Improving Changeover Times Using Group Technology Technique for Printed Circuit Board Assembly at Electronics Manufacturing

By:

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Abstract of Project Presented to the Graduate School of the University of Puerto Rico at Mayagüez in Partial Fulfillment of the Requirements for the Degree of Master in Business Administration

IMPROVING CHANGEOVER TIMES USING GROUP TECHNOLOGY TECHNIQUE FOR PRINTED CIRCUIT BOARD ASSEMBLY AT ELECTRONICS MANUFACTURING

By:

José O. González-González

2019

President: Roberto L. Seijo-Vidal, PhD

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This project presents how to improve the overall product changeover process for pick-and-place operations using the group technology technique for printed circuit board assembly at electronics manufacturing. It focuses exclusively on the pick-and-place operations given that this process is highly complex as the number of assemblies and components increase. Some of the steps followed were: 1) formation of families by printed circuit board type and side, and yearly demand percentages, 2) group technology software application to matrices of assemblies and components by means of Excel-based Visual Basic Application software code, 3) fixed and variable component assignment using group technology results, 4) distribution of workload among pick-and-place machines, 5) layout rearrangement of pick-and-place equipment, 6) component repetition analysis, and 7) measuring the impact of the methodology focusing on setup, run-time, and capacity improvements. The project demonstrates that it is beneficial to apply group technology, line balancing, and layout rearrangement of the surface mount technology assembly lines. The main results achieved include a 72 percent reduction in setup hours, 82 percent reduction in run-time hours, and a 75 percent reduction of capacity hours required for completing the yearly schedule.

Resumen de Proyecto Presentado a la Escuela Graduada del Recinto Universitario de Mayagüez de la Universidad de Puerto Rico en Cumplimiento Parcial de los Requisitos para el Grado de Maestría en Administración de Empresas

MEJORA DE LOS TIEMPOS DE CAMBIO UTILIZANDO LA TÉCNICA DE TECNOLOGÍA DE GRUPO PARA ENSAMBLAJE DE PLACAS DE CIRCUITO IMPRESO EN LA MANUFACTURA DE ELECTRÓNICOS

Por:

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2019

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Este proyecto presenta cómo mejorar el proceso de cambiar productos para las operaciones de recogido y colocación de componentes utilizando la técnica de tecnología de grupo para el ensamblaje de placas con circuitos impresos en la manufactura de electrónicos. Se enfoca, exclusivamente, en las operaciones de recogido y colocación de componentes dado a que este proceso es altamente complejo a medida que aumenta el número de ensamblajes y componentes. Los pasos incluyen: 1) formación de familias a base del tipo y lado de placa, y porcentajes de demanda anual, 2) aplicación de tecnología de grupo a matrices de ensamblajes y componentes por medio de programado usando la aplicación de Excel "*Visual Basic for Applications*", 3) asignación de componentes fijos y variables usando los resultados de tecnología de grupo, 4) distribución de la carga de trabajo entre las máquinas de recogido y colocación de componentes, 5) reordenamiento de las líneas de ensamblaje, 6) análisis de repetición de componentes para la nueva propuesta, y 7) medir el impacto de la metodología en los tiempos de cambio, tiempos de ejecución y mejoras de capacidad. El proyecto demuestra que es beneficioso aplicar tecnología de grupo, balanceo de línea y reordenamiento de las líneas de ensamblaje. Los principales resultados logrados incluyen: una reducción del 72 porciento en los tiempos de cambio, una reducción del 82 porciento en las horas de ejecución y una reducción del 75 porciento en las horas de capacidad requeridas para completar el plan de producción anual.

To my Family

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LIST OF ABBREVIATIONS

AOI	Automated optical inspection
BOM	Bill of materials
BOT	Bottom side of the printed circuit board
DS	Double-sided printed circuit board
ERP	Enterprise resource planning
GT	Group technology
IC	Integrated circuit
NVA	Non-Value Added
PCA	Printed circuit board assembly
PCB	Printed circuit board
QCO	Quick changeover
SAP	System application and products in data processing
SMD	Surface mount device
SMT	Surface mount technology
SOP	Standard operating procedure
SPI	Solder paste inspection
SS	Single-sided printed circuit board
TOP	Topside of the printed circuit board
VBA	Visual Basic for Applications

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GLOSSARY

1. **Automated optical inspection (AOI):** a machine that detects faults using an image recording system (cameras) for visual inspection of a printed circuit board assembly. (BMK Group GmbH & Co. KG, 2019)

2. **Bill of Materials (BOM):** list of materials, the quantity of each, and parent-child relationship from the final product, to sub-assemblies, and down to the supplier components required. (Hegge & Wortmann, 1991)

3. **Changeover:** is the overall process of converting a machine, production line, or process from producing one product to another. (Henry, 2013)

4. **Component:** electrical surface mount components (SMCs) that are used to assemble a printed circuit board (PCB) such as resistors, capacitors, inductors, transistors, diodes, integrated circuits (IC), connectors, among others. (Lee, 2001)

5. **Feeders unit cart:** a cart that handles multiple tape feeders of different width sizes. (Riley, 1988)

Figure 1: Example of a feeder unit cart

Retrieved from https://pfipcb.com/products/panasonic-cm402-cm602-gang-exchange-feeder-trolley-carts

6. **Enterprise resource planning (ERP):** is a software that helps companies manage all the information and business activities by sharing data. (Cambridge University Press, 2019)

7. **Group technology (GT):** is a manufacturing philosophy or concept to increase production efficiency by identifying and exploiting the sameness or similarity of parts

and operation processes in design and manufacturing. (Ham, Hitomi, & Yoshida, 1985)

8. **Operation:** the way that parts of a machine or system work together, or the process of making parts of a machine or system work together. (Cambridge University Press, 2019)

9. **Pareto analysis:** is a statistical method developed by the economist Vilfredo Pareto which helps identify the leading causes of a particular problem in which states that twenty percent of the possible causes are responsible for eighty percent of the outcomes or results. (Freivalds & Niebel, 2014)

10. **Pick-and-place:** the action of a machine picking up a component from a programmed location and placing it at the PCB at another the programmed coordinate. (Joseph & Cacace, 2018)

Figure 2: Example of a pick-and-place machine

Retrieved from http://jukiamericas.com/smt-products/flexible-high-speed/fx_series/fx3ra/img/fx3ra.png

11. **Printed circuit board assembly (PCA or PCBA):** printed circuit board with components assembled. (Marks & Caterina, 2000)

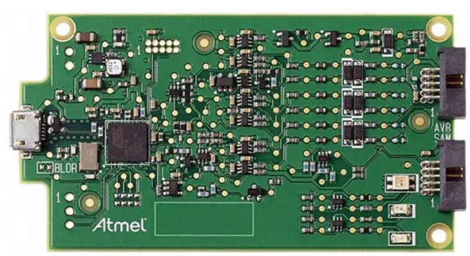

Figure 3: Example of a printed circuit board assembly (PCA)

Retrieved from https://www.digikey.com/product-detail/en/microchip-technology/ATATMEL-ICE-PCBA/ATATMEL-ICE-PCBA-ND/4753383

12. **Printed circuit board (PCB):** is a board which consists of internal electric conductive paths which interconnect different electrical components. (Prasad, 1997)

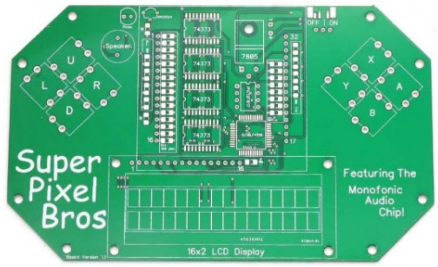

Figure 4: Example of PCB

Retrieved from https://www.itead.cc/bare-pcb-super-pixel-bros-board.html

13. **Surface mount technology (SMT):** most recent and preferred technology to obtain PCAs. Components are placed directly on the surface without any leads crossing through holes on the PCB. (Collin, 2004)

14. **Tape Feeder:** feeds mechanically or electrically electronic components in tape reels by advancing tape intermittently at the pick-and-place machine. (Riley, 1988)

Figure 5: Example of tape feeders

Retrieved from https://smtnet.com/media/images/md_Shutterless_Feeder_kl_432X289.jpg

1. INTRODUCTION

1.1 Sponsorship from *Electronic Systems*

Electronic Systems management agreed to sponsor the author of this project and allow him to lead an effort to optimize the current product flow at their manufacturing site. Among the opportunities identified and of greatest interest to *Electronic Systems* was the development of a practical scheme to improve changeover times for printed circuit board assemblies that compete for surface mount technology pick-and-place resources.

1.2 Company Background

Electronic Systems (a fictitious name for the company in order to comply with the agreed upon non-disclosure agreement) is a manufacturer from the United States of advanced aerospace and defense products for businesses and military. They have been serving the aerospace industry for more than a decade and currently serve customers from all over the world. *Electronic Systems* is currently growing and facing the challenge of keeping up with the demand from their customers. They currently have an extensive product portfolio and manufactures hundreds of products at the same site.

1.3 Justification

Electronic Systems currently offers a wide range of products that they manufacture at their facility. They are consistently performing changeovers from product to product. A changeover is the sequence of steps to convert a piece of equipment, production line, or process to be ready for the next product (Henry, 2013). Shingo (1985) states that changeovers are wasteful tasks that impact the available time and manufacturing capacity. Changeovers are non-value added (NVA) or waste that adds no value from the customer perspective (George, Rowlands, & Price, 2005). An example of a general changeover is, changing and configuring a new color cartridge for a 3D printer.

Electronic Systems would like to reduce changeover times which would boost machine utilization rates, increase capacity, reduce inventory, and reduce product lead-times. As requested by *Electronic Systems,* this project would focus exclusively in surface mount technology (SMT) pick-and-place operations using group technology (GT) technique for printed circuit board assemblies (PCAs) and components. The operation of SMT pick-and-place is the most complex within the SMT process due to the amount of PCAs and components that compete for pick-and-place resources (machines).

SMT is the most recent and preferred technology to manufacture PCAs, and its components are placed directly on the surface of a printed circuit board (PCB) without any leads (electrical conductors) crossing through holes. (Collin, 2004). An SMT pick-and-place machine is a preconfigured and programmed equipment that picks the components from a programmed location and places it at another programmed location over a surface of the PCB. (Joseph & Cacace, 2018)

A PCA is the combination of a PCB which consist of the internal electric conductive path that interconnects with different electrical component (e.g., resistors, capacitors, inductors, transistors, diodes, integrated circuits, connectors, and others) (Prasad, 1997). An example of a PCA includes computer and mobile phone motherboards which are composed of a variety of components (e.g., microprocessors, memory, USB ports, audio jacks, power port, among others).

GT technique is the assumption that many problems are similar, and that by grouping similar problems, a single solution can be found for a set of problems thus saving time and effort (Chang, Wysk, & Wang, 1991). Table 1 shows an example of ten components used by fifteen PCAs. After applying GT, components and PCAs are rearranged (Table 2), clearly showing how specific components and PCAs group into families, with an implication on how these can be organized, deployed and manufactured when changing from one PCA to another.

Table 1: Example of 15 PCAs and 10 components

Component # \ Printed Circuit Board Assembly #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1		X								X	X	X			
2			X		X			X					X		X
3	X					X			X					X	
4	X			X					X					X	
5			X		X			X					X		X
6	X			X		X			X					X	
7		X					X			X	X	X			
8			X		X			X					X		X
9				X		X			X					X	
10		X								X	X	X			

Table 2: Example of group technology technique applied

Component # \ Printed Circuit Board Assembly #	2	10	11	12	7	5	8	13	15	3	9	14	1	6	4
7	X	X	X	X	X										
1	X	X	X	X											
10	X	X	X	X											
2						X	X	X	X	X					
8						X	X	X	X	X					
5						X	X	X	X	X					
6											X	X	X	X	X
3											X	X	X	X	
4											X	X	X		X
9											X	X		X	X

1.4 Objective

The primary objective of this project is to reduce changeover times using the group technology (GT) technique for all those PCAs and components that compete for the pick-and-place resources in the surface mount technology (SMT) process at *Electronic Systems*. The technique should reduce the current overall time spent in changeovers and increase capacity. Stemming from the GT analysis, alternative layouts for the current equipment settings will be generated.

1.5 Scope

The scope of the project covers changeovers for the printed circuit board assemblies (PCAs) that require the pick-and-place operations exclusively as requested by *Electronic Systems.* The GT technique would be applied to PCAs and components that require pick-and-place operations considering the yearly customer demand. Figure 6 describes the complete manufacturing process flow at *Electronic Systems*, highlighting the SMT process, which is the most complex activity given that a large number of PCAs and components compete for the pick-and-place resources. Figure 7 shows the SMT process flow at *Electronic Systems*, highlighting the pick-and-place operation.

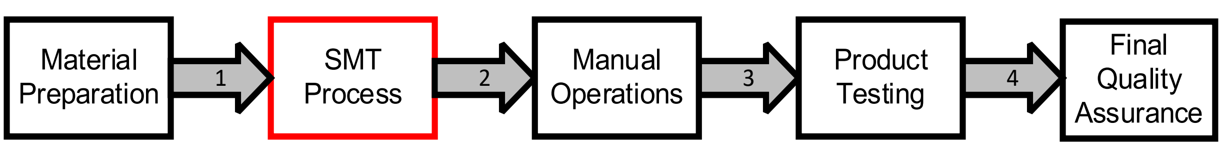

Figure 6: Manufacturing process flow at *Electronic Systems*

Figure 7: SMT process flow at *Electronic Systems*

1.6 Summary

This chapter presented brief information regarding the sponsorship, background of *Electronic Systems* Company, justification, objective, an example of GT technique application, and scope of this project which would be exclusively about the pick-and-place operation within the SMT process. Next chapter will present the literature review for the topics of management, operations management, processes, and GT. The third chapter will detail the methodology followed on this project. The Fourth chapter will detail the analysis and results, and the fifth chapter will present conclusions and future recommendations at *Electronic Systems.*

2. LITERATURE REVIEW

2.1 Introduction

This chapter reviews the literature concerning four subjects that are highly relevant for the project. The topics are management, operation management, processes, and group technology (GT).

2.2 Management

Management aims at attaining organizational goals in an efficient and effective way by integrating the work of people, through the primary management functions: planning, organizing, leading and controlling (Daft, 2016; Kinicki & Williams, 2018; Robbins & Coulter, 2016).

Being efficient will facilitate the achievement of organizational goals if resources (people, materials, energy, capital, time, and others) are used in a cost-effective way (Kinicki & Williams, 2018). Meanwhile, being effective is described as executing the necessary efforts to obtain the desired goals (Robbins & Coulter, 2016).

Planning sets, determines, and formulates how to meet the organizational objectives. Organizing establishes how resources will be assigned to achieve the desired objectives. Leading is how to influence employees and teams toward achieving objectives and controlling refers to comparing the current versus expected results and making corrections when needed. (Daft, 2016; Robbins & Coulter, 2016)

2.3 Operations Management

Operations management are the set of activities that an organization uses to generate products and services (Stevenson, 2017). According to Slack, Brandon-Jones, and Johnston (2013), “Everything you wear, eat, sit on, use, read, or talk about on the sports field comes to you courtesy of the operations managers who organized its creation and delivery" (p. 4). Operations management creates value in the form of goods and services by transforming inputs into final products (Heizer & Render, 2013); as described in Figure 8.

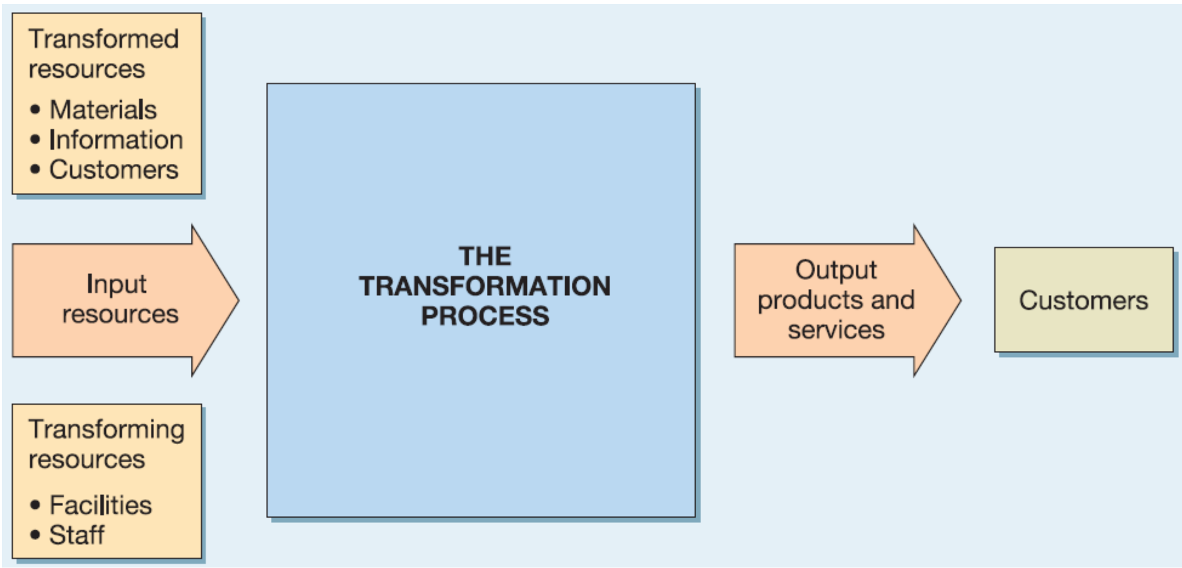

Figure 8: General transformation process model (Slack, Chambers, & Johnston, 2010)

Heizer and Render (2013) state that the main functions of any organization are; marketing which generates the demand for products and services, finance/accounting which tracks how well the company is doing, and production/operations which involves the process of creating the product or service. Manufacturers are the ones that produce tangible products (e.g., cars, computers, phones, watches, eyeglasses, among others.) while service businesses provide intangibles products (e.g., banking, accounting, cleaning, food and lodging, insurance, education, medical treatment, entertainment, among others). Figure 9 is an organizational chart example for a manufacturing company such as *Electronic Systems* which demonstrates the typical essential functions.

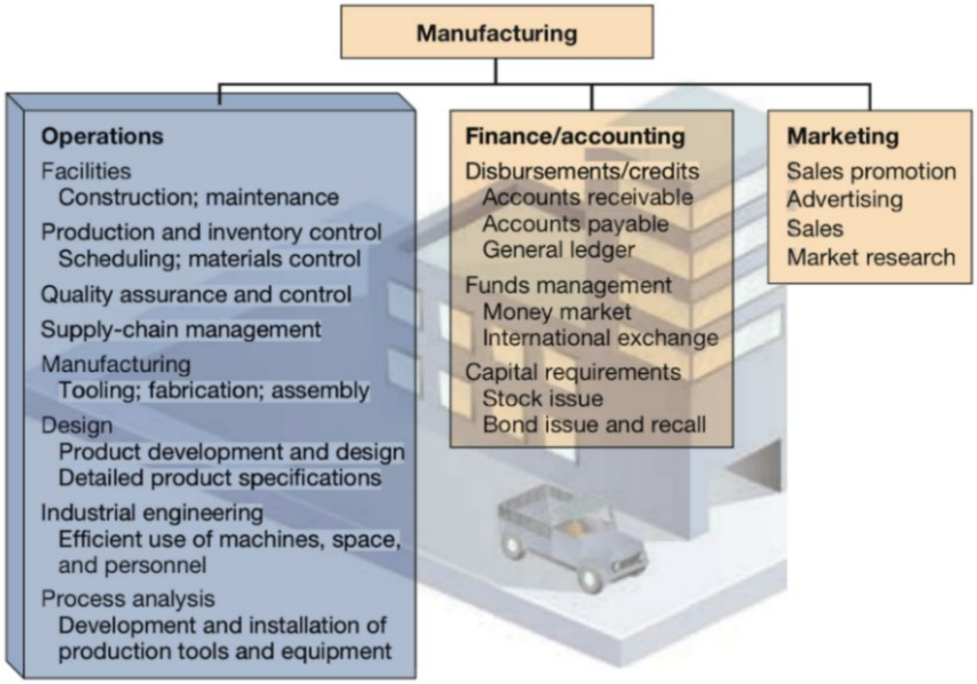

Figure 9: Manufacturing organizational chart (Heizer & Render, 2013)

Activities in operations management include organizing work, selection of processes, arranging layouts, locating facilities, designing jobs, measuring performance, assuring quality, scheduling work, managing inventory, and planning production (Russell & Bernard, 2011). Among all the activities in operations management, process planning determines how to produce or provide goods and services. It involves the decision of making or buying, process selection for manufacturing and delivery, and others. In the case of this project, the most important activities from operations management include process planning, product sequencing, and shop-floor layout. Low volume PCAs must be built with agility, aided by quick changeover (QCO) between products. QCO allow working each product in small quantities, increasing the chances of *Electronic Systems* to deliver orders on time.

2.4 Processes

Process selection is vital because it refers to figuring out the way to organize and produce goods or services (Stevenson, 2017). It is about how to transform inputs into products or services (Schroeder, Goldstein, & Rungtusanatham, 2010). Selecting a manufacturing process for a product or service can vary or depend on many factors. Some of the factors are capacity, cost, quality, reliability, expertise, and cost (Russell & Bernard, 2011).

For example, an electronic manufacturing company like *Electronic Systems* can assemble a printed circuit board (PCB) using one or multiple pick-and-place machines and can inspect the PCB using an automated optical inspection (AOI) equipment or using a person aided by a high definition camera or a magnifying glass. The process selection depends on the quality requirements, speed of production and budget available; it has significant implications on the design of work systems, capacity planning, layout of facilities, and manufacturing equipment because of the constant technological changes and the global competitive environment (Stevenson, 2017).

2.5 Group Technology (GT)

GT technique was developed in Russia and used during World War II. (Rajput, 2007). It seeks to rationalize production operations by capitalizing on the similarities of components of parts, and that formation of families is possible based on designs or manufacturing processes. (Ham, Hitomi, & Yoshida, 1985; Lea Hyer, 1984)

Family formation using GT also provides the advantages to have standardized processes, reduced time for design validations, variety reduction, fewer tooling, reduced lead times, reduced work-in-process, reduced material handling, and higher productivity (better usage of organizational resources). (Rajput, 2007) It also has the benefit of lowering the product cycle time since there is less idle time during work shifts, better customer service, and others benefits that translate into cost reductions. (Gunasekaran, Goyal, Virtanen, & Yli-Olli, 1994; Ham, Hitomi, & Yoshida, 1985)

Rajput (2007) states that a manufacturer that produces thousands of different products may be able to form less than a hundred families, this would result in better manufacturing efficiency due to fewer changeovers required to cover the portfolio of products. GT also has the versatility that it can be applied to process planning, production planning, production scheduling, layout planning, and others. (Ham, Hitomi, & Yoshida, 1985). In the case of this project, GT would be applied to PCAs and components that compete for pick-and-place resources, which relates to production planning.

2.6 Summary

This chapter presented information about management, operations management, processes, and the advantages of the GT technique. Next chapter will present the steps of the methodology used during this project at *Electronic Systems.*

3. METHODOLOGY

3.1 Introduction

This chapter presents the seven steps of the methodology used in this project. The overall project used the GT technique to increase production efficiency by grouping components that are needed by the printed circuit board assemblies (PCAs) families in order to reduce changeover times. Relevant topics in this chapter include: bill of material information, group technology software application, allocation of component reels to machine slots, balancing the pick-and-place workload among feeder unit carts and machines, documentation of the component assignment scheme, time and capacity estimation to ensure schedule feasibility, and benefits analysis presentation to *Electronic Systems* management.

3.2 Bill of Material Information

The first step involved gathering the bill of material (BOM) information for each PCA to assess if components could be organized into PCA families. In this project, eight PCA families were formed. These families resulted from demand percentage, PCAs with unique characteristics (e.g., odd-shaped versus rectangular printed circuit boards and odd component geometry) as well as specific process requirements (e.g., adhesive application to hold components, selective soldering, and others). For the PCAs with unique characteristics, it is necessary to use a specific pick-and-place equipment brand just like the case of *Electronic Systems.*

PCAs were arranged from the highest to lowest demand, and by doing a Pareto analysis, it was possible to separate high demand products from those that are manufactured infrequently. Figure 10 shows the yearly demand for 434 PCAs, which adds to 128,651 PCAs. The first 100 PCAs or 23 percent (i.e., 100 of 434) are responsible for

80 percent (i.e., 102,921 / 128,651) of demand; exceptionally close to the classic 80-20 rule from the Pareto statistical technique. The PCAs that are responsible for the 80 percent of the demand (labeled as high runners) were set aside from the remaining 20 percent (labeled as low runners). The Pareto principle was evident since the 80 percent group included a smaller PCA and component set when compared to the 20 percent group within each family. In summary, within each family, PCAs were divided between two groups, 80 percent and 20 percent of the demand.

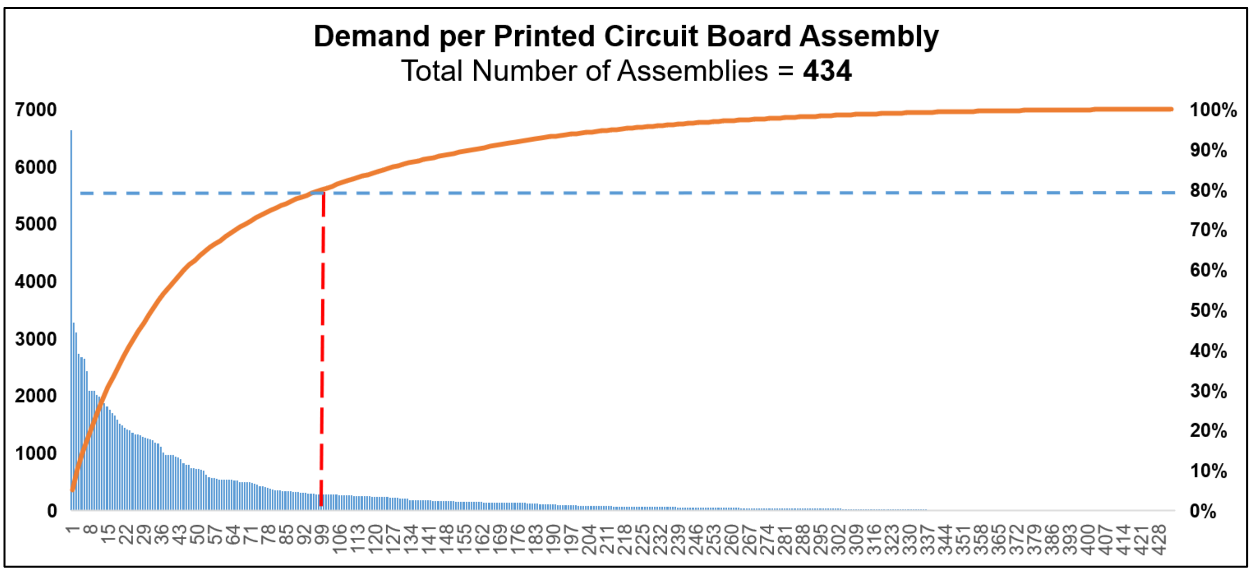

Figure 10: Pareto of demand per PCA

Another concern addressed for forming the product families relates to the placement of the components during the pick-and-place operations. Three possibilities of component placements need to be considered: (a) components only on the bottom side of the PCB, (b) components only on the topside of the PCB, and (c) components on both sides of the PCB. The first two cases are known as single-sided, while the latter is referred to as double-sided.

In summary, the criteria for the formation of the eight families are PCB type and side, PCB unique characteristics or requirements (e.g., odd shape PCB or component, adhesive application, among others), and demand percentage (80 or 20 percent). The PCAs with unique characteristics or requirements has to be handled with a specific pick-and-place equipment brand that *Electronic Systems* has.

3.3 Group Technology Software Application

The second step consisted of organizing the data on an Excel worksheet and applying the group technology software code to the tables formed from each family composed of components (rows) and PCAs (columns). The code was developed in Visual Basic for Applications (VBA) from Microsoft Excel (see Appendix A). The input data was read from a worksheet, and the results were displayed on another worksheet.

3.4 Allocation of Component Reels to Machine Slots

The third step consisted of the assignment of component reels to a fixed (component stays in place during a changeover of a PCA) or variable (component changes during a changeover of a PCA) location. The installation of a component reel takes place in a tape feeder that matches the component width reel size. A tape feeder mechanically or electronically feeds the pick-and-place machines by advancing tape intermittently to complete the pick-and-place operation (Riley, 1988).

The software logic used for this task attempts to maximize the number of components assigned to fixed positions. Since the candidate components come in varying reel width sizes (e.g., 8, 12, 16, 24, 32, and 44 millimeters), to conform with assigning the highest number of components, the smallest width size of component reels are assigned first. Assigning the smaller width size component reels first leaves the large size width components reels for last, which results in assigning them to variable positions.

3.5 Balancing the Pick-and-Place load Among Feeder Unit Carts and Machines

The fourth step consisted of assigning fixed components to the fixed allocated feeder unit carts for pick-and-place machines aiming for line balancing among the assigned feeder unit carts. A feeder unit cart is a cart that handles multiple tape feeders of different width sizes (Riley, 1988). The assignment sequence uses the results from the GT software application (from section 3.3) and allocates one component at a time, going from the first to the last machine, and then returns starting from the last and ending with the first machine. This sequential assignment continues until the allocation of all fixed components is completed. Figure 11 shows an example of the sequential assignment for ten components and five machines.

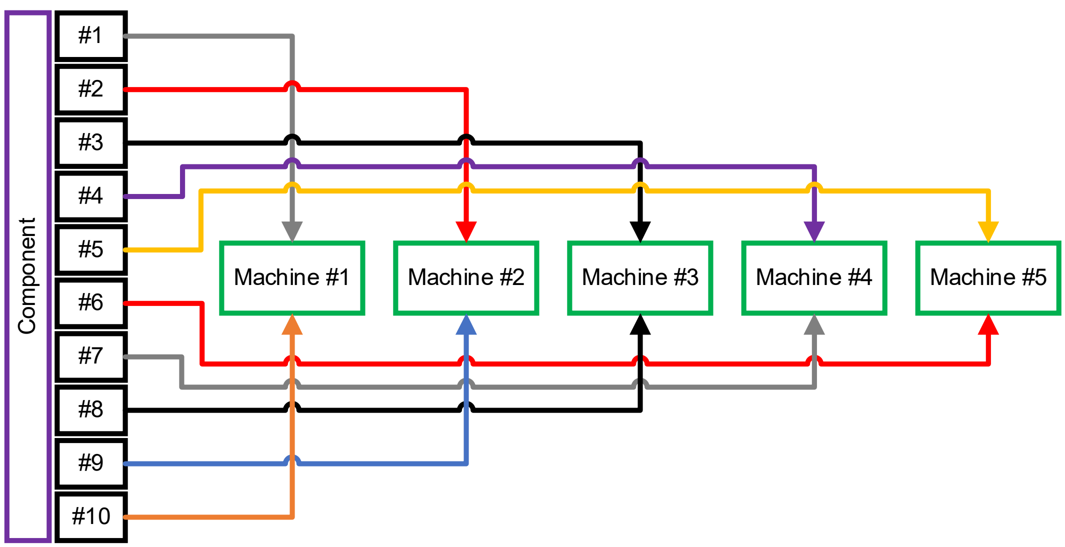

Figure 11: Example of the sequential assignment

3.6 Documentation of the Component Assignment Scheme

The fifth step consisted of developing a standard operating procedure (SOP) for the production personnel on how the production activity should be carried out. This step includes the number of machines, the deployment of fixed components through feeder unit carts and pick-and-place machines, and the arrangement of variable components for the 434 PCAs. To minimize changeover times, the SOP calls for preparing the tape feeders for the next product in the schedule while production is in progress (this is known as external setup).

3.7 Time and Capacity Estimation to Ensure Schedule Feasibility

The sixth step consisted of time and capacity evaluation to alert management of the benefits of the proposed approach. As part of the overall assessment, some components will be repeated among the families formed, for which additional tape feeders must be available. For time and capacity estimates, standard times from setup and production run-times from the pick-and-place operations were obtained from the SAP software, a well-known enterprise resource planning (ERP) system that is used at the site.

3.8 Benefits Analysis Presentation to *Electronic Systems* Management

A before and after analysis is needed to demonstrate the breakthrough results. The seventh and final step is to present the process followed in this project to management with suggestions for next step activities, aiming at continuous improvement in the manufacturing endeavors.

3.9 Summary

This chapter presented the seven steps of the methodology used at *Electronic Systems* which were: (a) BOM information, (b) GT software application, (c) allocation of component reels to machine slots, (d) balancing the pick-and-place workload among feeder unit carts and machines, (e) documentation of the component assignment scheme (f) time and capacity estimation to ensure schedule feasibility, and (g) benefits analysis presentation to *Electronic Systems* management. The next chapter will present the results obtained for all steps of the proposed methodology.

4. ANALYSIS AND RESULTS

4.1 Introduction

This chapter presents the analysis and results obtained from this project using the seven steps of the methodology. The chapter breaks down into the following sections: family formation, group technology application, fixed versus variable component assignment, component assignment aiming for line balancing, layout, component repetition analysis, setup times, run-times and capacities estimation.

4.2 Family Formation

Eight families were formed during this project and were divided by SMT pick-and-place equipment brand (Mycronic and Fuji), demand percentage, printed circuit board (PCB) type, and PCB side. Families were divided by SMT pick-and-place equipment brand because of the PCAs that have unique characteristics (e.g., odd-shaped versus rectangular PCB) and processes (e.g., adhesive application to hold components) that are required to be manufactured with a specific pick-and-place equipment brand. Demand percentages were used to separate those PCAs responsible for the 80 percent and 20 percent of the demand within each family. Moreover, the last consideration within each family formed was the PCB type (single or double-sided) and side (bottom or topside) which provides a more robust and detailed families.

Mycronic brand consisted of four families composed by a total of 111 PCAs from which 61 were single-sided (SS) bottom (BOT) and 50 double-sided (DS). Fuji brand also consisted of four families composed by a total of 323 PCAs from which four were SS BOT, 130 SS topside (TOP), and 189 DS. Tables 3 and 4 detail the families by equipment brand, PCB type and side, demand percentage, and the number of PCAs and components. It was essential to recognize the products responsible for 80 percent of demand and treat them separate to those responsible for the remaining 20 percent because products responsible for the 80 percent of demand are manufactured more frequently. In all cases, families from the 80 percent group include a smaller set of PCAs and components when compared to the families of the 20 percent group. An important observation to notice is that PCBs are grouped by PCB side independently if the PCB is SS or DS. In the case for the Mycronic families, family one and two has SS and DS PCBs type. Meanwhile, all families from Fuji has SS and DS PCBs type within each family.

Table 3: Mycronic families

Family #	PCB type	PCB side	Demand %	# PCAs	# Components
1	SS & DS	BOT	80	33	348
2	SS & DS	BOT	20	78	719
3	DS	TOP	80	15	424
4	DS	TOP	20	35	667

Table 4: Fuji families

Family #	PCB type	PCB side	Demand %	# PCAs	# Components
1	SS & DS	BOT	80	50	617
2	SS & DS	BOT	20	143	1527
3	SS & DS	TOP	80	80	1664
4	SS & DS	TOP	20	239	29640

4.3 Group Technology (GT) Application

For the application of GT, a matrix of PCAs and components was generated for each row from Tables 3 and 4 above. Figure 12 displays the initial matrix (12.a) that contains 617 rows (components) and 50 columns (PCAs) from family number one of the Fuji brand. Figure 13 shows a section (upper left corner) of the initial matrix composed of 25 components (rows) and 25 PCAs (columns). Each cell indicates the total number of the specific component used by the PCA. Cells with non-zero values are colored yellow, while cells with zero value are colored black.

A software code, written in Visual Basic for Applications (VBA) from Microsoft Excel, was applied to create the group technology (GT) structure. The code performs columns swap to the left (PCA), and rows swap to the top (component) until the best PCA and component groupings (or families) are defined. Figure 12 presents the new arranged matrix (12.b) where GT was applied, where Figure 14 shows a section of 25 components (rows) and 25 PCAs (columns) at the upper left section of this matrix.

The initial matrix (12.a) in Figure 12 shows a sparse matrix with 2,805 positive cells out of 30,850 (i.e., the product of 50 and 617) total cells, which represents 9.09 percent of non-zeros. In the initial matrix, yellow cells are randomly dispersed depending on the component usage (non-zero) by each PCA. By comparing Figures 13 and 14, there are more cells with non-zero values (yellows colored) in Figure 14.

An additional step in the creation of the final matrix (12.c) shown in Figure 12 is the sorting of rows by component reel width size (8, 12, 16, 24, 32, and 44 millimeters) which will maximize the number of components assigned to fixed positions. The same procedure was applied to the other seven families.

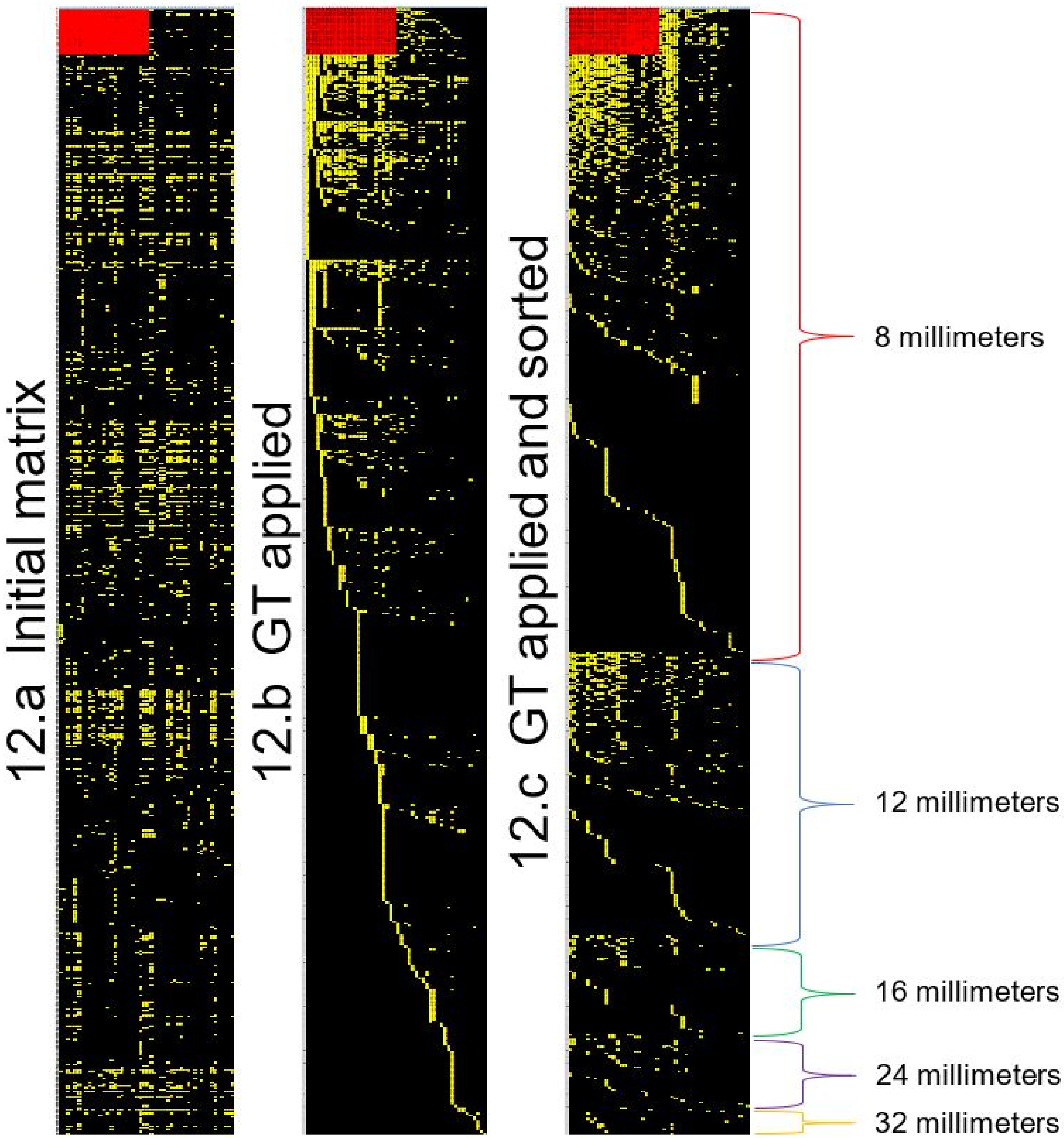

Figure 12: GT application

#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1			2																						
2														2											
3																									
4									1				8		1	8	4	2							
5																1									
6																					1				
7																					1				
8																							1		
9																							1		
10																							1		
11						1																			
12			3			6																	3		
13																									
14																3									
15																							21		
16															1										
17			3		3	2																			
18																							3		
19			7		7	2																			
20						2																			
21						2																			
22																								1	1
23	1		2		2	2						1			1	4							5		
24																								1	1
25																							1		

Figure 13: Initial matrix data section

#	26	6	37	18	17	45	50	31	35	34	23	32	15	3	24	25	27	4	48	49	9	14	47	12	33
263	49	34	16	7	17	31	2	58	10	8	33	20	23		74	74		11			1	9			
91	2	8	15	3	11	6	36				1	54	6	3	12	12	1	10	18	18		10	18	12	8
604	126	64	15	11	10	198	57	9	11	6	53	6	30	143	68	68	47	31	10	10					1
76	7	2	8	5	4	4	7	2	1	1	1	4		4	1	1		4	4	4	1	2	6	1	
284	3	16	6	3	4	19	2	1	4	2	10	3	1	4	5	5	37	21			1	2	2		8
594	18	16	15	18	13	74	4	3	2	2	3	48	2	18	5	5			3	3	5	15			4
376	121	42	96	143	170	255	63	164	105	68	1	39	30	124	38	38	28	1	6	6	48	20	4	108	
140	15	10	14	2	12	24	11	72	4	4	8	7	6	13	7	7	22	11	1	1					4
124	95	28	26	3	33	64	17	9	3	3	10	2	13	86	1	1	3				7			35	
278	20	11	15	22	6	70	4	3	12	3	1		4	16	3	5	7				6	1		9	
582	5	4	15	8	1	116	16		1	1	3	41	2	5	2	2			6	6		15			1
85	4	5	1	9		16	24				6	12	5	5	1	1			4	4	1	4			
34	209	148	133	237	174	450	118	209	205	88	115	121	11	174	9	8	2	4	4	4	77	76	4	61	7
228	16	8	2	2	5	22	2	1	2	2	2	2	4	20					1	1	2		7		4
93	1	5	42	11	12		31	30	22	14		7	4	1	5	5					1	39		4	48
82	18	12	11	4	1	2	20	1	1	1	3	38	21	18	4	4					2	3			8
255	45	10		6	3	37		5	7	4	11	10	7		2	2			6	6	7				5
243		3	2		10	24		4	5	3	40	1	1		6	6		12					3		15
377	2	3	21		3	154	4	22	2	2	13	10	6		5	5	2	12						2	
268	7	2			4	4	1		8	8	7	4	12	7	4	4					1				28
591	1	2	15	1	2	48	2	2	2	2	5		3	8	2	2					1			3	
33	104	67	85	87	94	92	48	100	44	36	28	61	13	96							45	14		15	9
384	4	1	10	26	10	62	7	104	17	3	11	39		4	1	1					2	12		20	
398	14	47	17	30	7	66	3	44	27	1		18	2	10	4	4	21							33	
375	3	19	23	13	12	9	22	97	4		27	19	3	13	15	15	1				7			56	

Figure 14: GT applied section

4.4 Fixed versus Variable Component Assignment

To assign fixed and variable components, the final matrix results (GT applied and sorted) for each family was used to establish the maximum number of slots (spaces at feeder unit carts) that can be fixed. A fixed component is a component that does not require to be changed when changing from one PCA to another. Meanwhile, during a changeover, a variable component does require to be changed for each new PCA to be assembled during the SMT process. The higher the number of fixed components, the fewer variable component changes are required during changeovers. The number of slots available for components is dependent on the machine brand (Fuji or Mycronic), its model, and component reel width sizes.

In order to maximize the number of fixed slots, components were arranged in ascending order by component reel width size (8, 12, 16, 24, 32, and 44 millimeters). Tables 5 and 6 include the decision for fixed and variable slots in columns five and six in order to accommodate all the necessary components required for a PCA. The percent of fixed slots for Mycronic is limited when compared to Fuji due to their machine slots capacity.

Table 5: Fixed versus variable slots for Mycronic

Family #	PCB type	PCB side	Demand %	# Fixed	# Variable	% Fixed Slots
1	SS & DS	BOT	80	112	80	58%
2	SS & DS	BOT	20	112	80	58%
3	DS	TOP	80	128	80	62%
4	DS	TOP	20	128	80	62%

Table 6: Fixed versus variable slots for Fuji

Family #	PCB type	PCB side	Demand %	# Fixed	# Variable	% Fixed Slots
1	SS & DS	BOT	80	550	130	81%
2	SS & DS	BOT	20	500	180	74%
3	SS & DS	TOP	80	640	283	69%
4	SS & DS	TOP	20	640	283	69%

4.5 Assignment of Components to Feeder Unit Carts Aiming for Line Balancing

The fourth step of the methodology focuses on distributing the workload among pick-and-place machines, and there are a total of 16 Fuji pick-and-place machines available at *Electronic Systems*. The proposal will dedicate eight pick-and-place machines for the bottom side and eight for the topside (this will be further discussed in Section 4.6). In assigning components to each side, it is of utmost importance to distribute components evenly among machines; this balances the workload and allows the lowest possible cycle time. Line balancing was only relevant for Fuji because it is possible to have multiple machines in series. In contrast, Mycronic has only standalone machines.

In this discussion, the first row of Table 4: Fuji families (80 percent of demand and BOT side) is used. Table 7 illustrates the scenario for the fixed components assignment for ten PCAs using six pick-and-place machines, where the first pick-and-place machine is assigned with the highest component placement activity. Thus, the first machine ends up with the most significant workload and becomes the bottleneck during manufacturing. This logic has been enhanced in Table 8 by assigning components through the pick-and-place machines assigning one component (rows from GT results, Figure 12.c, Section 4.3) at a time. After moving from the first to the last machine, the sequence of assignments continue returning from the last to the first machine. This sequential assignment is continued until all fixed components have been allocated. For PCA number one (in Tables 7 and 8) there is a reduction of maximum components placements from 1428 to 433 by following the allocation enhancement, which represents a 70 percent reduction in cycle time. The enhanced logic was applied to the Fuji brand because it is possible to have multiple machines in series.

Table 7: Before applying line balancing

Pick-and-place machine #	Printed Circuit Board Assembly # 1	2	3	4	5	6	7	8	9	10
1	1428	987	931	884	765	2931	640	1568	608	330
2	72	47	39	24	2	72	52	61	48	40
3	32	28	12	0	0	2	5	5	0	0
4	75	56	32	22	8	186	18	51	12	12
5	53	65	31	0	2	160	4	16	14	13
6	1	8	4	0	0	27	3	0	4	0
max	**1428**	**987**	**931**	**884**	**765**	**2931**	**640**	**1568**	**608**	**330**

Table 8: After applying line balancing

Pick-and-place machine #	Printed Circuit Board Assembly # 1	2	3	4	5	6	7	8	9	10
1	154	147	155	101	71	396	96	397	86	34
2	354	267	157	141	126	550	176	221	82	61
3	113	173	180	150	48	528	62	167	58	48
4	433	250	200	174	224	541	96	404	169	122
5	242	148	162	54	88	389	111	107	46	25
6	365	206	195	310	220	974	181	405	245	105
max	**433**	**267**	**200**	**310**	**224**	**974**	**181**	**405**	**245**	**122**

4.6 Layout – Current Versus Future

Electronic Systems currently has six production lines, four Fuji and two Mycronic. The Fuji lines have three, five, four, and four pick-and-place machines in series each. Figure 15 shows the before (left) and after (right) layout with the recommended rearrangement of pick-and-place equipment. The proposed layout for Mycronic relocates lines five and six closer to each other to minimize the distance the operators have to walk between them and reduce the risk of mishandling a PCB. The proposed layout is to relocate lines one through four into a single line with some minor additional equipment (e.g., PCB inverter, conveyors and turning tables).

The reason to relocate lines one through four from Fuji into a single line is that *Electronic Systems* has to perform two changeovers/setups to manufacture a DS PCA. By putting all pick-and-place machines together, the number of slot positions is maximized allowing fewer changeovers. In the current state, pick-and-place resources within the same production line are shared for BOT side and TOP side when assembling a DS PCA. With the proposed layout, the PCA BOT side and the TOP side has its pick-and-place resources, and changeover only occurs once, resulting in fewer changeovers.

The green color represents the fixed feeder unit carts, and the orange color represents the variable feeder unit carts. The production line starts in the lower right corner, has eight pick-and-place machines for bottom side components, which is followed by soldering. Afterward, eight additional pick-and-place machines are for the topside components, which is also followed by soldering.

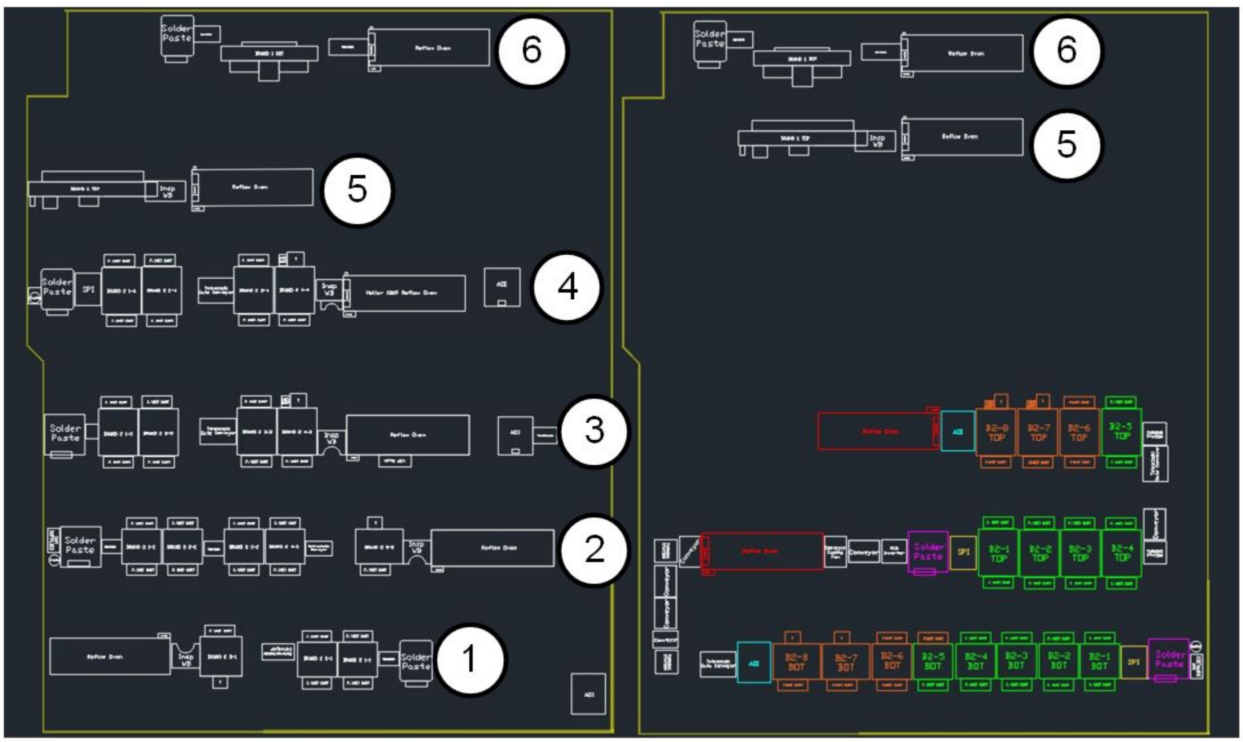

Figure 15: Current versus future layout

4.7 Component Repetition Analysis and PCAs Summary

The component repetition analysis consisted of counting how many times a component repeats among the eight families of PCAs studied, using the proposed layout and comparing it with the current state. Table 9 and 10 shows in detail the number of times a component repeats for the current versus future state, exclusively for fixed components. When comparing current and future state, the fixed component assignment increases the number of fixed components by 282 percent; i.e., there is an increase in the number of fixed components from 300 (in Table 9) to 1147 (in Table 10). Thus, there are 847 (1147 minus 300) fewer components to be dealt with during the yearly production schedule. For further details regarding the percent of fixed components per equipment brand and PCAs refer to Appendices B and C.

Table 9: Current state fixed components

# times repeated	# components	%
1	131	43.7%
2	46	15.3%
3	30	10.0%
4	93	31.0%
Total	**300**	**100%**

Table 10: Future state fixed components

# times repeated	# components	%
1	509	44.4%
2	271	23.6%
3	100	8.7%
4	161	14.0%
5	55	4.8%
6	20	1.7%
7	19	1.7%
8	12	1.0%
Total	**1147**	**100.0%**

4.8 Setup Times, Run-times, and Capacity Estimates

Current standard times from pick-and-place operations were obtained from the SAP software, a recognized enterprise resource planning (ERP) system. Setup time from the SAP software at *Electronic Systems* refers to the time it takes to prepare and modify the production line for a different PCA, also known as a changeover. Changeover includes changes in PCA-dependent programs (e.g., reflow oven, AOI, SPI, and others); conveyor widths; paste dispensing material, stencil and machine settings; and exchange (out and in) of variable feeder carts.

To compare the total setup hours per year of the current state versus the new proposed approach for all PCAs, the amount of lots per PCA (yearly demand per PCA divided by lot size) was multiplied by the new number of variable components per PCA, then multiplied by the time it takes to replenish or change a tape feeder. For run-time estimates, new times were calculated for each PCA using the standard time specified by the brand manufacturer of the pick-and-place machine plus an additional fifty percent of time to be conservative.

Table 11 details the total setup and run-time hours per year from the SAP system versus the proposed system segregated by brand, PCB side, and demand percentage. Comparing the SAP system (red) data with the proposed system (blue), there is a 72 percent reduction in setup hours, while there is an 82 percent reduction in run-time hours.

Table 11: SAP system versus the proposed system

			SAP SYSTEM		PROPOSED SYSTEM	
Equipment Brand	**PCB side**	**Demand %**	**total setup hours per year**	**total run-time hours per year**	**total setup hours per year**	**total run-time hours per year**
Mycronic	**BOT**	80	1,855	2,211	575	1,023
		20	605	1,079	447	449
		Σ	**2,459**	**3,290**	**1,022**	**1,472**
Mycronic	**TOP**	80	1,566	1,904	623	312
		20	843	1,285	496	210
		Σ	**2,409**	**3,189**	**1,119**	**522**
Fuji	**BOT**	80	26,242	15,211	1,942	4,550
		20	27,180	6,671	4,092	1,172
		Σ	**53,422**	**21,883**	**6,033**	**5,722**
Fuji	**TOP**	80	41,277	19,797	19,684	2,099
		20	35,172	10,495	10,540	575
		Σ	**76,449**	**30,292**	**30,224**	**2,674**

Table 12 illustrates the hours of capacity required to complete the yearly production schedule using the SAP system against the proposed approach. The total hours required decrease significantly from 193,393 (for SAP) to 48,789 (for the proposed approach), which results in a dramatic 75 percent reduction.

Table 12: Capacity hours SAP system versus the proposed system

			SAP SYSTEM	PROPOSED SYSTEM	
Equipment Brand	**PCB side**	**Demand %**	**setup+run-time hours per year**	**setup+runtime hours per year**	**Hours of capacity % reduction**
Mycronic	**BOT**	80	4,066	1,598	61%
		20	1,683	896	47%
		Σ	**5,749**	**2,494**	**57%**
Mycronic	**TOP**	80	3,470	935	73%
		20	2,128	706	67%
		Σ	**5,598**	**1,641**	**71%**
Fuji	**BOT**	80	41,454	6,492	84%
		20	33,851	5,263	84%
		Σ	**75,305**	**11,755**	**84%**
Fuji	**TOP**	80	61,075	21,783	64%
		20	45,667	11,115	76%
		Σ	**106,742**	**32,898**	**69%**
		Σ	**193,393**	**48,789**	**75%**

4.9 Summary

This chapter described in detail:

a) The composition of the eight families formed;

b) The application of GT to PCAs and components matrices;

c) Fixed and variable components assignment considering their reel width size;

d) The balancing of pick-and-place workload among Fuji machines;

e) The component repetition analysis for fixed components;

f) The proposed layout; and

g) Setup times, run-times, and capacity analysis for the current and future states.

Next chapter will present conclusions and future recommendations, aiming at continuous improvement at *Electronic Systems.*

5. CONCLUSION AND FUTURE RECOMMENDATIONS

5.1 Introduction

This chapter presents conclusions based on the procedures presented on this project for the *Electronic Systems* company. In addition, recommendations will be made to apply this methodology in other businesses given the positive results obtained at *Electronic Systems* for the eight PCA families considered.

5.2 Conclusion

This project presents a methodology for decreasing changeover times using the GT technique for PCAs and components that compete for pick-and-place resources at *Electronic Systems*. Once the information regarding the PCAs and components was obtained, the methodology to achieve improvement of changeover times using group technology technique was applied.

The following five steps are considered the most important from the methodology: (a) acquiring the complete and correct bill of material (BOM) information for all PCAs for family formation; (b) group technology software application; (c) line workload balancing for feeder unit carts at pick-and-place machines; (d) documentation of the component assignment scheme; and (e) layout recommendations for pick-and-place machine deployment on the shop-floor.

Using the methodology established in this project, eight families were formed based on the pick-and-place equipment brand because of special characteristics that some PCAs have. Also, demand percentages (80 versus 20 percent), PCB type (single or double-sided), and side (bottom or topside) were considered.

Layout rearrangement for Mycronic pick-and-place machine brand consisted of getting the fifth and sixth production lines closer to each other to minimize the distance the operator has to walk between them and reduce the risk of mishandling a PCB. In the case of Fuji, the rearrangement of pick-and-place machines consisted of combining the production lines one through four into a single line resulting in 50 percent fewer changeovers for double-sided PCAs because changeovers are performed once instead of twice (for each side).

The project demonstrated that it is beneficial to apply GT, line workload balancing, and layout rearrangement to the SMT assembly lines, as described in previous chapters. The main results achieved for the yearly customer demand include:

a) total of allocated fixed components increases from 300 to 1147 (282 percent improvement), representing 847 fewer components to deal with during the year;
b) total production run-time reduction, from 58,654 to 10,391 hours (82 percent improvement), because of the pick-and-place production line workload improvement with the proposed layout;
c) total setup/changeover time reduction, from 134,739 to 38,398 hours (72 percent improvement), because of the improvement of the allocated fixed components and production line workload balancing with the proposed layout; and
d) capacity requirements reduction from 193,393 to 48,789 hours (75 percent improvement), because of less run-time and setup/changeover time required during the yearly schedule.

The effect of the main results was drastic and positions *Electronic Systems* to bring in new products and aim for higher profitability.

5.3 Future Recommendations

It is imperative to remember that group technology has the versatility to be applied to other processes/operations in manufacturing besides pick-and-place. To help *Electronic Systems* keep growing and expanding it is recommended that they apply the procedure presented on this project to other areas outside of pick-and-place operations (within the SMT process). Figure 16 identifies additional processes where the methodology is applicable.

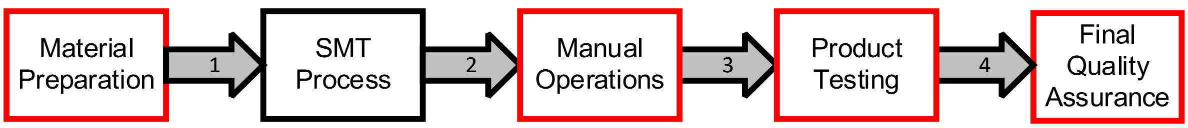

Figure 16: Other processes outside of pick-and-place

Thanks to the results obtained during this project, *Electronic Systems* management wants to use the methodology described above for a new SMT line that should arrive in the near future. There are opportunities for applying the methodology to processes outside of pick-and-place. The cost impact of this project until now represents a yearly cost saving of $2.1 million.

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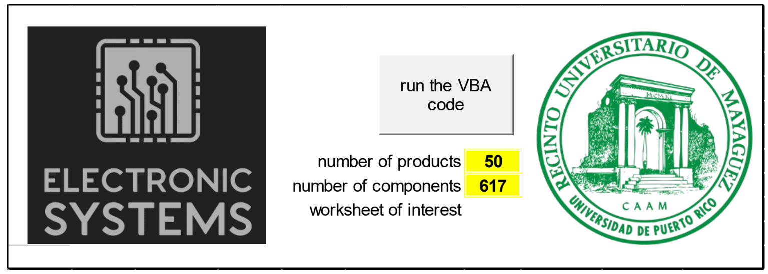
APPENDICES

Appendix A: VBA code which generates the GT results




```
'*********************************************************************************************
'Developed by Dr. Pedro Resto for PR's Aerospace Industry (Resto-Batalla, 2009)
'*********************************************************************************************
'Sub gt()
''*********************************************
'define the number of products and the number of components
Sheets("gui").Select
'
productqty = Cells(8, 9)
componentqty = Cells(9, 9)
'read from the correct spreadsheet
Sheets("full_data").Select
'
'Read the product names
For column = 3 To productqty + 2
   product(column - 2) = Cells(3, column)
Next column
Debug.Print "number of products", productqty
Debug.Print "sample products", product(1), product(15), product(productqty)
'*********************************************
'Read the component names and reel slots used (-1 implies tray, 0 implies TBD, positive implies magazine)
For row = 4 To componentqty + 3
   component(row - 3) = Cells(row, 2)
Next row
'Print sample output in immediate window
Debug.Print "number of components", componentqty
Debug.Print "sample components", component(1), component(componentqty)
'*********************************************
'Read the component quantities per product
total_cells = productqty * componentqty
nonzero = 0
For row = 4 To componentqty + 3
   For column = 3 To productqty + 2
      If Cells(row, column) = "" Then
         a(row - 3, column - 2) = 0
      Else
         nonzero = nonzero + 1
         a(row - 3, column - 2) = Cells(row, column)
      End If
   Next column
Next row
sparsity = CDbl(nonzero) / CDbl(total_cells) * 100#
'Print sample output in immediate window
Debug.Print "sparsity(%)=", sparsity
' Cells printed yellow on worksheet
Debug.Print "sample quantities", a(1, 1), a(componentqty, productqty)
'
'************************************************************************
Do
swapflag = 0
'
'++++++++++++++++++++++++++++++++++++++++
'logic for column competition
For j = 1 To productqty - 1
   'set column j as smallest
   'find a smaller column in the remaining columns
   For j1 = j + 1 To productqty
      For i = 1 To componentqty
         If a(i, j) > a(i, j1) And a(i, j1) = 0 Then
            GoTo nocolumnswap
         ElseIf a(i, j) < a(i, j1) And a(i, j) = 0 Then
            GoTo swapcol
         End If
      Next i
      GoTo nocolumnswap
swapcol:
      'swap column j1 with column j
      swapflag = 1
      tempoproduct = product(j)
      product(j) = product(j1)
      product(j1) = tempoproduct
      For i = 1 To componentqty
         tempovalue = a(i, j)
         a(i, j) = a(i, j1)
         a(i, j1) = tempovalue
```

```
      Next i
nocolumnswap:
   Next j1
'identify jth column
   'Debug.Print "prod "; product(j);
   'For i = 1 To componentqty
      'Debug.Print " "; a(i, j);
   'Next i
   'Debug.Print ""
'move to next column
Next j
'++++++++++++++++++++++++++++++++++++
'logic for row competition
For i = 1 To componentqty - 1
   'set row i as smallest
   'find a smaller row in the remaining rows
   For i1 = i + 1 To componentqty
      For j = 1 To productqty
         If a(i, j) > a(i1, j) And a(i1, j) = 0 Then
            GoTo norowswap
         ElseIf a(i, j) < a(i1, j) And a(i, j) = 0 Then
            GoTo swaprow
         End If
      Next j
      GoTo norowswap
swaprow:
      'swap row i1 with row i
      swapflag = 1
      tempocomponent = component(i)
      component(i) = component(i1)
      component(i1) = tempocomponent
      For j = 1 To productqty
         tempovalue = a(i, j)
         a(i, j) = a(i1, j)
         a(i1, j) = tempovalue
      Next j
norowswap:
   Next i1
'identify ith row
   'Debug.Print "comp "; component(i);
   'For j = 1 To productqty
      'Debug.Print " "; a(i, j);
   'Next j
   'Debug.Print ""
'move to next column
Next i

Loop While swapflag = 1
'
Debug.Print "No more swaps"
'**************************************************
'write into the correct spreadsheet
Sheets("full_gt").Select
'print the transformed table into the worksheet
For j = 1 To productqty
   Cells(2, j + 2) = product(j)
Next j
For i = 1 To componentqty
   Cells(i + 2, 2) = component(i)
   For j = 1 To productqty
      Cells(i + 2, j + 2) = a(i, j)
      If Cells(i + 2, j + 2) > 0 Then
         Cells(i + 2, j + 2).Interior.Color = RGB(255, 255, 0)
      Else
         Cells(i + 2, j + 2).Interior.Color = RGB(0, 0, 0)
      End If
   Next j
Next i
Debug.Print "JOB DONE"
'
End Sub
```

Appendix B: Fixed components percent for Mycronic

PCA#	Mycronic 80% BOT	Mycronic 80% TOP	Mycronic 20% BOT	Mycronic 20% TOP
1			100.0%	
2			100.0%	
3			100.0%	
4	100.0%			
5			100.0%	
6			100.0%	
7	98.6%	33.3%		
8			87.5%	
9			86.0%	58.7%
10			82.9%	53.4%
11			82.9%	53.4%
12			82.9%	54.0%
13			82.8%	55.6%
14	81.8%			
15			81.2%	53.5%
16			79.4%	53.8%
17	75.0%			
18	75.0%	26.4%		
19			75.0%	
20			75.0%	
21			75.0%	
22			73.8%	42.6%
23	66.7%	20.0%		
24			66.7%	
25			66.7%	
26	64.7%			
27	61.9%			
28	25.0%	61.1%		
29	60.0%			
30			60.0%	
31			58.3%	
32	57.1%	7.3%		
33			56.3%	9.1%
34			56.0%	
35			55.3%	
36			50.0%	
37			50.0%	7.1%
38			50.0%	
39	50.0%			
40			50.0%	14.8%
41	50.0%			
42			47.6%	7.7%
43			45.7%	11.8%
44	38.5%			
45	28.6%	38.5%		
46	37.0%			
47	35.3%			
48			34.9%	
49			33.3%	12.9%
50	33.3%			
51			33.3%	
52			23.1%	33.3%
53			11.8%	33.3%
54			33.3%	
55			32.3%	4.8%
56	31.6%			
57			31.0%	0.0%
58			27.8%	
59			25.6%	11.9%
60	25.0%			
61			25.0%	
62	24.5%	14.3%		
63			23.8%	
64			23.5%	
65	23.3%	17.9%		
66			23.1%	
67			22.7%	18.5%
68			22.2%	12.4%
69	22.2%	17.7%		
70	21.8%	18.2%		
71			21.4%	12.9%
72			21.2%	21.2%
73			20.7%	16.7%
74	20.0%	0.0%		
75			20.0%	
76	20.0%			
77			20.0%	
78	20.0%	0.0%		
79			18.2%	
80	17.6%	9.2%		
81	17.5%	14.6%		
82	17.1%			
83	17.1%	14.8%		
84			16.9%	13.8%
85			16.7%	
86			16.7%	9.1%
87			12.5%	16.7%
88			14.9%	16.5%
89			14.9%	16.3%
90			14.7%	15.8%
91			15.5%	12.3%
92			15.4%	0.0%
93			14.3%	
94			13.7%	12.5%
95			11.1%	
96			9.5%	
97			9.1%	0.0%
98			7.7%	7.8%
99			4.7%	
100			3.8%	
101			2.3%	
102			0.0%	
103			0.0%	
104	0.0%			
105			0.0%	
106			0.0%	
107			0.0%	
108	0.0%			
109			0.0%	
110			0.0%	
111			0.0%	

Appendix C: Fixed components percent for Fuji

PCA #	Fuji 80% BOT	Fuji 80% TOP	Fuji 20% BOT	Fuji 20% TOP
1			100.0%	71.0%
2			100.0%	40.0%
3				100.0%
4	100.0%	69.4%		
5	100.0%	46.2%		
6		100.0%		
7	100.0%	0.0%		
8			100.0%	59.0%
9				100.0%
10			100.0%	55.2%
11	100.0%	37.1%		
12				100.0%
13			100.0%	12.5%
14				100.0%
15	100.0%	64.9%		
16				100.0%
17	100.0%	61.8%		
18			100.0%	40.0%
19	97.8%	51.5%		
20	97.6%	30.6%		
21	97.3%	32.1%		
22			97.3%	58.1%
23	97.1%	71.7%		
24	95.7%	46.3%		
25	95.7%	71.9%		
26	95.7%	44.4%		
27	95.5%	17.4%		
28	95.5%	58.5%		
29	95.3%	51.0%		
30			95.2%	68.1%
31	95.1%	51.3%		
32			95.0%	58.1%
33	94.5%	48.5%		
34	94.1%	33.3%		
35			94.1%	72.3%
36	93.8%	67.2%		
37			93.6%	71.2%
38			93.2%	52.7%
39			92.9%	80.0%
40	92.7%	22.5%		
41	92.6%	56.3%		
42			92.5%	71.9%
43			91.8%	77.6%
44	91.7%	53.7%		
45			90.8%	38.9%
46			90.8%	53.4%
47	90.6%	77.4%		
48			90.2%	56.4%
49			90.2%	49.5%
50			90.2%	42.9%
51			90.2%	57.4%
52	90.1%	56.8%		
53	89.9%	36.5%		
54			89.9%	48.6%
55			89.7%	59.3%
56			89.5%	60.0%
57	89.3%	48.6%		
58	89.1%	51.6%		
59	89.1%	53.1%		
60	88.8%	50.3%		
61			88.8%	42.4%
62			88.7%	55.6%
63			88.5%	56.2%
64			88.3%	44.3%
65	88.2%	40.5%		
66	87.1%	47.6%		
67	87.1%	47.6%		
68			86.7%	43.9%
69	86.6%	43.9%		
70	86.4%	48.4%		
71			86.0%	53.8%
72			85.9%	54.8%
73	85.7%	51.4%		
74	85.7%	42.2%		
75			85.5%	51.3%
76			85.5%	46.8%
77			85.3%	48.6%
78			85.3%	54.8%
79	85.0%	48.3%		
80	84.8%	35.0%		
81			84.6%	53.3%

PCA #	Fuji 80% BOT	Fuji 80% TOP	Fuji 20% BOT	Fuji 20% TOP
82			84.2%	52.9%
83			84.2%	55.6%
84			83.3%	43.8%
85	83.3%	38.4%		
86	82.9%	45.8%		
87			81.9%	54.5%
88			81.4%	46.3%
89			80.8%	50.0%
90			80.3%	63.3%
91	79.7%	44.4%		
92			79.5%	43.0%
93			79.2%	35.8%
94			79.1%	49.5%
95			78.9%	42.4%
96			78.8%	56.0%
97			78.8%	47.8%
98			78.7%	29.1%
99			78.6%	46.9%
100			78.4%	52.0%
101			77.8%	37.5%
102			77.6%	49.4%
103			77.6%	50.0%
104			77.6%	53.3%
105			77.0%	48.4%
106	76.9%	57.1%		
107			75.9%	57.5%
108			75.8%	52.8%
109			75.0%	59.5%
110			75.0%	68.9%
111			75.0%	0.0%
112			75.0%	68.9%
113			75.0%	53.1%
114				75.0%
115			74.7%	42.5%
116	74.5%	22.6%		
117			74.5%	42.0%
118			74.4%	57.7%
119			73.5%	45.9%
120			73.4%	39.2%
121	72.7%	52.6%		
122		72.3%		
123			72.3%	49.5%
124			72.0%	28.1%
125			71.4%	71.8%
126			71.7%	42.5%
127			71.4%	62.3%
128			71.4%	40.4%
129			71.3%	57.1%
130			71.1%	39.6%
131			71.0%	44.6%
132			70.7%	55.4%
133			70.7%	44.9%
134			70.4%	61.2%
135			70.1%	54.5%
136			69.8%	27.3%
137			69.4%	59.0%
138			68.5%	27.3%
139			68.3%	34.8%
140			68.1%	53.3%
141		68.1%		
142				67.7%
143			67.5%	43.4%
144			67.4%	50.5%
145			67.1%	44.6%
146			67.1%	51.1%
147				66.7%
148			66.7%	41.6%
149	66.7%	66.7%		
150				66.7%
151			33.3%	66.7%
152			66.7%	60.8%
153			66.4%	61.8%
154			66.1%	54.9%
155			65.9%	62.8%
156		65.7%		
157			65.6%	55.7%
158			65.0%	52.2%
159		64.8%		
160		64.8%		
161		64.8%		
162			64.4%	39.0%

PCA #	Fuji 80% BOT	Fuji 80% TOP	Fuji 20% BOT	Fuji 20% TOP
163				64.3%
164			63.8%	40.8%
165			28.0%	63.7%
166			63.5%	32.8%
167				63.2%
168			63.2%	33.3%
169				62.9%
170		62.7%		
171				62.7%
172			62.7%	44.3%
173			62.5%	48.7%
174			60.5%	62.3%
175		62.0%		
176				60.7%
177		60.5%		
178			60.2%	51.4%
179				60.1%
180				60.0%
181				60.0%
182				59.4%
183				59.2%
184				58.4%
185				58.4%
186				58.3%
187			50.0%	58.3%
188			58.0%	46.5%
189			57.7%	44.1%
190				57.7%
191			57.5%	
192				57.4%
193		57.4%		
194				57.3%
195			57.1%	19.5%
196				57.1%
197				57.1%
198				56.9%
199			56.6%	56.8%
200				56.8%
201			56.7%	41.8%
202				56.2%
203				56.0%
204		56.0%		
205		55.4%		
206		55.2%		
207		55.0%		
208		53.6%		
209			52.9%	38.9%
210				52.8%
211		52.3%		
212				52.0%
213				51.5%
214				50.3%
215				50.0%
216			50.0%	50.0%
217	50.0%	50.0%		
218		49.6%		
219				49.5%
220				47.3%
221				46.0%
222				45.5%
223			33.3%	44.4%
224				44.4%
225				43.4%
226		43.4%		
227				43.2%
228				41.1%
229				40.7%
230				40.6%
231		40.3%		
232			40.0%	40.0%
233			40.0%	33.3%
234			0.0%	40.0%
235				39.6%
236				38.5%
237				38.5%
238				37.8%
239		37.6%		
240				37.5%
241			37.5%	8.8%
242			25.8%	37.1%
243				36.4%

PCA #	Fuji 80% BOT	Fuji 80% TOP	Fuji 20% BOT	Fuji 20% TOP
244		36.4%		
245			34.2%	35.7%
246		35.0%		
247				34.2%
248			33.3%	28.6%
249		33.3%		
250			33.3%	27.3%
251				33.3%
252			33.3%	0.0%
253				32.4%
254				32.1%
255			31.7%	7.7%
256				31.6%
257			31.6%	5.9%
258		31.6%		
259			31.1%	13.6%
260		30.8%		
261				30.1%
262				29.2%
263			28.6%	
264				28.0%
265				27.3%
266				27.3%
267				26.3%
268				26.3%
269				25.9%
270		25.0%		
271	25.0%	0.0%		
272			25.0%	20.0%
273				25.0%
274				24.6%
275				24.5%
276			24.2%	17.6%
277				23.3%
278		23.1%		
279				21.6%
280		21.4%		
281				21.3%
282				21.3%
283				21.3%
284				21.3%
285				20.9%
286			20.0%	20.0%
287				19.5%
288				19.0%
289			10.4%	18.6%
290				17.6%
291			6.9%	17.5%
292				17.1%
293			14.3%	15.4%
294				15.0%
295				15.0%
296				14.3%
297			13.8%	13.8%
298				13.2%
299				13.0%
300				12.5%
301			0.0%	12.5%
302		12.5%		
303			7.1%	10.5%
304				10.0%
305				9.7%
306				9.4%
307				9.1%
308				9.1%
309				8.6%
310				8.6%
311				7.7%
312				7.7%
313				7.7%
314		5.3%		
315				0.0%
316		0.0%		
317				0.0%
318				0.0%
319	0.0%			
320	0.0%			
321			0.0%	0.0%
322			0.0%	0.0%
323			0.0%	0.0%