207	0	0	0	0	0
W041,W073,W061	151	400	0	31106	0	0
W041,W073,W071	175	500	350	44975	31500	31500
W041,W036,W091	192	350	350	34560	34560	34560
W038,W048	179	0	0	0	0	0
W034,W048	164	0	0	0	0	0

W035,W048	158	0	0	0	0	0
W041,W038,W048	157	0	0	0	0	0
W034,W073	152	0	0	0	0	0
W041,W034,W071	152	500	350	39064	27360	27360
W036,W047	151	0	0	0	0	0
W038,W041,W073,W061	115	400	0	23690	0	0
W038,W073	137	0	0	0	0	0
W041,W038,W035,W073	134	0	0	0	0	0
W041,W071,W072,W073	131	500	350	33667	23580	23580
W041,W035,W073	122	0	0	0	0	0
W041,W071,W072,W034	119	500	350	30583	21420	21420
W041,W034,W048	114	0	0	0	0	0
W041,W036,W071	112	500	350	28784	20160	20160
W071,W091	106	150	0	8162	0	0
W048,W092	104	350	350	18720	18720	18720
W034,W041,W047,W071	104	500	350	26728	18720	18720
W047,W048	103	0	0	0	0	0
W041,W034,W038,W073	103	0	0	0	0	0
W036,W073	101	0	0	0	0	0
W041,W071,W048	100	500	350	25700	18000	18000
W041,W035,W047,W071	96	500	350	24672	17280	17280
W048,W061	94	400	0	19364	0	0
W041,W073,W048	90	0	0	0	0	0
W035,W041,W047	88	0	0	0	0	0
W041,W034,W038,W061	88	400	0	18128	0	0
W047,W071	86	500	350	22102	15480	15480
W041,W038,W047	86	0	0	0	0	0
W041,W035,W048	85	0	0	0	0	0
W041,W071,W072,W035	85	500	350	21845	15300	15300
W041,W071,W	84	500	350	21588	15120	15120

072,W036						
W035,W038,W041,W061	79	400	0	16274	0	0
W036,W038,W041,W073	72	0	0	0	0	0
W048,W073	78	0	0	0	0	0
W047,W071,W072	78	500	350	20046	14040	14040
W041,W061,W048	78	400	0	16068	0	0
W034,W091	77	350	350	13860	13860	13860
W036,W041,W047,W071	77	500	350	19789	13860	13860
W041,W034,W091	76	350	350	13680	13680	13860
W041,W035,W061	76	400	0	15656	0	0
W041,W092,W048	70	350	350	12600	12600	12600
W048,W036,W038	68	0	0	0	0	0
W047,W073	65	0	0	0	0	0
W041,W036,W092,W047	64	350	350	11520	11520	11520
W072,W073	63	500	350	16191	11340	11340
W071,W092	60	150	0	4620	0	0
W041,W073,W047	58	0	0	0	0	0
W036,W041,W073,W071	57	500	350	14649	10260	10260
W041,W034,W038,W048	53	0	0	0	0	0
W048,W038,W034	52	0	0	0	0	0
W041,W038,W035,W048	52	0	0	0	0	0
W041,W034,W061	51	400	0	10506	0	0
W048,W038,W035	50	0	0	0	0	0
W041,W061,W073	50	400	0	10300	0	0
SUM	32385	20120	11550	2271821	1399320	1412424
%DECREASE			-0.426		-0.384	-0.378

Appendix F: Sub(routings) suitable for cellular manufacturing

This annex answers the research question and presents a list of the (sub)routings suitable for being processed in the first and the second cell.

CELL 1	CELL 2
71,73	41,71,72,91
41,73,61	71,72,91
41,73,71	72,91
73,61	36,41,91
38,41,73	41,91
36,41,73	41,47,71,72
34,41,73	41,71,72
41,73	71,72
34,73	41,47,71
38,41,61	41,71
41,61	
38,41,48	
36,41,48	
41,48	
38,48	
36,48	
34,48	
35,48	
36,41,47	
35,41,47	
34,41,47	
41,47	
34,47	
35,47	
36,38,41	
35,38,41	
34,38,41	
38,41	
36,41	
34,41	
35,41	
35,38	
34,38	
36,38	