A CHARACTERIZATION FOR A PLACEMENT MACHINE IN A SURFACE MOUNT TECHNOLOGY ASSEMBLY LINE

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Abstract

This project presents the development of a computer based model to characterize the assembly time for a placement machine in a *Surface Mount Technology* assembly line. This model estimates the assembly time for a Printed Circuit Board with any configuration. The characterization of a placement machine is an important tool for the electronics industry due to the need to improve the process time in the whole assembly line. The analysis shows that the *Characterizer* application has an average error of 4.69%, as compared to the current application of 20.39% and *Fuji* of 67.17%.

The model program is developed using Microsoft Visual Basic ® for Applications in Excel. The computer application is performed under a human-machine interface environment in order to illustrate the viability, flexibility and capability of the proposed model.

Resumen

El presente proyecto presenta el desarrollo de un modelo computarizado que caracteriza el tiempo de una máquina de colocación de componentes en una línea de ensamblaje de *Tecnología de Montaje de Superficie*. Este modelo estima el tiempo de ensamblaje para cualquier configuración de un *Printed Circuit Board*. La caracterización de la máquina de ensamblaje es una herramienta importante para la industria electrónica debido a la necesidad de mejorar el tiempo de proceso de toda la línea de ensamblaje. La validación muestra que nuestro programa tiene un promedio de error del 4.69%, la actual aplicación tiene 20.39% y *Fuji* tiene 67.17%.

El programa modelo es desarrollado usando Microsoft Visual Basic ® for Applications en Excel. El modelo de computadora es realizado bajo una interfase hombre-máquina para ilustrar la viabilidad, flexibilidad y capacidad del modelo propuesto.

In memory of the matriarch Virgelina

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IMC: Insertion Mount Component

MFU: Multiple Feeder Unit

MTU: Multiple Trace Unit

PCB: Printed Circuit Board

PCBA: Printed Circuit Board Assemblies

PWB: Printed Wiring Board

SMC: Surface Mount Component

SMT: Surface Mount Technology

THT: Through the Hole Technology

VBA: Visual Basic for Applications

Chapter I: Introduction

Surface Mount Technology (SMT) refers to an advanced technology of interconnection of components using planar mounting. SMT includes several circuit technologies which do not use Through the Hole Technology (THT) assembly, another widely known technique in the electronics industry.

SMT is considered as the latest and most important technology in electronics assembly. Unlike traditional Through the Hole Technology, where the Insertion Mount Components (IMC) are placed through the board, the surface mount components (SMC) are soldered directly to the board surface. This difference has important impact on the composition of the products and their manufacturing processes. As a result of this technology, the products are smaller, lighter and less expensive to manufacture. Tables 1.1 and 1.2 show a comparison between equivalent SMSs and IMCs.

component	IMC DIP	SMT SOIC
16-Pin	0.044	0.004
20-Pin	0.055	0.021
40-Pin	0.245	0.071

Table 1.1 Comparison between equivalent SMCs and IMCs in $inches^3$

component	IMC DIP	SMT SOIC
16-Pin	1200	130
20-Pin	1500	650
40-Pin	6580	1850

Table 1.2 Comparison between equivalent SMCs and IMCs in mg

Consequently, the electronics industry is changing toward SMT. The reductions in Printed Circuit Board (PCB) real state, quicker switching speeds, improved reliability, simplified assembly automation, and lower costs in supplies and factory assets are the primary reasons of this change.

Other advantages of SMT are related with the PCB performance such as the circuit propagation delays, noise immunity and crosstalk. Additional advantages of SMT are the PCB manufacturability, the flexibility of the placement machine when handling the assembly; and the PCB quality due to the degree of process control on the assembly line.

Most SMT assembly processes in modern electronics industry are similar and highly automated. Computer controlled assembly machines are placed in a production line or a manufacturing cell. The number of SMCs to be placed on a board fluctuates from a few hundred to several thousand. Placement machines differ on the range of SMCs styles, SMCs sizes they can handle, and the production rates.

Every placement machine in the assembly line has one or more feeders holding the SMCs to be mounted. When the production line is changed to another type of board, a setup is required to change the component feeders and to reprogram the assembly process.

In SMT assembly lines, setups are time consuming and costly. Appropriate arrangement of product sequence can considerably reduce general manufacturing time and cost.

Minimizing the total system setup is one of the major worries in SMT production scheduling, since system setup often requires considerable amount of time. Optimal SMT scheduling models may be developed but its optimization is very challenging.

Work to be performed on an assembly line must be broken down into tasks for every workstation. The cycle time is defined as the maximum time required at any workstation in an assembly line. The cycle time is affected by the line speed, equipment reliability, complexity of the tasks, etc. We are interested in the particular case where the placement station is the bottleneck of the total assembly process.

Thus, the overall objective when designing and controlling a PCB assembly line is the reduction of total setup time and processing time to increase throughput. Characterization is needed to recognize the way a placement machine works when several parameters change. For instance, line balancing benefits from mathematical characterization of the operations. Then, process planning can take place to improve setup and cycle time by means of optimization techniques.

The characterization estimates and typifies the behavior of a machine according to its parameters. The parameters change due to different situations. In our case, some of the parameters vary as a function of the characteristics of the PCB.

This project tries to characterize a placement machine in a PCB assembly line with a computer-based model. Such placement machine is the FUJI IP III located in the Model Factory at the Industrial Engineering Department of the University of Puerto Rico at Mayagüez Campus (UPRM).

1.1. The SMT Manufacturing Process

Generally, the assembly process is made up of six stages: attachment media dispending, component placement, attachment media curing, soldering, cleaning and testing.

The attachment media is usually a viscous substance or paste composed of solder material and flux. Its function is to attach permanently the components to the board and form the electrical connections. In the reflow soldering technique, the solder paste is distributed in a screen or stencil printer, the components are placed on the board and sent trough a reflow oven. In the wave soldering technique, the components are glued to the board and then passed through a solder bath that produces electrical connections among the PBC and the SMCs.

Automated PCB assembly uses modular placement machines. Similar to assembly lines, they require the workload distributed between the modules or placement heads. In order to achieve the desired output rate these modules need a balance. For the placement machine under study, such modules are called Multiple Feeder Units (MFU).

Modular placement machines consist of several individually operating placement units, each of which comprises its own component magazine and transfer system. The modules are linked by a conveyor system that transports the PCBs from one module to another. The modules are designed to operate according to specific placement principles, pick and place with single transfer of SMCs from the magazine to the board.

Most of the assembly processes are conducted by highly automated placement equipment. An automatic pick and place machine selects, orients and places a diversity of SMCs on a board. Thus, assembly with SMT allows flexible production scheduling, but requires a great computer control. That is why; the placement equipment is classified by its style of processing, level of flexibility and level of automation.

The style of processing refers to the volume of operation. There are low volume machines that assemble one SMC at the time. The medium volume machines include robotics to improve the placement reliability. The high volume machines have several heads operating concurrently, placing even millions of SMCs in a single cycle machine.

In summary, these machines can place from thousand to millions of SMCs in a day. Some of them only put a set of similar components and others place a high variety of components. Pick and place machines also differ in features as production output, flexibility, speed and accuracy.

The automated placement machine to be studied, works with two banks of feeders. Each feeder is serviced by a different head and contains a reel of SMC. The two placement heads operate concurrently and share a common working space. Every SMC is taken from the feeder by a placement head and then moved to a table that embraces the PCB. When a head is not doing any placement, the other head moves to the placement location and places the SMC over the PCB. After the placement is done, the head leaves the table and the other head is able to perform its placement task.

The placement of one component is performed in the following way. The head leaves its position above the PCB and moves toward the feeder slot position where the component is located. The head picks up the component. The component is brought back to the PCB location, where it is placed over to the PCB if the other head is out of the way.

Certain components require high precision which is ensured by the visit of the head to a centering station after the SMC is picked up and before it is brought to the table. Sometimes the head needs a special nozzle for a component. Then it replaces the current nozzles for a new one before a new placement cycle begins.

The placement process constitutes the bottleneck of the assembly process. In the literature, machine optimization is studied to improve this condition. Minimizing the time it takes the machine to complete all the placements is the objective. The strategy consists of optimizing the placement sequence and the feeder assignment. The placement sequence indicates the order in which every SMC is placed over the PCB. The feeder assignment indicates where the components are staged on the machine.

Another important issue in the literature is collision avoidance. As the placement heads operate concurrently and share the same working space, collision avoidance techniques must be implemented to avoid damage to the machine.

Sometimes, the attachment media must be cured before the soldering stage. In this step, the sub assembled part is heated, in order to evaporate volatile material from the solder paste, avoiding a quick boil off which could create defects in the assembled board.

Soldering is the stage subsequent the media curing. It consists of adding adequate heat to melt the applied solder paste. Sometimes the SMCs are exposed to high temperatures and its survival and reliability become an issue to be concerned about.

Cleaning is the stage where hazardous contaminants substances are removed off the circuit board. Some of the principal techniques are cleaning with saponifiers, without saponifiers, and ozone friendly chemistries.

Finally, testing is a very difficult stage. Physical testing leads with spaces in millimeters and stretched geometry that visual examination has to face. In addition, the density of the components in the board makes the problem harder. Electrical testing concerns with electrical defects analyzed with circuit testers solder joint quality tested with vision systems, contaminants remaining are tested with conductometers.

Figure 1 shows the SMT assembly process as followed at the Model Factory at the UPRM. This project focuses the placement stage.

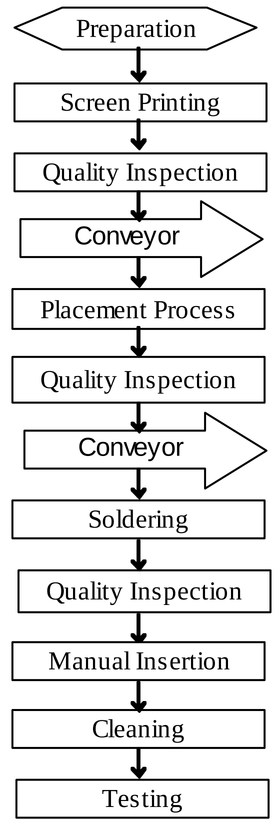

Figure 1. SMT Process at UPRM

1.2. Justification

The pressure imparted by aggressive competition, forces the electronics industry, like many other industries, to keep costs down and reduce product cycle time. These competition pressures affect all the phases of product manufacturing and direct attention to new approaches for planning, scheduling and control. The electronics industry is particularly sensitive to these issues due to rapid changes in technology. Because of the short life cycle of products, minimizing the time of PCB assembly is crucial for the electronics industry.

The estimation of the assembly time is an important tool for the electronics industry due to the need for tight product introduction planning, scheduling and the control thereof.

Part of the assembly time is due to placement. A relevant issue in an assembly line is to optimize this time. However, a characterization of the machine is necessary before any optimization efforts. The automatic placement machines are expensive, and are usually the bottleneck of the line.

The assignment of different components to the machine is critical, since it determines the efficiency and the productivity of the line. Assigning different PCBs to assembly lines is a relevant activity. This task must consider specific elements of each line, such as machine capacity, to match the quantity and technical requirements of board types with machines.

The problem is the allocation of the SMCs on the placement machine and placement sequence on the PCB. Different assembly times may occur, considering the SMCs are located at different feeder locations. The assembly line problem is equivalent to balancing it without large component rearrangement between model changes.

This project analyzes a special type of pick and place machine that assembles components to a PCB. The main goal is to characterize the placement machine. The characterization is used to estimate the assembly time of different PCB types. Better production plans can be generated with the help of the characterization. Indirect results from this project are lower production costs, flexible manufacturing and maximization of the production throughput.

The objective of the *Characterizer* is to estimate cycle time, which is defined as the maximum time a PCB has to spend on the machine. With the characterization, it is possible to obtain reliable estimates of the cycle time of the placement machine.

The assembly time is function of the component allocation problem, which determines how component types are assigned to machines to balance the workload across machines. The production time is needed to allocate boards to production lines.

However, production time is sequence-dependent. This means that the specific sequence of different PCBs to be produced on each line and the board assignment to production lines both have to be known to estimate production time.

Component assignment and placement sequence depend on each other, necessitating the incorporation of the component allocation issue in the board assignment problem and vice-versa. The automatic placement machines should be characterized in order to get high utilization and minimal assembly time.

The predominant objective in scheduling the operations of the assembly equipment is to minimize the processing time for each board manufactured. This objective is achieved by fine tuning the operations of the assembly equipment used when characterization is employed; in particular, when the assembly time is characterized, optimization of the sequence of the placement operations and the component assignment line can be achieved. As a result, the output of the assembly line can be improved.

The study takes place in the assembly line at the SMT Model Factory of the Industrial Engineering Department at the University of Puerto Rico Mayagüez Campus. The pick and place machine is the FUJI IP III.

1.3. Objectives

The objectives of this project are the following:

- Develop a computer-based model to characterize the placement machine performance, and standardize the representation of relevant data. The characterization should provide a reliable estimation of the machine cycle time.
- Develop a human-machine interface for data input. Such graphical interface is the tool that allows interaction between user and the computer program.
- Identify the relevant machine parameters for the model.
- Identify the relevant characteristics for every PCB.
- Use the model to predict the output of the assembly process by simulating the machine routine providing the time required to assemble a PCB.

The model must be able to predict with some accuracy the assembly time. Every assembly time varies according to changes in the parameters and the machine configuration. Characteristics of each PCB type define the parameters used in the model, *i.e.* variety and number of components.

Current PCB assembly utilizes computerized machines and highly automated equipment. As equipment becomes more productive, efficient planning and organization are needed to increase production throughput. To reduce the placement time of SMCs on to PCBs, three particular problems are identified: allocation of component types to machines, allocation of component types to feeder locations at the machine, and sequencing of placement operations for the machine and each PCB.

1.4. Organization

This report is divided into five chapters in addition to the introductory one. The material presented in each chapter is presented next.

In chapter II, literature review is presented. The chapter includes several research papers that focus in the assignment and balancing problem.

In chapter III, an overview of the different placement machines is presented. However, the chapter focuses in the FUJI IP III and its characteristics.

In chapter IV, the characterization model is created and analyzed.

In chapter VI, the characterization model is analyzed and compared.

In chapter VI, the model is implemented through a graphical interface tool.

Chapter VII includes conclusions and future work.

Chapter II: Literature Review

The analysis of electronic assembly machines found in the literature mainly focuses in the optimization of the assembly time, the scheduling of the line or the component allocation and assignment. *Maimon and Braha (1998)* address the problem of scheduling *N* printed circuit boards (PCBs) on a single machine equipped with an automatic component interchange mechanism. The problem consists of finding the order to schedule the PCBs on the axial insertion machine and the components to place on the spool before each PCB is processed. The performance criterion is to minimize the total number of component switches. This problem is addressed employing a genetic algorithm to search the space of alternative solutions.

Sawik (2001) presents a mixed-integer programming approach to simultaneous or sequential balancing and scheduling of SMT lines for printed wiring board (PWB) assembly. The problem objective was to determine an assignment of components to feeder slots at each placement station and to determine an assembly schedule for a mix of board types to complete the boards in minimum time.

Lapierre, Debargis and Soumis (2002) address the problem of allocating and arranging the components on several placement machines, organized into one or several assembly lines, while considering a different assembly time if components are located at different feeder locations. The objective of their research is to minimize the weighted sum of each assembly PCB cycle time. They solve this problem with Lagrangian relaxation techniques. They also compare the global performance of five placement machines if they are organized as a single assembly line or broken down into two or more assembly lines.

Hernández (1996) presents the multi-zone work center model which provides the basis for the analysis of pick and place machines with multiple manipulators and interference. His model is applied to an electronic assembly machine with two placement heads which share a common working area where interference avoidance is considered. He presents the problem with mathematical model and show that simple procedures can be used for the generation of feeder assignment and placements sequences.

Wan and Ji (2001) discuss the component assignment problem in PCB assembly, where assigning components to appropriate machines, in order to get a minimum assembly time for the assembly line, can be formulated as an integer linear programming model. In order to obtain the optimal solution to the component assignment problem, the branch-and-bound method is proposed. However, it is not efficient. They apply the tabu search heuristic to the component assignment problem.

Grunow, Gunther, and Schleusener (2003) present an integer programming model and two different heuristic solution procedures in the problem of similar assembly lines when they require the workload between their modules to be balanced in order to achieve the desired output rate. The approaches presented are especially designed to consider the technological constraints arising from the design of modular placement machines.

Haberle, Burke and Graves (2002) introduce a new approach to the problem called *activation*, which is used to build a cycle time estimation model for the design phase for printed circuit board assemblies (PCBA). This problem in the estimation of the development cycle time is an important tool for the electronics industry due to the need for tight product introduction planning and the control thereof. A small-scale case study using data obtained from electronics designers demonstrates the capability of their method.

Neammanee and Randhawa (2003) describe an approach to minimize makespan for assigning boards to production lines. Due to sequence-dependent setup times, board assignment and component allocation have to be performed concurrently. They develop an integrated methodology to obtain a solution to these two problems. The methodology consists of seven phases: printed circuit board grouping, family decomposition, subfamily sequencing, Keep Tool Needed Soonest (KTNS) procedure, component setup determination, component allocation and board assignment. Application of their methodology to industrial problems demonstrates that it can solve large-scale problems efficiently.

Again, *Sawik (2002)* presents new mixed integer programming formulations for blocking scheduling of SMT lines for printed wiring board assembly. The SMT line consists of several processing stages in series, separated by finite intermediate buffers, where each stage has one or more identical parallel machines. A board that has completed processing on a machine may remain there and block the machine until a downstream machine becomes available for processing. The objective of his research is to determine an assembly schedule for a mix of board types so as to complete the boards in a minimum time. Scheduling with continuous or with limited machine availability is considered.

Wei-Shing and Chiuh-Cheng (2001) say that in a high-mix middle-volume production environment for PCB assembly, the production efficiency strongly depends not only on the tactical level of how to group PCBs but also on the operational level of how to assign feeders and determine placement sequences in the group setup strategy. Their study discusses the problem of clustering PCBs into groups in such a way that total placement and setup time can be minimized. Also, their research incorporates placement time into the PCB job grouping and presents a weighting similarity measure. To solve component-feeder assignment and placement sequences for a family of PCBs, they develop an efficient procedure based upon an ant colony optimization (ACO) algorithm.

Sze, Ji and Lee (2002) consider a production planning problem in PCB assembly. A PCB assembly line has several non-identical placement machines, so the placement times by different machines are various to the same type of components. They formulate several mathematical models in order to obtain a best assignment of components to machines with the objective of minimizing the cycle time to have the best line throughput. Moreover, they analyze data structures of the models and compare with other similar models to search a good available algorithm.

Grandjean and Schewntick (2002) present two algebraic characterizations of machine independent in an assembly line. The algebraic characterizations are in terms of recursion schemes that define unary functions. One of these schemes defines several functions simultaneously, while the other one defines only one function.

Saavedra, Smith and Miya (1999), examines a machine (computer) characterization. They report an approach to machine characterization. Their idea is to create a machine characterizer, which measures the performance of a given system in terms of a computer language. Also, they present measures of different types of machines and combine these measurements into group of parameters which relate to specific aspects of the machine implementation, and use these groups to provide overall machine characterizations.

Few authors discuss the topic of machines characterization in relation to SMT assembly lines. Other authors present mathematical characterization to represent different kind of high technology machines such as computers and other manufacturing machines. Most of them discuss the optimal configuration of the placement machine. However, none discuss mathematical or a computer-based characterization.

Chapter III: The Placement Process and the Fuji IP III

Pick and place is the process of picking the surface mount components (SMCs) used to build a printed circuit board (PCB) assembly, and placing them on the board. SMCs are placed on a PCB after deposition of solder paste. The components can be placed on the board by manual placement, semiautomatic or automatic placement. The pick and place equipment is normally referred to as placement machines.

Manual placement of SMCs is not reliable. However, this method can be used for prototyping applications, rework, and sometimes have to be used when the characteristics of the PCB do not allow automatic placement. In this method, a person takes the components and puts them on the appropriate spot by hand.

Some problems associated with manual placement of components are wrong orientation and accuracy. Even if a component is hand placed in the right spot, operator could place it in the wrong orientation causing the board to fail. The likelihood of errors increases when operator is hand placing a part. When getting into fine pitch components, it is very difficult to achieve the accuracy necessary due to scale of measures i.e. millimeters. Some advantages related to manual placement are low capital cost and low prototyping cost.

Automatic placement machines are necessary for high volume production because the manual method technique turns out to be very slow. Also, reliable quality levels are possible to achieve. Usually, vision capability is required for placement of fine pitch components and the associated cost is added to the overall cost of the equipment.

Companies have to choose the placement machine appropriate to their needs and the future requirements. Some important parameters when selecting the equipment are placement speed, placement accuracy and precision, and the variety of components that the machine should handle. Placement speed refers to the number of components that the machine should be able to place per hour.

Companies choose its type of placement machine according to the volume and diversity in the demand of products. A combination of technologies to assemble variety of boards some times is convenient. For instance, about 80 per percent of the components on a board are resistors and capacitors, which need to be placed quickly. With these components, an accurate placement machine is not as critical as with other components on the board. Fine pitch components need higher placement accuracy, then speed should be sacrificed in this case.

There are several types of SMT placement machines available, such as sequential pick and place, rotary disk turret, concurrent pick and place, etc. These types of SMT placement machines have different characteristics and restrictions.

Placement machines could be classified also by its mechanical structure. Cartesian gantries, cylindrical, spherical, articulated and parallel are some examples. However, most of the placement machines used in PCB assembly industry are cartesian gantry robots.

Typically, each placement machine has a feeder carrier or feeder magazine, a PCB table, a head, a nozzle and a tool magazine. The feeder carrier, the PCB table and the head can be either fixed or moveable depending on the specification of the machine. In some cases, the feeder magazine is divided into separate feeder banks, each consisting of feeder slots. A typical feeder carrier consists of either several tape reels and/or vibratory ski slope feeders.

The feeder reels are positioned in the feeder slots according to the arrangement given in the setup stage. Feeders present components to the machine by reels, delivering the components individually so the arm can pick them up, inspect them and place them.

The vacuum nozzle is a tool that sucks up a SMC to the head machine and carries it through the processes of alignment, inspection and placement. The nozzle grasps the component from the feeder and then mounts it over the PCB.

The placement arm is equipped with heads, which are in charge of the picking and placing procedure. Each arm has one or more heads and each head has one or more nozzles. The size of the nozzle depends on the size of the component to be placed. Hence, a tool magazine is required to provide the exact nozzle size. There are many types of placement heads, such as a rotating turret head, or a positioning arm head. The PCB tables are required to position the PCBs during placement operation. The tables could be stationary, an X-Y motion system table or a conveyor system.

The board is brought into the machine either manually or by conveyor depending on the level of automation. Once loaded, placement machines use optical correction to determine if the board is exactly where it should be and make corrections if it is not. Boards can be located by using fiducial marks and shapes. Fiducial marks are used to calculate the allocation of the components to the board. Fiducials are placed on the board at the same time as the land patterns for the components and are aligned perfectly with these same patterns. Using fiducials, the machine can place the correct components in the correct places.

The PCB production and scheduling procedure are influenced by the type of placement machine to be used. Appendix A provides information about different placement machines used currently at the SMT lines.

3.1. The FUJI IP III Placement Machine

The Fuji IP III machine has two placement heads mounted at the end of every arm. The arms can only move in the X-direction. A nozzle on every head can move in Z-direction to perform pick and place operations. Simultaneously with the head movement, the Y-direction is performed by a table. The table is the place which the PCB lays on. The placement arm begins by moving to the tool magazine to equip itself with the appropriate nozzle. Next, it moves to pick a particular component from the feeder location, and then places the component at the proper location on the PCB. If the following component is of the same type, the arm moves directly to feeder slot to perform the subsequent pick and place operation. Otherwise, the arm goes to the tool magazine and changes the nozzle if necessary. In other variations of a placement machine, the arm moves in the X-direction only and the head in the Y-direction. Figure 3.1 illustrates the Fuji IP III.

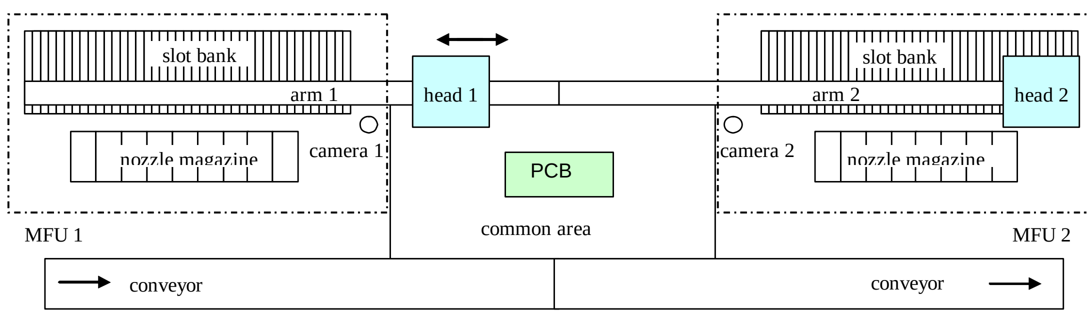

Figure 3.1 Diagram of the Fuji IP III

Each side of the machine has one slot bank, one arm, one head over the arm, and one magazine tool for the nozzles. Each side of the machine may work independently. Thus, the center of the machine, where the table is situated, becomes the common area. Figure 3.2 illustrates the placement process.

The slot bank, called Multiple Feeder Unit (MFU), contains thirty eight slots. A slot is the place where a feeder is inserted. A feeder is the tool where a reel of the same SMC type is set. The feeder width may vary depending on reel width. Thus, a feeder could occupy one or two slots. Actually, the feeder could occupy 1.5 slots, but two are compromised. Figure 3.3 shows a feeder and a slot bank.

The reel contains the SMCs in small places sealed with a tape. Depending on the SMC size, the reel can contain between 1,000 and 10,000 SMCs.

Different feeders are placed in different slots and the location of such feeders is an optimization problem by itself. The configuration of such feeders is suggested by an optimization software. Some of the input data required by such program includes the following:

- The number of MFUs used
- The SMC type allocation on the board

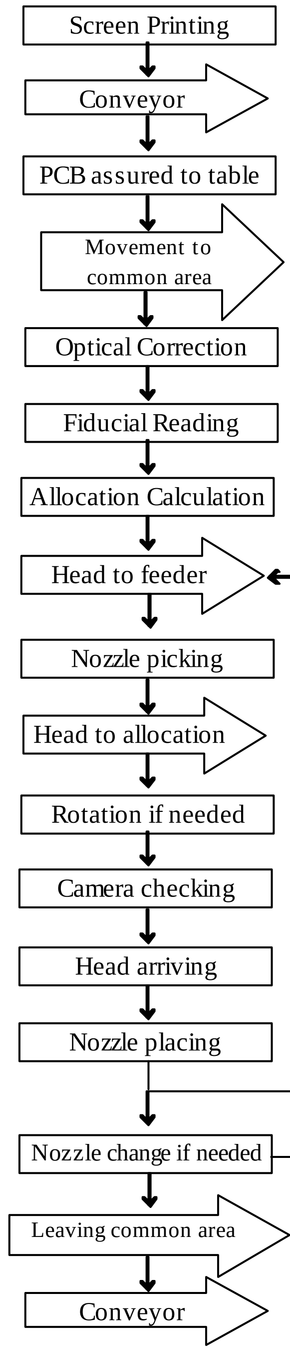

Figure 3.2 The placement process

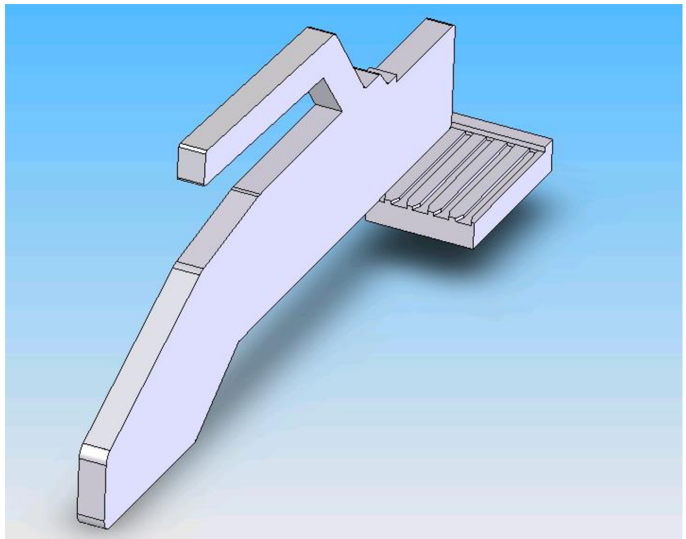

Figure 3.3 A bank of slots and a feeder

Some of the outputs of the optimization program are the following:

- The reel allocation on every MFU
- The insertion order for every SMC
- The forecasted placement time for the PCB

However, it is possible to obtain many different configurations. Different algorithms provide different solutions for the configuration problem. Genetic algorithms, neural networks, and ant colony are some of the configuration optimization techniques. Problems like scheduling, integer programming, and traveling salesman are used to find the optimal configuration.

Our proposed model, works on the forecasting placement time problem, not on the configuration problem. For any configuration the model should forecast with some accuracy the placement time.

The nozzles are other important part of the process and the machine. The nozzles are the tools which pick and place the SMCs. They vary in their hole width. According to the size of the SMC is the nozzle width that will pick and place it. However, a SMC could be picked or placed with a nozzle or a range of nozzles. Figure 3.4 shows a nozzle.

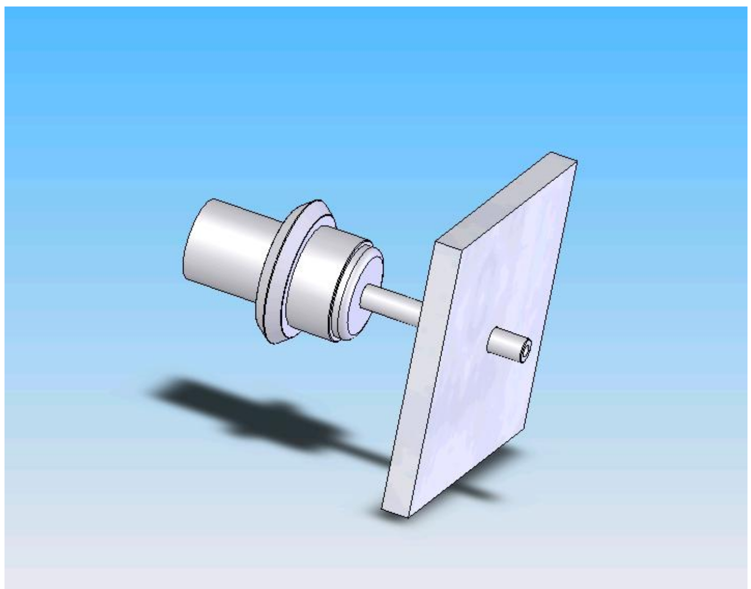

Figure 3.4 A nozzle

When the board leaves the screen printing stage, the machine receives it. The PCB is carried toward the placement process through a conveyor. Then, the PCB is placed on the table where it is secured. Consequently, the table moves forward to the common area. Then, the heads use optical correction to determine if the board is exactly where it should be and make corrections if it is not. Consequently, the heads reads the fiducial marks and the PCB is seen as cartesian coordinates. Now, the machine may calculate the required allocation of every SMC.

Next, every head, working independently, goes for a SMC in a feeder. When the head arrives to the slot, the nozzle moves down and sucks the SMC up. Then, the head returns through the arm. In this returning stage, the nozzle could rotate the SMC if needed. That is because sometimes the SMC must be placed in a different rotation than it is picked. Subsequently, while the head is in movement, the camera checks the SMC. This checking process is done in milliseconds. When the head arrives to the correct position on the board, the nozzle moves down and places the SMC. Then, the nozzle moves to the placement location if no collision risk is presented. The cycle is repeated for each SMC on the board. The head may reach the same SMC again to place it over another board position or may reach another SMC.

When all SMCs are placed, the PCB is moved back to the conveyor and goes out of the machine to the following SMT process.

There exists another part of the machine called Multiple Trace Unit (MTU). Such units are at each side of the machine, as the MFU units. The MTU is used to assemble SMCs that requires an extra care in the placement process. Such SMCs are known as fine pitch and extra fine pitch components. The MTUs are not considered in the characterization because they are extra accessories of the machine and are not widely used.

3.2. Additional Considerations on the Placement Process

Sometimes, when the nozzle moves down it fails to grasp the SMC. There are two reasons for such behavior. The first is that simply, there is no SMC in the reel. The manufacturer of the component cannot assure the total amount of components in the reel. The second reason may be the tape that sealed the reel. The tape could not be removed to allow the suction of the SMC. When one of these situations happen, the machine stops. Then, the operator may do the corrective actions.

Each type of SMC should be placed at a different speed rate. Furthermore, there are three different speeds to be considered. The pick speed and the place speed are correlated. Theses speeds vary according to the SMC type. If the SMC is very delicate, the pick and place speed should be low to avoid damage. The translation speed refers to the velocity of the arm. This speed varies according to the SMC size and weight. If the SMC is very heavy, the translation speed should be low to avoid inertia when the head stop to allow the place exercise.

The camera does a physical evaluation of the SMC. Depending on the image tolerance, the camera may or may not reject the SMC. The operator changes the tolerance according to the quality standards of the SMT line. However, a low tolerance may result in the rejection of a good SMC, and a high tolerance, may result in the acceptance of a bad one. The tolerance is measured in millimeters. It gives an idea of the camera capacity. If the camera rejects the SMC, the head goes to a specific place to discard it. Then the head has to return to the same feeder.

When a head finishes the placement of a SMC type, then it has to move to another slot position to pick another SMC. So, the cycle begins again, placing the same SMC type over different positions at the PCB. However, this new SMC type could be of a different shape, size or weight. Then, the current nozzle may be inadequate, and the head would have to go to the magazine tool, leave the current nozzle and collect an adequate one. Which nozzle should the head gather? It has several alternatives. The operator writes a range of different nozzle widths that could perform the suction up and place down operation. Again, this is part of the configuration optimization problem.

3.3. The Printed Circuit Boards

The quantity and diversity of SMCs over a PCB depends on its design. Each PCB that is assembled in a SMT line has a specification that is provided by the designer. There is a drawing that specifies every SMC type and its position on the board. Generally, the SMC type is identified by a numeric name or “part number”. Although two SMCs may look similar, the part number provides information about their electrical characteristics. For assembly purposes, the part number is not considered. That is, same nozzle could be used for two different SMCs. The shape, size or weight determines the kind of nozzle as explained in the previous section.

An empty board could contain a whole PCB, or could contain several. When a board contains several PCBs, it is called an image. So, the whole board is called a panel, and every image is called a board. Before the assembly, an operator sets the coordinates of the main image. As said, the coordinates are the location where each component will be assembled. Then, the software of the machine calculates a penalization. A penalization consists of transferring the initial coordinates to another part of the board where the images will be assembled.

3.4. The Surface Mount Components

SMT technology provides two major advantages over THT technology. Smaller components allow lighter and space saving boards. Additionally, SMT allows populating both sides of the board.

SMCs may be classified in two different kinds, the passives and the actives. *Hollomon* describes passives are circuit elements (components) which do not change their basic character when an electrical signal is applied. Passives include capacitors, resistors, inductors, coils and others. Actives include diodes, transistors, integrated circuits, and others. Other kinds may be added to such classification as connectors, sockets, switches, relays, jumpers, thermistors, and inductors.

Nevertheless, this classification does not affect the assembly time. The assembly time is not influenced by their electric or functional categorization. It is influenced by the quantity and diversity type of the SMCs.

Chapter IV: Proposed Characterization

The present chapter discusses the methodology followed in this project. The development consists of five stages. In the first stage, possible parameters are analyzed. An analysis is performed on the relevant parameters, its specific requirements and characteristics. The second stage includes the development of the conceptual structure of the model, analysis of required tasks, tools, and methods used. The third stage, involves the model assumptions. The fourth stage contains the model development and its requirements. The fifth stage is discussed on the next chapter. It will deal with the implementation and analysis of the model.

4.1. Background

Current literature focuses in the problem of the whole assembly time for batches of PCBs; including setup activity, feeder assignment, and placement scheduling. This point of view makes researches center their attention on the macro problem, providing a simplistic determination of the placement time. Literature solves the optimization problem of the shortest path for assembling with several methods such as linear programming, scheduling, the traveling salesman and genetic algorithms, among others. The disadvantage when they apply these methods is that they ignore important parameters that might affect the placement time and centers in the idea of the overall assembly time.

Our analysis reveals a basic need; the estimation of the placement time requires a deeper analysis. It motivates us to develop a computer model which deals with parameters not considered previously. Furthermore, literature does not focus in characterization but optimization. Therefore, it is imperative that this project focuses on the placement time characterization.

4.2. Analysis of Input Data

To analyze the input data, relevant parameters are identified as candidates to be included in the model. The sources of information include the machine documentation, technicians, operators inputs, production history, among others.

The parameters are classified as continuous, discrete, and dynamic.

Some continuous parameters are:

- The failure rate for the components.
- The translation speed rate of the arm (X-direction)
- The pick speed rate of the head (Z-direction)
- The place speed rate of the head (Z-direction)
- The speed rate of the table (Y-direction)
- The rotation speed rate of the nozzle
- The tolerance of the camera

Some discrete parameters are:

- The number of components required for the PCB.
- The quantity of nozzle changes during the cycle time

Some dynamic parameters are:

- The quantity of heads to be used
- The configuration of the MFU
- The distance from the slot to the assemble location
- The machine wear and tear
- The machine maintenance

There are also other parameters which affect the assembly time for a whole batch of PCB's. Some of them are related to the machine and others to the process dynamics.

- The speed rate of the conveyors
- The operator availability
- The SMC quantity into the reel
- The machine availability

After an analysis, we concluded that not all the parameters need to be incorporated into the computer model. Such analysis began by studying the machine performance. The placement dynamic was analyzed and our decision was supported by the SMT process administrators. Parameters like the machine wear and tear and the machine maintenance are difficult to control and to measure. The parameters to analyze are those that affect the assembly time. Furthermore, the parameters should be measurable and controllable.

4.2.1. The failure rate of the SMC’s

Like any other product, SMCs are subject to quality issues. Failure rate for every SMC type is usually known historically. In the placement process failure refers to a SMC never placed due to shape issues. Other kind of failures can be identified. Sometimes, the SMC does not work properly electrically. It should be removed and replaced at the testing stage. Therefore, the electrical failure is not considered for the placement time forecasting.

The failure rate information is obtained from the SMT process administrator. Some failures are associated with the camera. The machine finds a physical dissatisfaction between the SMC measures and the image from camera. Then, the head does not perform the placement action and places the SMC in a disposal conveyor. Also, failures relates to inertia. A high speed of the head trough the arm makes the SMC fall off from the nozzle.

4.2.2. The translation speed rate

The translation speed refers to the velocity of the head trough the arm. This speed may be changed in the configuration stage. However, it is measured as a rate. Therefore, the change varies between zero and one. The translation speed is associated with the SMC size. Bigger or heavier SMCs should be transported at low rates to avoid loosening from the nozzle as explained in the previous section. Smaller or lighter SMCs could be transported at high rates.

4.2.3. The pick and place speed rate of the SMCs

These two kinds of speeds are analogous. Both are independent but perform their action in the Z-axis. A high speed rate may diminish the assembly time but also may damage of the SMC when the nozzle picks or places.

4.2.4. The speed rate of the table

The velocity of the table is a controllable and measurable parameter. It does not affect greatly the assembly time. The table moves in small distances while the head moves in large distances. When the head arrives to the X position, the table is already in the Y position. Rarely, the head has to wait for the table to arrive to the Y position. So, it is not going to be considered on the model.

4.2.5. The tolerance of the camera

As explained in section 3.3, the camera does a physical evaluation of the SMC. Depending on the image tolerance, the camera may or may not reject the

SMC. The operator changes the tolerance according to the quality tips of the particular assembly line. However, a low tolerance may result in the rejection of a good SMC, and a high tolerance, may result in the acceptance of a bad one. Therefore, this parameter is not included in the computer model. The camera tolerance becomes a redundant parameter with the historical failure rate.

4.2.6. The number of SMC's required for the particular PCB

Obviously, the quantity of SMCs to place affects the assembly time. The higher the number of SMCs, the larger the time required to complete the PCB. Additionally, the slot where the SMC feeder is placed is correlated with the time. The longer distance the feeder is located, more time is required by the head to reach the SMC and place it.

4.2.7. The quantity of nozzle changes during the cycle time

As explained in section 3.2, different nozzles may suck up different SMC types according to its size. When the nozzle finishes the placement process of a particular SMC, it begins the process for a new one. If the next SMC could not be picked or placed with the same nozzle, the head changes it. So, the placement cycle is interrupted, causing a delay. Then, the head goes to the magazine and changes the current one for the right one. Consequently, the number of times the head changes the nozzle affect the placement time.

4.2.8. The quantity of heads

According to necessities or problems at the line, it may be possible to use one or more head. That is, the machine may work with one or two of its MFUs. Furthermore, the assembly line may work with one or more placement machines. Usually, the two heads are used and the configuration program tries to balance the work of every head. Analogous, several placement machines are used if available. So, the process administrator tries to balance the work of every machine.

4.2.9. The configuration of the MFU

As explained in section 3.2, there are several optimization techniques to create a configuration for the MFU. Their objective is to minimize the assembly time. The output becomes the slots where feeders must be placed. This defines the distance to travel by the placement heads. At a same velocity, a SMC located in a near slot is placed faster than another placed in a far slot. Therefore, distance is a dynamic parameter significant on the assembly time.

The next parameters to analyze are not related with a single PCB assembly time. Moreover, they are related with the batch assembly time. That is, these parameters affects the time when we are considering several PCBs. Changes in such parameters does not affect the assembly time for a single PCB.

4.2.10. The speed rate of the conveyors

The conveyors are located at every side of the machine. The first one carries the PCB from the screen printing stage into the machine. The second one carries the PCB from the placement stage to the next stage. The follow stage could be another placement stage or the soldering stage. For every conveyor, the process administrator selects a convenient speed rate. Usually, the second one goes slower. Inertia affects the recently placed SMCs and tend to move them if the speed is high.

4.2.11. The operator availability

The operator works at different stages of the SMT process. So, when a machine stops the operator may or may not be available to focus on the machine problem. In that way, the assembly time for the whole batch of the particular PCB fluctuates.

4.2.12. The quantity of SMCs in a reel

As explained at section 3.2, the feeder is the tool placed on the slots and contains the SMC reel. So, the feeder can contain different kinds of SMC reels. Reels differ by the quantity of SMC that can hold. Obviously, if the reel can hold a large quantity of SMCs, then they are small. The range of SMC into a reel is between 500 to 5000 units. Consequently, this parameter affects the assembly time for the whole batch. The machine stops when the reel goes empty causing a delay. Then, the operator should replace it and restart the machine. This single event may happen several times during the production of a particular batch of PCBs.

4.2.13. Machine availability

Some of the reasons for the downtime of the machine are:

- The tape that sealed the reel was not removed, so the nozzle could not suck up the SMC.
- There was not a SMC into the nest of the reel, so the nozzle could not pick up the SMC.
- The SMC was turned into the nest of the reel, so the nozzle could not pick it up.

In that order, the operator should go to the machine to fix the problem and stop such delay.

4.3. Model Assumptions

In order to simplify the analysis, two assumptions for the assembly time of a single PCB and one assumption for the assembly time of a batch of PCBs are presented.

4.3.1. Same placement location

The SMCs are placed at several locations over the board. The time the head take to pick and place the SMC is related with the speed and the distance. The number of SMCs in a PCB could fluctuate from fifty to two thousands units. There are as many different distances as SMCs over the PCB. So, there could be thousands of different distances. A single distance is from the feeder location to the cartesian location of the SMC. As input, this parameter could be very time consuming for the user. Besides, the reports data from the machine software does not provide the cartesian location but the reference designator. Due to this difficulty, we will assume all the SMC are placed at the center of the PCB. This will reduce the input data and the time to enter the input data.

4.3.2. A single nozzle

As explained in section 3.2, the size of the SMC determines the nozzle width required to pick and place it. That is, a small SMC should be picked and placed with a narrow nozzle while a large SMC should be picked and placed with a wide nozzle. However, at the configuration moment; the operator is able to enter a specific nozzle width or a range of nozzle widths. That is, a SMC could be picked and placed with several nozzles. Nevertheless, the operator has evaluated different possibilities previously. So, this range of nozzle widths may be able to perform the placement properly. This possibility represents an advantage about the minimization of the placement time. One single nozzle may be used to pick and place several SMC sizes. Less nozzle changes mean less placement time.

For simplicity of the characterization it is assumed that each SMC can be handled by a single nozzle.

4.3.3. Brand new SMC reels

When the whole batch assembly time is under consideration, the change of the reel affects it. If the reel becomes empty, it has to be changed by the operator, causing a delay. The operator may insert a brand new reel or a used one. The quantity of SMC in a reel is a known parameter when it is new. If the amount of SMC is known, it is easy to know the moment the reel needs replacement. Furthermore, it is easy to know the number of times the reel is changed. Then it is easy to know the time it takes to replace them and associate this time to the whole batch time. However, it is difficult to establish the exact quantity left at the beginning of each batch. Moreover, it is difficult to establish a reliable quantity left in the reel. Several techniques to find such quantity have been proved. One of them is through the reel radius. As the initial radius of the reel, the initial amount of SMCs and the left radius are known, the left quantity of SMCs could be known. However, the reel tightness may vary due to the lack of control from the manufacturer. This makes the technique inaccurate.

4.4. Development of the Model

Our computer program is called *The Fuji IPIII Characterizer*. It contains the database and the algorithm for the assembly time characterization. It also contains the PCB products the Model Factory build. This PCBs may be characterized under different configuration providing different assembly time. Additional PCBs could be added and characterized.

4.4.1. The database

A database was created to access information necessary to characterize every particular PCB. It is written in an MS Excel sheet and contains information about all the SMC that are used in the Model Factory. Every SMC in the database is related with several parameters. They are: type, failure rate, transport speed rate, pick speed rate, place speed rate, reel quantity and nozzle. Our database is dynamic so the user may change one or more of this parameters. Moreover, the user may add new SMC and its parameters to the database. However, such changes are made through the computer program not directly into the database. It is due to integrity issues. The database structure is composed by several tables; figure 4 shows the entity relationship diagram. Table 4.1 also shows an example of the SMC database; the numbers provided are not real due to confidentiality issues.

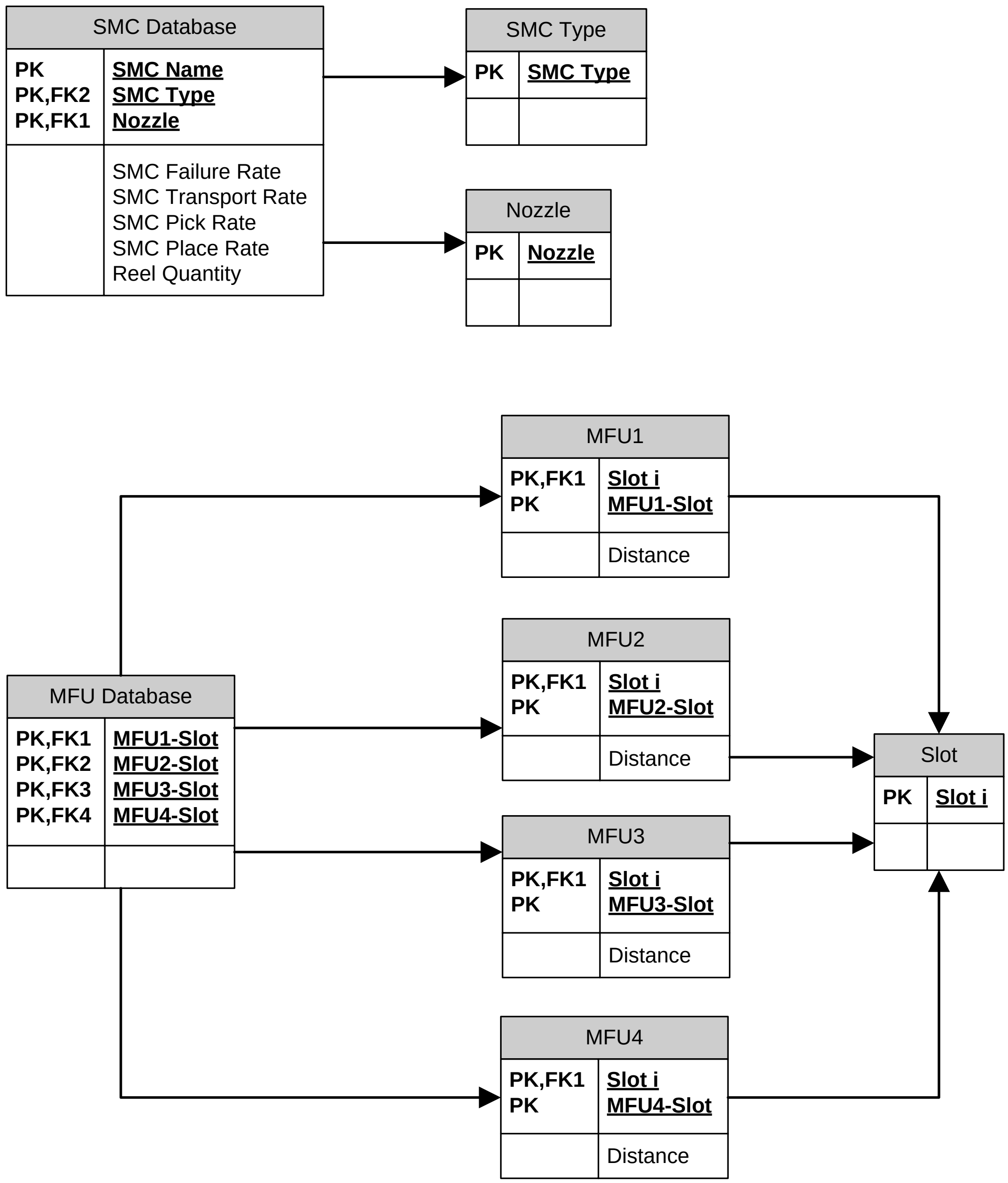

Figure 4. Entity relationship diagram

SMC Name	Type	Failure Rate	Transport Rate	Pick Rate	Place Rate	Reel Quantity	Nozzle
00001-00001	Capacitor	0.04	0.5	0.1	1	5000	010-007-L10
00001-00002	Crystal	0.02	1	0.50	1	3000	010-010-L10
00001-00003	Diode	0.03	0.5	0.1	1	1000	031-013-L26
00001-00004	Integrated Circuit IC	0.03	1	0.09	0.5	3000	031-018-L26
00001-00005	Inductor	0.05	0.5	0.1	1	3000	031-025-L26
00002-00001	Resistor	0.04	0.8	0.1	1	2500	031-037-L26
00002-00002	Transistor	0.03	0.5	0.1	0.5	3000	052-070-L26
00002-00003	Voltage Regulator	0.03	0.5	0.1	1	800	102-200-L26
00002-00004	Switch	0.03	1	0.09	1	1000	010-007-L10
00002-00005	Ball Grid Array BGA	0.04	0.1	0.1	0.05	1000	010-007-L10

Table 4.1 SMC database

Other information in the database is the nozzle types and the SMC Types. The nozzles vary in its width as explained previously. The SMC vary according to its shape and its electrical objective. Again, the user will be able to add items to this two database objects. The name of every nozzle type provides information about its width in millimeters. Tables 4.2 and 4.3 show the nozzle table and the SMC types table from the database.

Nozzle Name
010-007-L10
010-010-L10
031-013-L26
031-018-L26
031-025-L26
031-037-L26
052-070-L26
102-200-L26

Table 4.2 Nozzle Table

Types of SMC
Ball Grid Array BGA
Capacitor
Coil
Connector
Crystal
Diode
Integrated Circuit IC
Inductor
Jumper
Relay
Resistor
Socket
Switch
Thermosistor
Transistor
Voltage Regulator

Table 4.3 SMC Types Table

Other part of the database contains the information about the MFUs and the slots. This MFU are all the Model Factory has. However, more could be added. The slots provide information of the distance from the slot to the table center. Table 4.4 shows such information in inches.

MFU	MFU1	Distance
MFU1	Slot-01	42.75
MFU2	Slot-02	42
MFU3	Slot-03	41.25
MFU4	Slot-04	40.5
	Slot-05	39.75
	⋮	⋮
	Slot-38	15

Table 4.4 Distance from slots to the table center in inches

The last part of the database contains the parameters that affect the assembly time for a whole batch of PCBs. The user may characterize a PCB with the default parameters of the SMT line or change them. Table 4.5 shows the availability of the operator to solve a problem with the placement machine.

Operator	Min
High	3
Medium	6
Low	10

Table 4.5 Operator Availability

Table 4.6 shows the default availability of the machine as an uptime.

Machine Uptime	Rate
High	0.90
Medium	0.85
Low	0.75

Table 4.6 Machine Availability

Table 4.7 shows the speed rate of the conveyors trough the SMT line under study.

Conveyor	Rate
MTU2inA	1
MFU2inA	1
MFU1outA	0.7
MTU1outA	0.7
MTU4inB	1
MFU4inB	1
MFU3outB	0.7
MTU3outB	0.7

Table 4.7 Conveyors Speed Rate

4.4.2. The creation of a PCB

In the computer program, the user may create a PCB and add its different characteristics. So, the user adds the name of the PCB, a description, the images per panel, the configuration and the reference designators. After the optimization program provides an optimal configuration, the user may add it to the PCB creation subprogram. Furthermore, the user may create several versions of the same PCB but in different configuration. The configuration provides every SMCs needed, the quantity of units for every SMC, the pick position and the place position. The pick position is the MFU and slot where the feeder contains the SMCs. The place position is the different reference designator where every SMC is going to be placed. When the total configuration is finished, all the information is inserted in a new MS Excel sheet. Table 4.8 shows an example.

SMC Name	Board Quantity	Position		Reference Designator
00001-00001	4	MFU1	Slot27	R2 - R4
00001-00002	1	MFU1	Slot31	R1 - R3
00001-00003	2	MFU1	Slot32	C5 - C6

Table 4.8 Example of a PCB Configuration

Additional information is taken from the database. As the user provides the SMC name, the database inserts its type, its failure rate, its translation speed rate, its pick and place speed rate, its reel quantity and the nozzle it uses. Additionally, the panel quantity per SMC is added and the slot distance where it is placed. So, the whole necessary information necessary to characterize the PCB is included. Such sheet is named with the PCB name and the creation date. Tables 4.9 and 4.10 show the complete information generated by the *Characterizer*.

SMC Name	Board Quantity	Position		Reference Designator	SMC Type	SMC Failure Rate
00001-00001	4	MFU1	Slot27	R2 - R4	Resistor	0.04
00001-00002	1	MFU1	Slot31	R1 - R3	Resistor	0.03
00001-00003	2	MFU1	Slot32	C5 - C6	Capacitor	0.04

Table 4.9 Example of PCB Information

SMC Speed Rate	SMC Pick Rate	SMC Place Rate	Reel Quantity	Nozzle	Panel Quantity	Slot Distance
1	0.1	1	1000	010-010-L10	12	22.5
0.5	0.1	0.5	3000	010-007-L10	18	21
0.8	0.9	1	4000	031-018-L26	6	19.5

Table 4.10 Example of PCB Information Continuation

Finally, with this information, the computer program is able to characterize the PCB with the specific configuration. As explained previously, other forecasting should be made when other configuration is given.

4.4.3. The assembly time

A large subroutine was developed to characterize the machine assembly time for a single PCB and a whole batch. As every arm and head works independently, the mathematics is the same for every one. Every MFU works and returns a different assembly time depending on its configuration. However, the machine assembly time is the greater between the two MFU.

First, the user enters information about the PCB and the configuration. Such data is the PCB name, the quantity of images. Then, the user enters the configuration per se: the SMC type, the quantity of that type and their position. This stage is repeated for all the different SMCs.

Second, the *Characterizer* creates a sheet with this information and searches in the database additional parameters for every SMC type. Such parameters are the failure rate, the different speeds rate, the reel quantity and the nozzles the SMC uses. When the sheet is completed, the user may start the third stage: characterize the PCB.

Third, the code creates unknown size arrays for the different parameters. They are the slots distances, the quantity of SMCs in the whole panel per MFU, the translation speed rate of every SMC type per MFU, the pick speed rate of every SMC type per MFU, the place speed rate of every SMC type per MFU, and the failure rate of every SMC type per MFU. Fourth, the code find out how many SMCs types are assembled per MFU. Fifth, now the code realizes the size of the arrays for the different parameters. Sixth, the code characterizes two assembly times per MFU. One includes the failure rate and the other does not. In that way, the user realizes the effect the failure rate has over the assembly time.

Next, the code characterizes the assembly time for a whole batch of the particular PCB. The applicable parameters are the size of the batch, the availability of the operator to change reel and the availability of the machine as an uptime.

First, the code finds when a reel change has to be done. This exercise is made per MFU. The output is written in the same row of the SMC. In that way, the user realizes the moment the reel has to be changed. Second, the code finds how many reels of every SMC are needed for the particular batch size. In that way, the time the process stops to re-setup is characterized.

Third, the code finds how many different nozzles are used per MFU. Then it is known the amount of nozzle changes performed per MFU. Thus, the time the machine takes to change the nozzles is added to the placement time.

Finally, the application characterizes the time the machine takes to build a particular PCB batch. Two times are shown. One includes the machine uptime and the other does not. In that way, the user realizes the effect the uptime has over the batch time.

4.4.4. Additional information

The *Characterizer* creates additional information that is useful for the SMT line administrators. Such information is not relevant for a single PCB assembly time but for a batch production time. Table 4.11 shows such information.

SMC Name	Change Reel in Panel	Quantity of Reels for the Batch
00001-00001	240	2
00001-00002	160	2
00001-00003	N.A.	1

Table 4.11 PCB Additional Information

The *Change Reel in Panel* section informs the operator to change a reel when a particular number of PCBs are assembled. Currently, the operator realizes the reel is empty only when the machine stops and he/she verifies the reason. This could help to minimize the re-setup time. Furthermore, knowing how many times a reel is going to be changed will help to know the batch production time.

The *Quantity of Reels for the Batch* informs the operator how many reels of a particular SMC are needed for the whole batch.

4.4.5. Output information

The output data is divided in two major parts. The PCB Time Report and the PCB Detailed Time Report. The first report provides general information about the PCB characterized. It shows the time taken by the machine to assemble a PCB at every placement machine. It helps, the operator realizes if the placement machines are well balanced. Furthermore, it shows the assembly time by MFU, especially useful to determine if the MFUs are well balanced.

Information about a whole batch is also displayed. The operator and machine availabilities, and the batch size selected by the user affect the production time. Table 4.12 shows an example of a Time Report.

PCB Time Report		
Date	4-Oct-05	
Time	17:09	
MFU1	298 secs	54.43%
MFU2	250 secs	45.58%
FUJI IP3A	308 secs	100%
MFU3	351 secs	41.18%
MFU4	501 secs	58.83%
FUJI IP3B	512 secs	100%
Operator Availability	Medium	
Machine Availability	Medium	
Batch Size	300	
Batch Time FUJI IP3A	30.2 Hours	37.60%
Batch Time FUJI IP3B	48.9 Hours	62.41%
Batch Time	50.2 Hours	96.91%
Total Process	51.8 Hours	100%

Table 4.12 PCB Time Report Example

The assembly time of the placement machine is the slowest performed by a MFU plus the time the PCB is over the conveyors. The batch time for the production is the slowest performed by a placement machine plus the time the operator takes to change the reels. The different times are also shown as percentages to facilitate the reading and comprehension of the report.

The PCB detailed report shows the different times in a specific way. Helping the operator to realize which times affect the most the assembly time. Table 4.13 shows an example for a PCB Detailed Time Report. The first part contains complete information about a single PCB. It shows every placement machine and its MFUs. The numbers between brackets are related to the failure rate of the SMCs. It is to show the operator how much this parameter affects the assembly time. For this example, the failure rate of the SMCs causes a delay of ten seconds in the assembly of a single PCB at the MFU1. It also shows how much of the whole panel time is taken by the nozzle changes and by the conveyors.

PCB Detailed Time Report		
Number of Placements in MFU1	102 [107]	
Average Placement Time per SMC in MFU1	2.83 [2.79]	
Assembly Time in MFU1	288 [298] secs	54.43%
Nozzle Changes in MFU1	1	
Nozzle Changes Time in MFU1	5 secs	1.68%
Number of Placements in MFU2	108 [113]	
Average Placement Time per SMC in MFU2	2.24 [2.21]	
Assembly Time in MFU2	242 [250] secs	45.58%
Nozzle Changes in MFU2	3	
Nozzle Changes Time in MFU2	15 secs	5.04%
Panel Time in Fuji IP3A	288 [298] secs	96.65%
Conveyor In Time in Fuji IP3A	5 secs	1.43%
Conveyor Out Time in Fuji IP3A	7 secs	2.04%
Total Panel Time in Fuji IP3A	299 [308] secs	100%
Number of Placements in MFU3	102 [107]	

Table 4.13 PCB Detailed Time Report First Part

The second part refers about information of the batch entered by the user. In that way, the user remembers the parameters selected for the particular batch. The operator availability, machine availability and the batch size are these parameters. Table 4.14 shows this part.

PCB Detailed Time Report		
Operator Availability	Medium	
Operator Time to Change Every Reel	6 min	
Machine Availability	Medium	85%
Batch Size	300	

Table 4.14 PCB Detailed Time Report Second Part

The third part is about the behavior of the batch at every placement machine. The numbers between brackets are related to the failure rate of the SMCs. It shows the operator how much this parameter affects the batch time. For this example, the failure rate of the SMCs causes a delay of almost one hour in the production time of a batch of PCBs at the placement machine A. It also shows how much of the whole process time is taken by the reel changes in every MFU. Table 4.15 shows this part.

PCB Detailed Time Report		
Batch Time FUJI IP3A	29.3 [30.2] hours	98.38%
Reel Changes in MFU1	3	
Reel Changes Time in MFU1	0.3 hours	1.03%
Reel Changes in MFU2	2	
Reel Changes Time in MFU2	0.2 hours	0.69%
Process Time in FUJI IP3A	29.8 [30.7] hours	100%
Batch Time FUJI IP3B	48.9 [50.2] hours	96.91%

Table 4.15 PCB Detailed Time Report Third Part

The fourth part refers to the batch itself. The batch time per machine is shown as percentage of the whole batch time process. The reel time changes are also shown per machine, showing its effect over the whole batch time process. The slowest batch time at the machines is the batch time process. The shifts needed to complete the batch are also shown. Table 4.16 shows this part.

PCB Detailed Time Report		
Total Placements in Batch	120600 [126300]	
Batch Time FUJI IP3A	30.2 Hours	37.60%
Reel Changes FUJI IP3A	5	
Reel Changes Time FUJI IP3A	0.5 hours	1.00%
Batch Time FUJI IP3B	50.2 Hours	62.41%
Reel Changes IP3B	16	
Reel Changes Time FUJI IP3B	1.6 hours	3.10%
Total Reel Changes	21	
Total Reel Changes Time	2.1 hours	4.07%
Process Time in FUJI IP3A	29.8 [30.7] hours	59%
Process Time in FUJI IP3B	50.5 [51.8] hours	100%
Total Process	50.5 [51.8] Hours	100%
Shifts to Complete Total Process	6.31 [6.47]	

Table 4.16 PCB Detailed Time Report Fourth Part

4.4.6. Assembly time estimation

The computer program allows the user to perform several tasks. The main task is the characterization of the assembly time for a particular PCB according to a configuration. The user may enter different configurations for the same PCB, getting different time. The following pseudo-code presents how the program performs the assembly time calculation of one machine when a configuration is already suggested.

REM Get several parameters from configuration and database
REM Get the placement time for the MFUs
10 For i =1 to n
20 $PT_i = 0$
30 For j =1 to k_i
40 $PT\ i = PT_i + PK_{ij} + \frac{TT_{ij}}{1-FR_{ij}} + PL_{ij}$
50 Next
60 Next
70 $AT_i = PT_i + (NC_i \times NCT)$
80 $MAT = \text{minimum}\ (AT_i \mid i=1,2, \ldots, n)$

The following pseudo-code presents how the program performs the assembly time calculation of the suggested batch size right after the assembly time calculations for several machines.

REM Get the assembly time for a batch
90 $TM_h = MAT + (CS \times CSR)$
100 $BT_h = \frac{(TM_h \times BS)}{MU} + (RC_h \times RCT)$
110 $TBT = \text{minimum}\ (BT_h \mid h=1,2, \ldots, m)$

Where,

n: number of selected MFU in the machine
i: MFU index, for $i= 1, 2, \ldots , n$
k_i: number of occupied slots at MFU_i
j: slot index, for $j = 1$ to k_i
PT_i: placement time for MFU_i
PK_{ij}: pick time for the SMC in slot j at MFU_i
TT_{ij}: transport time for the SMC in slot j at MFU_i
PL_{ij}: place time for the SMC in slot j at MFU_i
FR_{ij}: failure rate for the SMC in slot j at MFU_i
AT_i: assembly time for MFU_i
NC_i: number of nozzle changes for MFU_i
NCT: nozzle change time
MAT: machine assembly time
m: number of machines
h: machine index, for $h= 1, 2, \ldots , m$
TM_h: time in machine m

CS: conveyor speed
CSR: conveyor s peed rate
BS: batch size
BT_h: batch time in machine m
RC_h: number of reel changes for machine m
RCT: reel change time
MU: machine up-time (availability)
TBT: total batch time

Chapter V: Model Analysis

This chapter presents the analysis of our computer program: *The Fuji IP III Characterizer*. The performance of our model is analyzed in two stages. The first stage consisted in the comparison between assembly time forecasted and the real assembly time. A percentage of error will show the accuracy of our model. The second stage consisted in a statistical comparison using the t-test. The PCBs to validate are provided by the Model Factory at UPRM. These products are evaluated at the two placement machines, providing six different scenarios to analyze. Our computer program is tested against the real time, against the assembly time forecasted by *Fuji*, and against the assembly time forecasted by the current computer program used in the Model Factory. This computer application is called *Flexa*.

Flexa is the computer program used by the Model Factory to create an favorable configuration. Additionally, *Flexa* provides estimation for the assembly time. However, it works with one product at time. As the Model Factory assembles several PCBs, its optimal suggestion is not follow. That is because there are several SMCs in common between the PCBs. So, it is more comfortable to establish these common SMCs at the same place avoiding a large re-setup time. For that reason the configuration created is not optimal generating unbalance at the MFUs or the placement machines per se. Then several scenarios have to be proved in order to balance them. Such scenarios demand great effort and time. As the *Flexa* application estimation time is unreliable, our computer program becomes a great help for the Model Factory and other SMT lines. Several scenarios may be compared at the program, not in the line per se. The re-setup time will be the time to enter data to the program and run it.

5.1 Percentage of Error

Due to confidentiality issues, the names of the products cannot be shown. Neither the parameters for every product can be shown. However, the performance for the different PCBs that the Model Factory assembles are shown in table 5.1. The three products were evaluated in each placement machine providing different scenarios to validate.

Assembly Time	PCB 1-A	PCB 1-B	PCB 2-A	PCB 2-B	PCB 3-A	PCB 3-B
Real	242.53	234.60	245.05	237.18	286.49	469.79
Characterizer	253	244	270	248	300	485
Flexa	168.22	198.71	260.46	214.41	251.21	243.25
Fuji	156.6	162	183.6	162	189	172.8

Table 5.1 Assembly Time in Seconds

It is shown that our computer program trend to overestimate the assembly time. That is because it is counting additional nozzles changes. As explained previously, the optimization program allows a range of nozzles to be used over a

SMC instead a single nozzle. However, *Flexa* has no tendency at all. Sometimes it underestimates and sometimes it overestimates. The formula of the percentage of error is shown next:

$$\% \text{ of Error} = \frac{\text{Real Value - Theoretical Value}}{\text{Real Value}}$$

Table 5.2 shows de percentage of error for the assembly times in the same PCBs.

Error	PCB 1-A	PCB 1-B	PCB 2-A	PCB 2-B	PCB 3-A	PCB 3-B
Characterizer	4.32%	4.01%	10.18%	4.56%	4.72%	3.24%
Flexa	30.64%	15.30%	6.29%	9.60%	12.31%	48.22%
Fuji	54.87%	44.82%	33.47%	46.41%	51.58%	171.87%

Table 5.2 Percentage of error for the assembly time

It is shown that our computer program is more accurate in five of the six scenarios. The only scenario where *Flexa* is more accurate is PCB 2-A. At this PCB, one of the two MFUs is loaded with many different SMCs. Then, the *Characterizer* application is counting many nozzle changes and the accuracy is compromised. As explained at section 4.2.2, the *Characterizer* deals with the time characterization, not optimization. Then, a single nozzle instead a range of nozzles is an assumption for the SMC. However, our average error is 4.69% while

Flexa is 20.39% and *Fuji* is 67.17%. It is clear that our computer application is more effective when estimating the assembly time.

5.2 T-test

The 1-sample t test was done to perform a robust statistical validation. The probability plots for the six scenarios show normal distributions for the assembly times of the PCBs under study. It validates the assumptions required to perform a T-test. Appendix B shows the probability plots. The boxplots for the six show that in five of the six scenarios, Characterizer is closer to the no rejection zone than *Flexa*. Figures 5.1 to 5.6 show the boxplots for the scenarios.

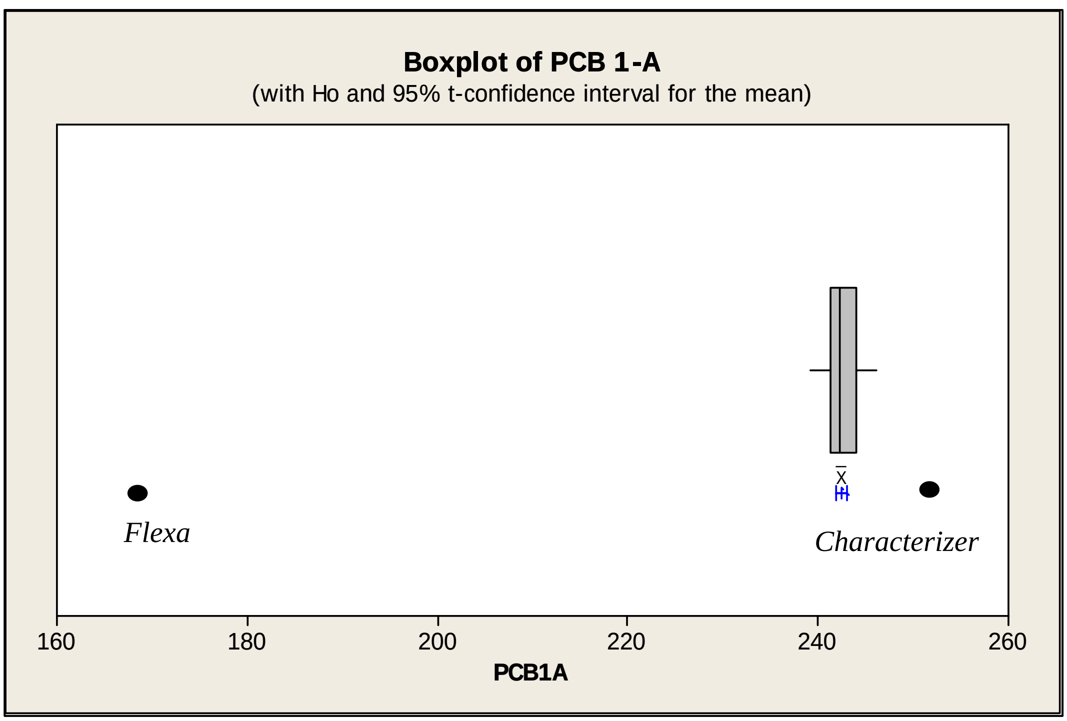

Figure 5.1 Boxplot PCB 1-A

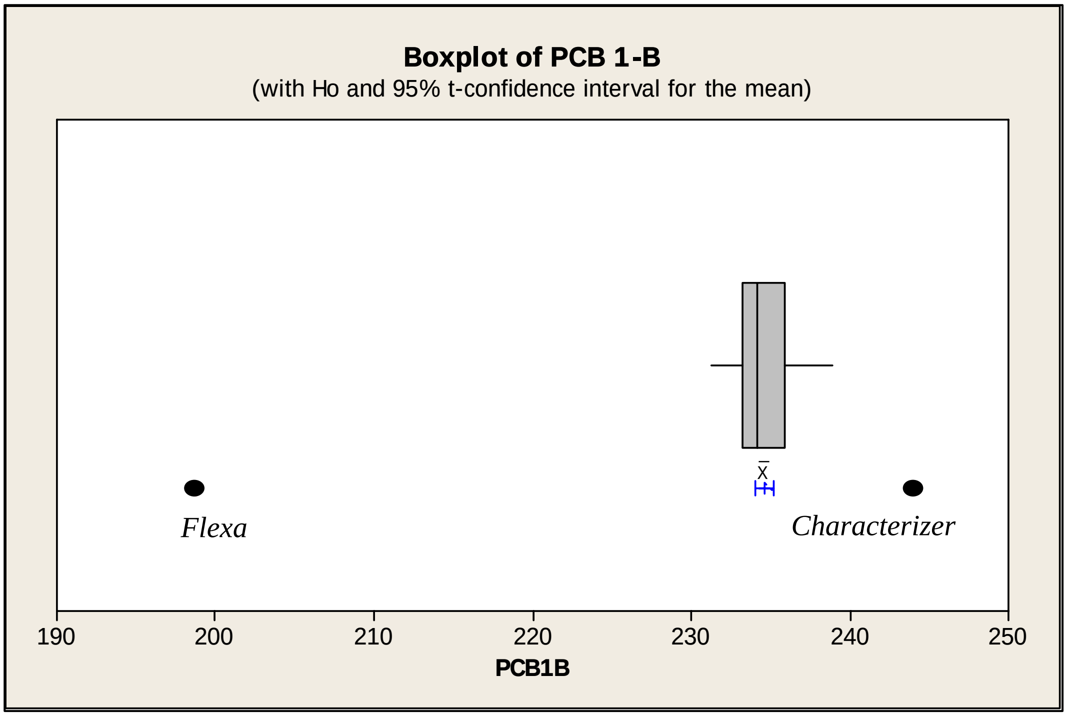

Figure 5.2 Boxplot PCB 1-B

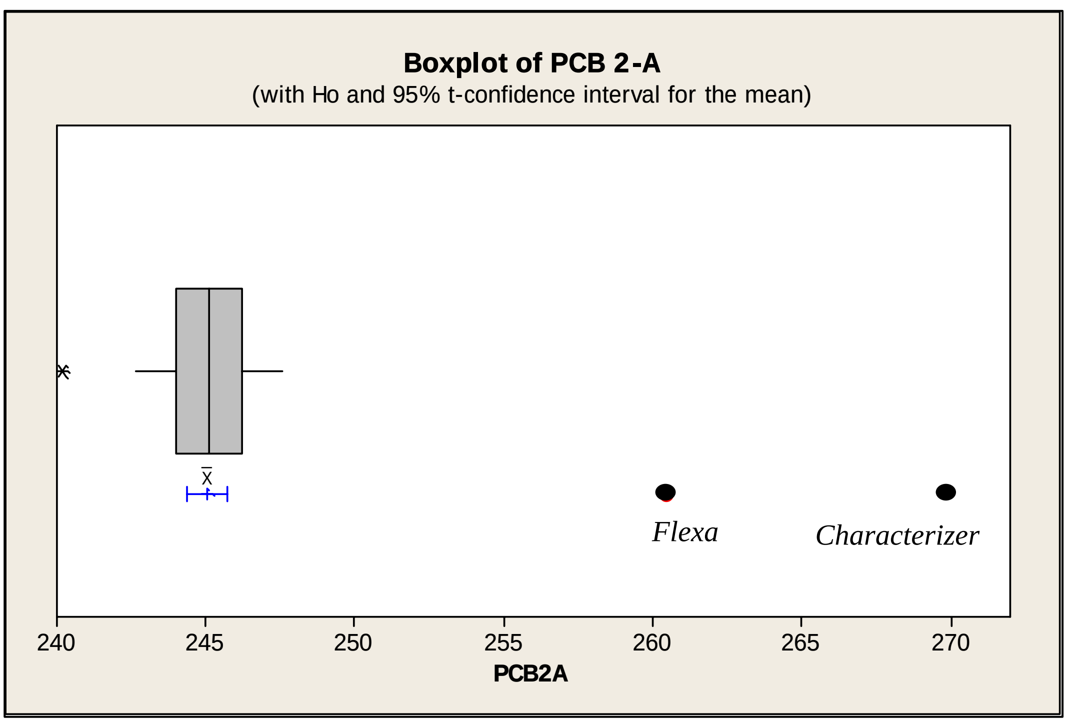

Figure 5.3 Boxplot PCB 2-A

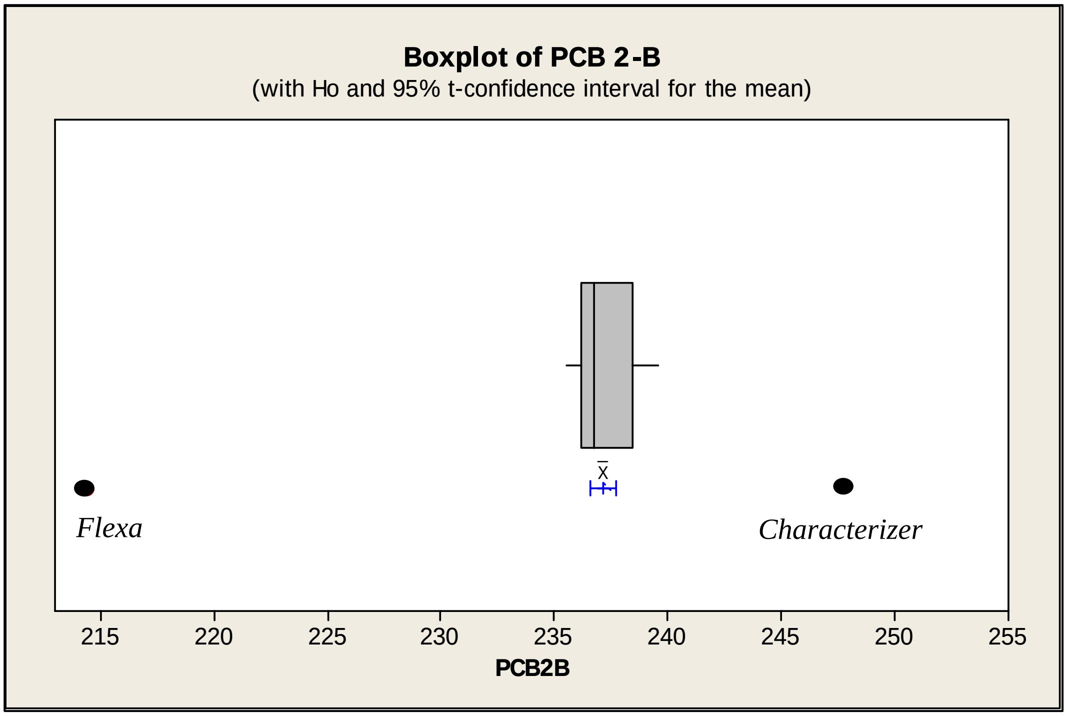

Figure 5.4 Boxplot PCB 2-B

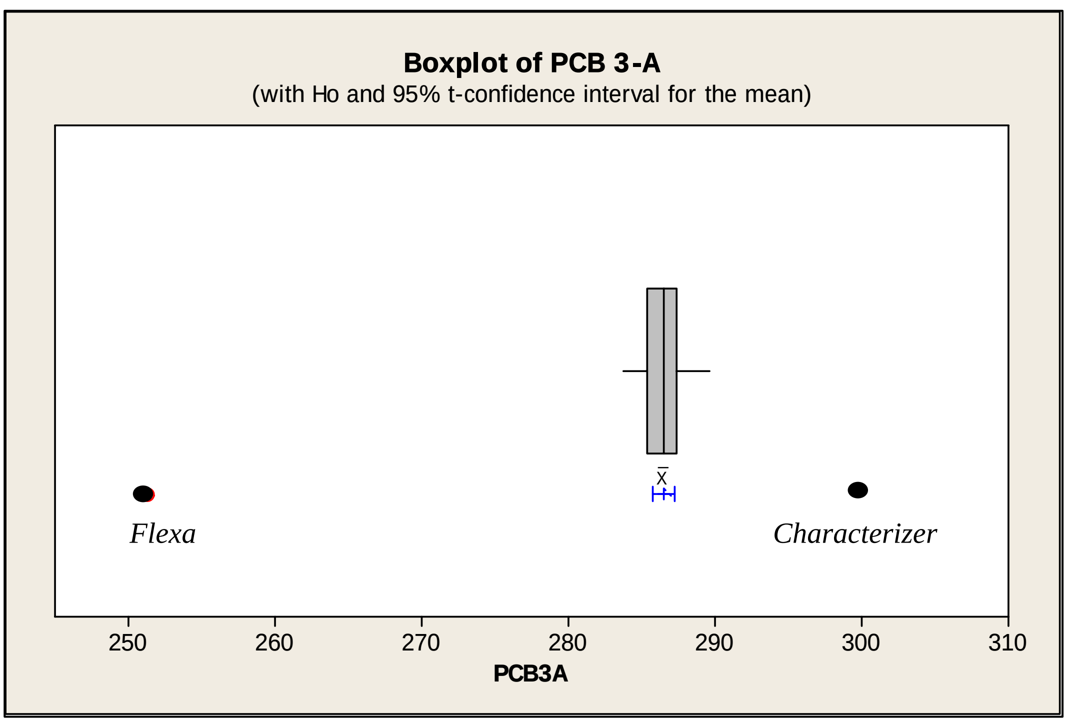

Figure 5.5 Boxplot PCB 3-A

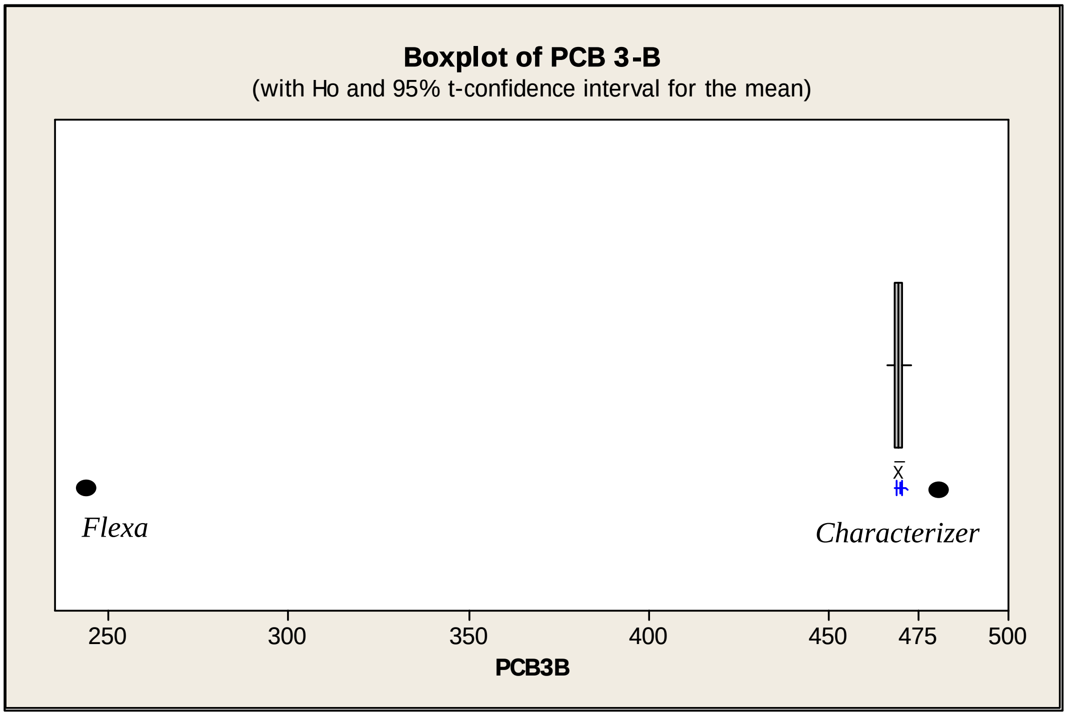

Figure 5.6 Boxplot PCB 3-B

Chapter VI: Model Implementation

This chapter presents the implementation of *The Fuji IP III Characterizer*. Several user interface windows were designed. Some of them collect the input data necessary for the characterization. Others return output data to the user. The purpose of this implementation is to improve the interaction between the user and the computer program. The user enters the necessary data in a graphical interface. *The Fuji IP III Characterizer* was developed using Microsoft Visual Basic ® for Applications in MS Excel. The forms contain clear instructions necessary to perform several activities avoiding the necessity for a user manual. The graphical interface is presented in the following section. Figure 6.1 shows a hierarchy diagram for the windows in the application.

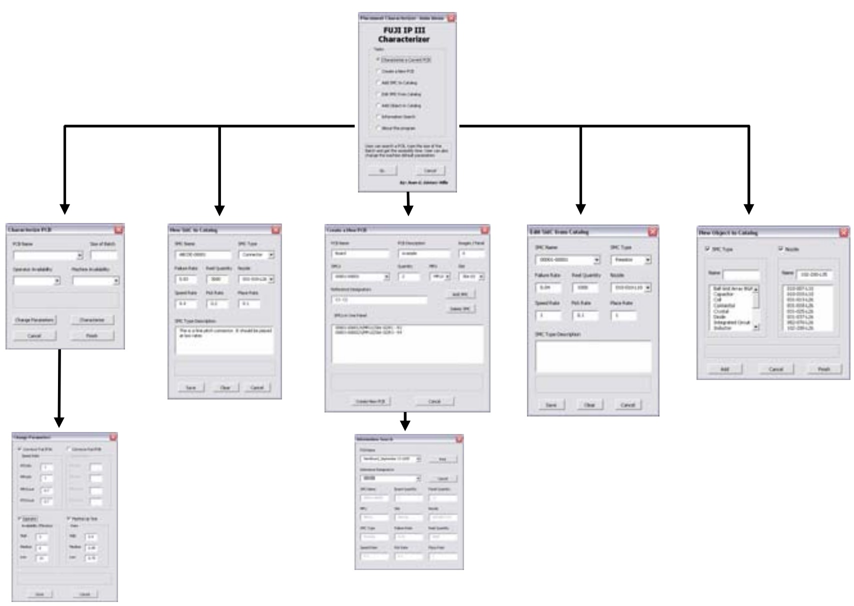

Figure 6.1 Hierarchy diagram for the user forms

6.1. The *Main Menu* window

The process to characterize a PCB begins when the user access the MS Excel file. The program keeps data in some worksheets which the user cannot modify. Only through the *Characterizer* application, the user may add, edit data in the database. The opening worksheet contains a button that activates the program. Figure 6.2 shows the initial user form when a user has activated *The Fuji IPIII Characterizer*.

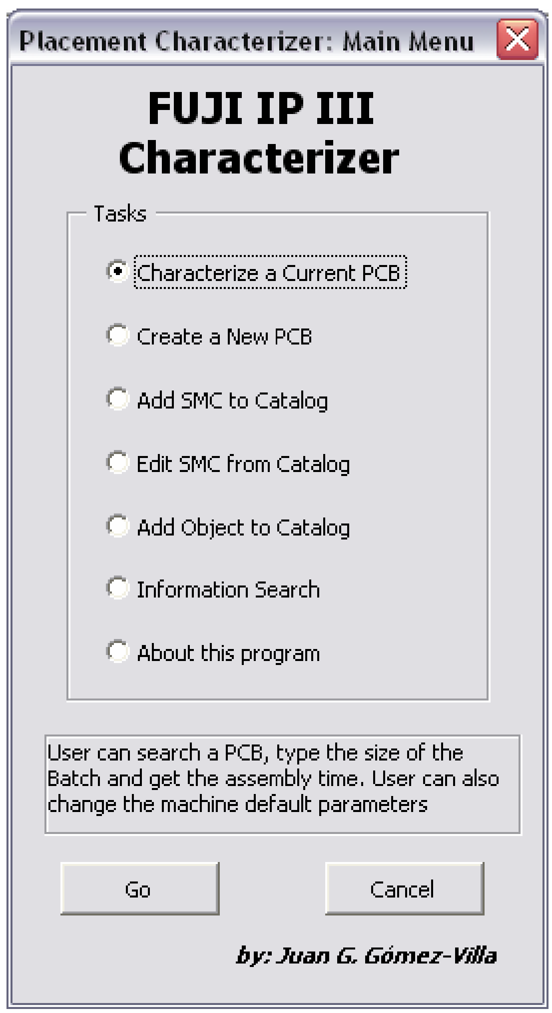

Figure 6.2 The *Main Menu* window

The *Main Menu* window informs the user the different tasks that may be performed by the computer program. Trough option buttons, the user selects the activity to perform. Additionally, when the user clicks an option button, information about the activity is displayed under the tasks frame. The *cancel* button ends the application. The *Go* button activates the window corresponding to the selected option button.

6.2. The *Characterize PCB* window

From this window, see figure 6.3, the characterization is executed. The user selects a PCB from the combo box.

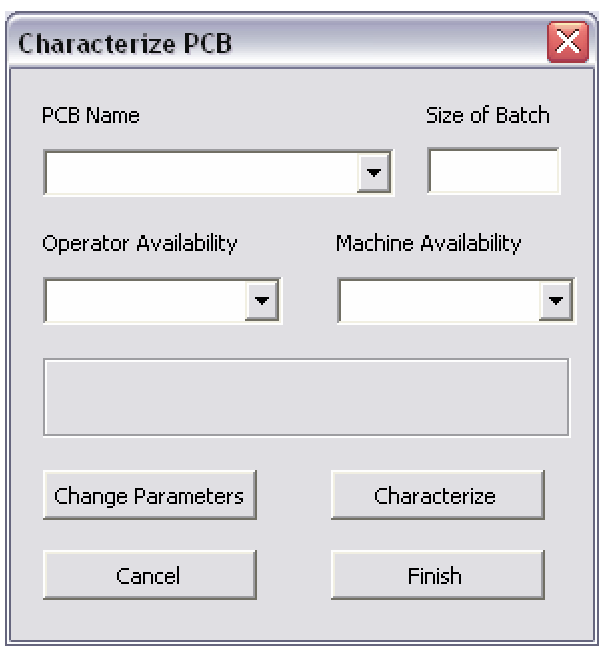

Figure 6.3 The *Characterize PCB* window

The combo box is filled with names of PCBs created previously by the user. The creation of a PCB is explained in a following section. The user enters the size of the batch to be characterized. Only positive integer numbers are allowed in this field. If the user enters characters not allowed, they are automatically deleted and an explanation is displayed. The explanation varies according with the type of error. The errors could be three:

- if a letter character is inserted when only numeric data is allowed
- if a minus character is inserted when only positive numbers are allowed
- if a dot character is inserted when only integer numbers are allowed

Furthermore, this error corrections and explanation are developed for all the windows in the program if needed.

The other combo boxes in this window are the *operator availability* and the *machine availability*. The *operator availability* is related with re-setup activity. When a reel needs to be changed, the operator may or may not be available to attend this situation immediately. The default time to attend a re-setup activity is three minutes for high availability, six minutes for medium availability and ten minutes for low availability. However, these times may be changed when the user clicks the *change parameters* button. The *machine availability* is related with the machine activities. Several reasons make the machine to stop creating up and down times. The default up time rate is 90% for high availability, 85% for medium availability and 75% for low availability. Again, these rate times may be changed when the user clicks the *change parameters* button.

If all the fields are filled, the user may click the *characterize* button. An explanation is displayed if some field is empty. Finally, the program runs and the user may see the results in the same sheet where the PCB information was inserted.

- **The *Change Parameters* window**

This window is activated when the user decide to change some parameters during the information input at the characterization stage. See figure 6.4. Such window has four check boxes and four frames. If the user clicks a check box, its frame becomes enabled. Every frame contains the parameters that have been registered as default. As explained previously, such parameters do not affect the assembly time for a single PCB but the production time for a batch. The user may change the conveyor parameters if required. The user may also change the operator and machine parameters if the dynamic at the SMT line change. Again, the fields to enter the information are error proof. Then mistakes are automatically deleted and an explanation is displayed.

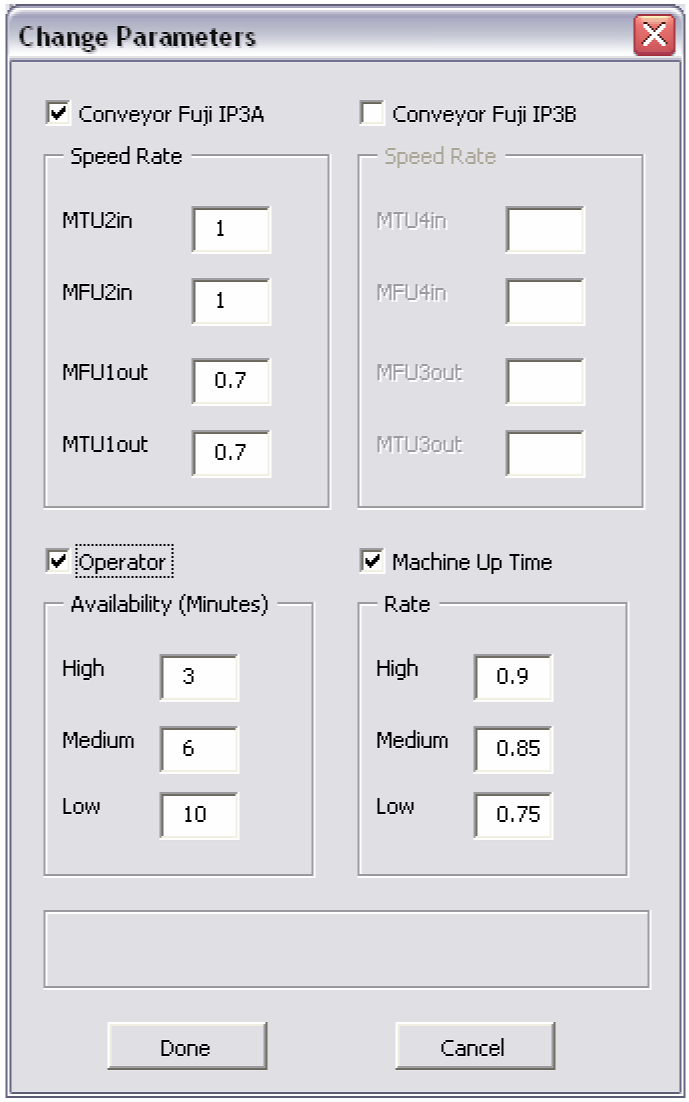

Figure 6.4 The *Change Parameters* window

6.3. The *Create a New PCB* window

The user employs this window to define a PCB and its configuration after the configuration is given. See figure 6.5. The user must enter a name for the PCB, a description and the number of images. The user selects the SMCs from a combo box which is filled with the SMCs from the database. The quantity for a single PCB, the MFU and slot where located, and the reference designator where the SMC is placed.

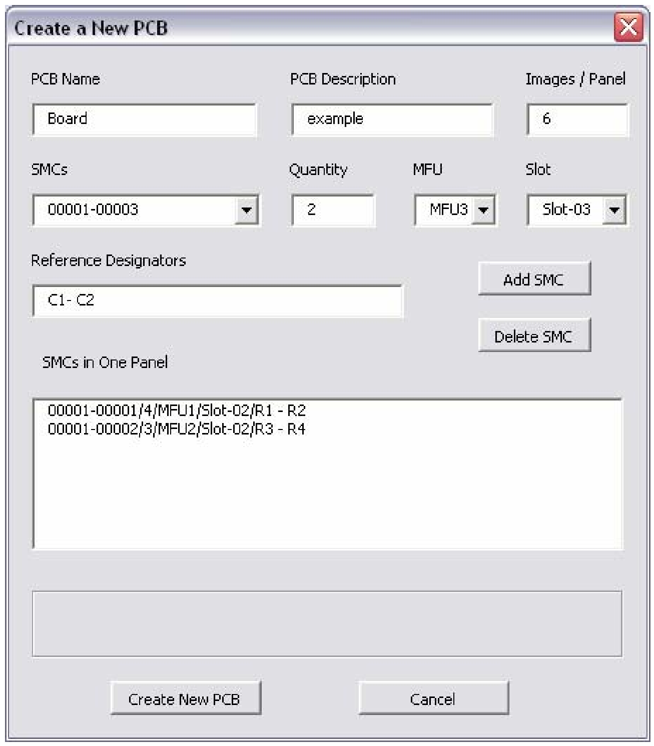

Figure 6.5 The *Create a New PCB* window

Finally, the user clicks the *Add SMC* button to enter the information in a list box. The information is entered for each SMC. If any information is missing, an alert is displayed and the operation is not done after all fields are filled. The second stage is repeated until the configuration is ready. The SMC information cannot be edited, but instead delete or reenter the correct information. Again, the fields to enter the information are error proof. Then mistakes are automatically deleted and an explanation is displayed.

Finally, when all the necessary information is entered, the user may click the *Create New PCB* button. Then, the program creates a worksheet with the information shown at tables 4.9 and 4.10

6.4. The *New SMC to Catalog* window

This window allows the user to add a new SMC to the database along with its parameters. See figure 6.6.

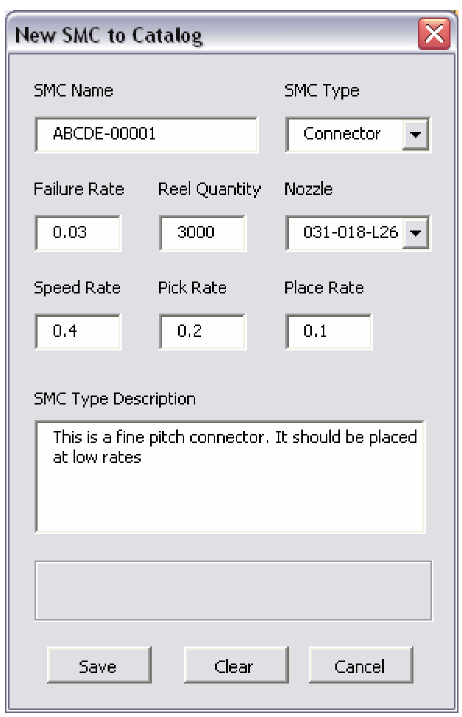

Figure 6.6 The *New SMC to Catalog* user form

Due to integrity issues, the user cannot deal with data directly. So, the user enters a name for the SMC, selects the SMC type and the nozzle required to pick and place it. The failure rate, the reel quantity and the different speeds rates are required parameters as well. The fields to enter the information are error proof. Then mistakes are automatically deleted and an explanation is displayed. A description related with the SMC is optional.

Finally, the user may click the *save* button to add the information to the database. If saved, the database is sorted according to the SMC name. If any information is missing, an alert is displayed and the operation is not performed.

6.5. The *Edit SMC from Catalog* window

This window allows interaction between the user and the database. See figure 6.7. It allows the user to edit a SMC from the database when some information needs to be corrected or changed. It is similar to the *New SMC to Catalog* window. In this window the SMC name is not a text box but a combo box. Such combo box contains the existing SMCs. When this window is activated, all the fields are blank. Once, the user selects a SMC from the combo box.

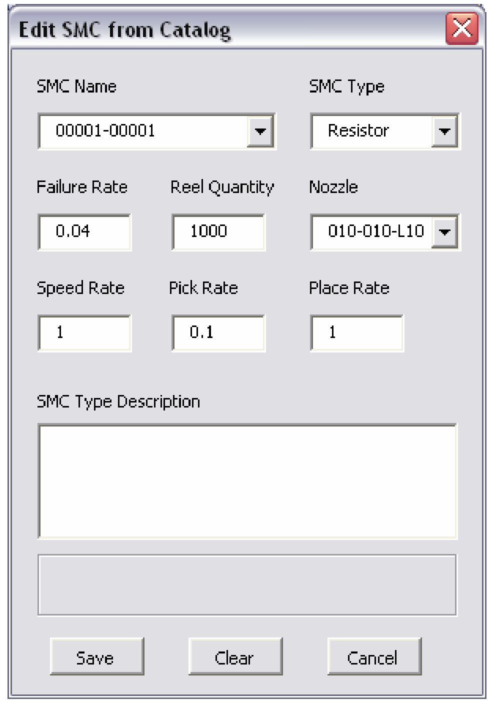

Figure 6.7 The *Edit SMC from Catalog* window

The other combo the text boxes are filled with the parameters of the specific SMC selected. The fields to enter the information are error proof. The mistakes are automatically deleted and an explanation is displayed.

Finally, the user may click the *save* button and the SMC and its parameters are edited from to the database. Then, the database is sorted according to the SMC name. If any information in this window is missing, an alert is displayed and the operation is not done.

6.6. The *Add Object to Catalog* window

This window allows the user to add a new object to the database. See figure 6.8. It allows adding an object which is not currently used in the SMT line.

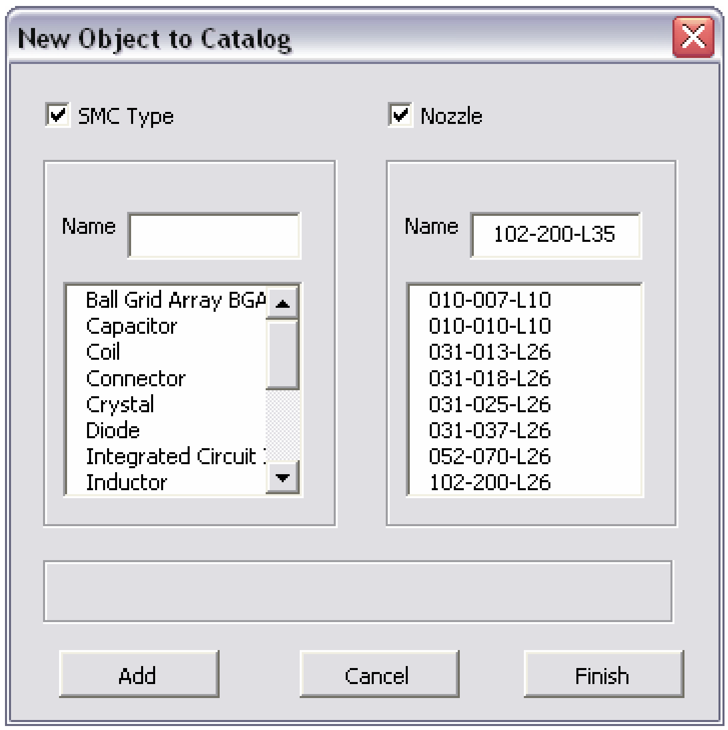

Figure 6.8 The *New Object to Catalog* window

Furthermore, adding an object which has not been invented yet. This window has two check boxes and two frames. If the user click a check box, its frame becomes enable. One frame contains a list box with the different SMC types. This list box is filled with, from the database. The other frame contains a list box with the different nozzles used in the SMT line. This list box is also filled with, from the database. The user may add a new object and click the *Add* button. If this new objects already exists in the database, an alert is displayed and the operation is not completed.

6.7. The *Information Search* window

This window is used to search relevant information from a PCB. See figure 6.9.

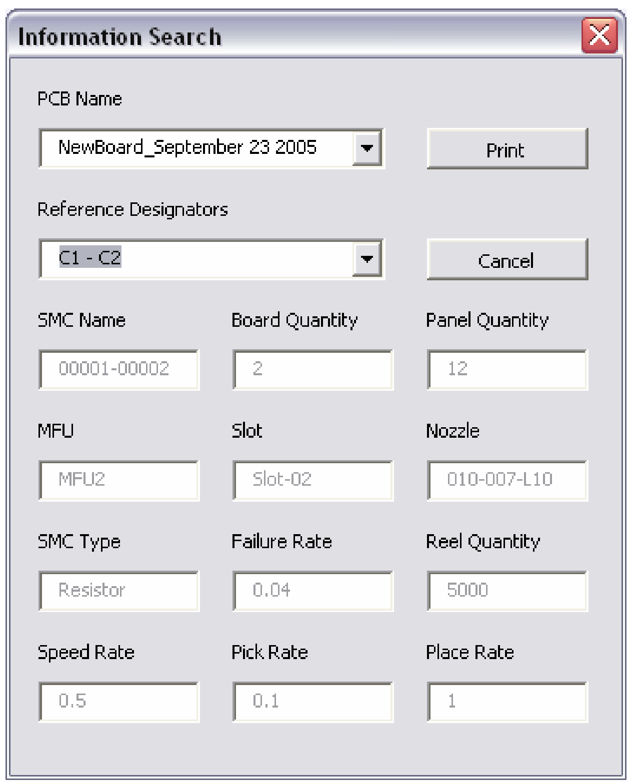

Figure 6.9 The *Information Search* window

The user selects from a combo box, one of the several PCBs added. This combo box is filled with, from the database. After the PCB is selected, the user selects one of the several SMC added to the board. If the user selects first the *Reference Designators* combo box, it will be empty because it is filled from the sheet that contains the PCB information. After the selection is made in the correct order, the other text boxes are filled with the SMC parameters according to the PCB selected. Such fields are only for information, so they are disabled to manipulation. The user may also print the whole information trough the *print* button.

Chapter VII: Conclusions and Future Work

7.1 Conclusions

The main contribution of this project is the development of a computer-based model to characterize the placement process in a Surface Mount Technology Assembly Line.

The project was accomplished in four stages. The first stage included an extensive study of the dynamic in an SMT assembly line. The study was particularly deeply in the placement process. The second stage was the development of the methodology to build the conceptual structure of the computer model. The third was the model analysis. It shows that the *Characterizer* application has an average error of 4.69%, as compared to the current application of 20.39% and *Fuji* of 67.17%. Finally, the fourth stage was the development of the model under a human-machine graphical interface environment. Such environment allows a friendly interaction between the computer model and the user. So, the characterizer program becomes a useful tool, easy to understand and to operate.

Several input parameters were evaluated. Not all of them needed to be incorporated; only those that affect greatly the assembly time. The parameters should be measurable and controllable. The incorporated parameters are: the failure rate of the SMCs, the translation speed rate, the pick and place speed rates, the amount of SMCs required for the particular SMC, the quantity of nozzle changes during the cycle time, the quantity of heads used and the configuration of the MFUs.

In general, the forecasted assembly time for the machine is overestimated. The deviation from the actual assembly times is possibly explained by the parameters not included, the estimation of some parameters, but especially by the assumptions of the model. Some of them tend to underestimate the model while others tend to overestimate it. The overall effect is somehow balanced. Related to the model assumptions, the most critical issue is the range of nozzles used by a SMC type. The model assumes that only one nozzle is available by the SMC type, while in reality a range of nozzles could be used. This causes more nozzle changes according to the model, increasing the estimated time. The assumption of constant velocity underestimates the assembly time by no considering the acceleration factor. Likewise, when ignoring the head collision the model underestimates the assembly time by the assumption of collision avoidance. The impact of other assumptions, same placement location, is difficult to analyze. It is expected that net effect is zero because for some placements the head needs to travel farther while for others the travel is shorter.

A database was created, saving the different SMCs and its parameters. A humane-machine environment was also created. It links the database and the computer program with the user.

The proposed graphical interface allows the user to perform several tasks. The first task executes the assembly time subroutine. This part of the whole program collects information from the user. Such information includes the PCB to characterize, the size of the batch, the operator availability and the machine availability. The user may also change some parameters in this same stage. These parameters are the conveyor speed rate, the estimator for the operator availability, and the estimator for the machine availability.

The second task creates a new PCB and its configuration on the machine. This part of the whole program collects information necessary to forecast the assembly time. Such information includes the PCB name and the SMC name with its setup. The setup contains the number of components per board, the MFU and its slot to be located.

The third task creates a new SMC and its parameters on the database. This part of the whole program collects information of the SMC. Such information includes the SMC name, the SMC type, its failure rate, the reel quantity, the nozzle which will suck it up, and the different speed rates.

The fourth task, similar to the third task, edits the SMC parameters. This part of the program is necessary when a parameter of a SMC has changed by decision of the SMT process administrator.

The fifth task adds a new object on the database. In this accelerated technological world new entities are being developed. So, there exists a form where the user may adjoin new devices such as SMC types or nozzles widths.

The sixth task presents the user information. With the PCB and SMC name, the user get complete information of the particularly SMC on the particularly PCB.

The characterization presented appears to be an excellent tool in different areas. The reliable assembly time estimation helps managers of SMT lines to perform several strategies to reduce products cycle time keeping costs down. It also help them to improve planning, scheduling and control thereof due to different scenarios may be evaluated without high cost incurring.

The computer program also helps the SMT lines supervisor to estimate the product delivery time for customers. Furthermore, they should be able to estimate raw material, financial and human resources necessary for different scenarios.

It helps the operator to realize if the placement machines are well balanced moreover, if the MFUs are well balanced.

Finally, this computer program could be used with diverse optimization algorithms to appropriately estimate the assembly time. It avoids the necessity to prove these algorithms on the SMT line directly.

7.2. Future Work

As a future research, a complete evaluation of this model should be integrated with other computer programs. CAD and CAM systems will help form the creation of a PCB in its graphical form to the development of its manufacturing process.

Another work that can be developed in the future is to evaluate the behavior of the model running at other SMT lines. In this way, the model could be transformed in a powerful instrument to be applied in a more challenging environment.

Also, the computer model should be tested on other placement machines in SMT lines. Theoretically, the model works reliably on similar architecture machines than the Fuji IP III. Experimentation on these machines could prove the power and importance of the program.

Finally, a time characterization for the whole SMT process should be done. Our characterization is the first step in the effort to give a trusty estimation of the delivery time to the client. However, the complete process characterization will be the ultimate answer and solution for the SMT line.

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Appendixes

Appendix A: Other Placement Machines Used at SMT Lines

A-1. Dual Delivery Placement Machine

This machine operates with a PCB table which can moves in both X and Y directions and must be aligned under the head to perform the placement operation. The placement arms and two component delivery carriers move in the X-direction, only. The pick and place heads are mounted at the two ends of a fixed length arm, which can move only between two fixed positions in the Y-direction.

Each placement component operation interchanges among two sides. While one head is performing the picking operations, the other one is placing SMCs on the PCB. For this machine, all movements of the PCB table and feeder carrier are frozen during the pick and place operations. Therefore, the maximum time taken by the arm, PCB table and feeder carrier movements will determine the cycle time.

A-2. Multi-Station Placement Machine

This machine has more than one placement station. Each one is mechanically similar and able to assemble SMCs concurrently. The stations are connected by a conveyor system to transfer PCBs between the stations. First, each station receives all the necessary pick and place coordinate data for one machine cycle. One machine cycle is the interval between two conveyor steps. Second, the station completes the cycle’s placement sequence separately and concurrently with the other stations. Third, after all stations have finished, the conveyor is moved, and the placement procedure continues.

A-3. Turret Style Dual Delivery Placement Machine

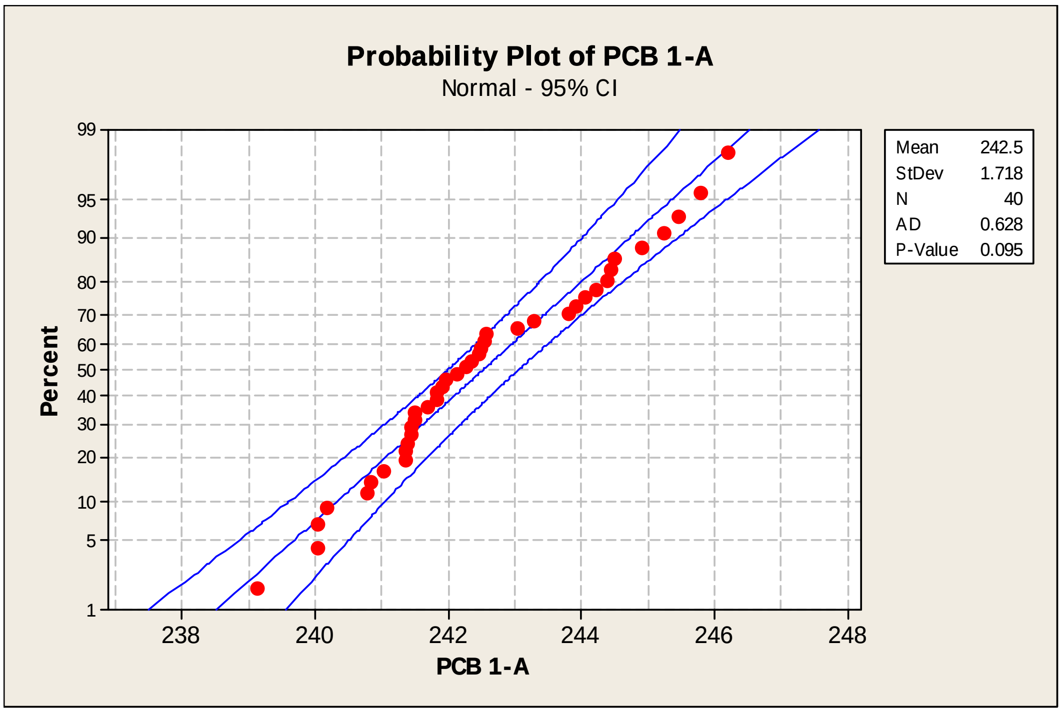
This machine uses a placement mechanism mounted on a rotating turret, which has multiple placement heads. The turret rotates from a fixed picking location to the placement location. Each pick and place operation begins by retrieving a single SMC at the grip station, while the placement station concurrently mounts other single component at a pre-specified location on the PCB. Then, the feeder rack travels to get the next proper feeder in position, and the PCB table simultaneously moves to position the next location under the placement station.

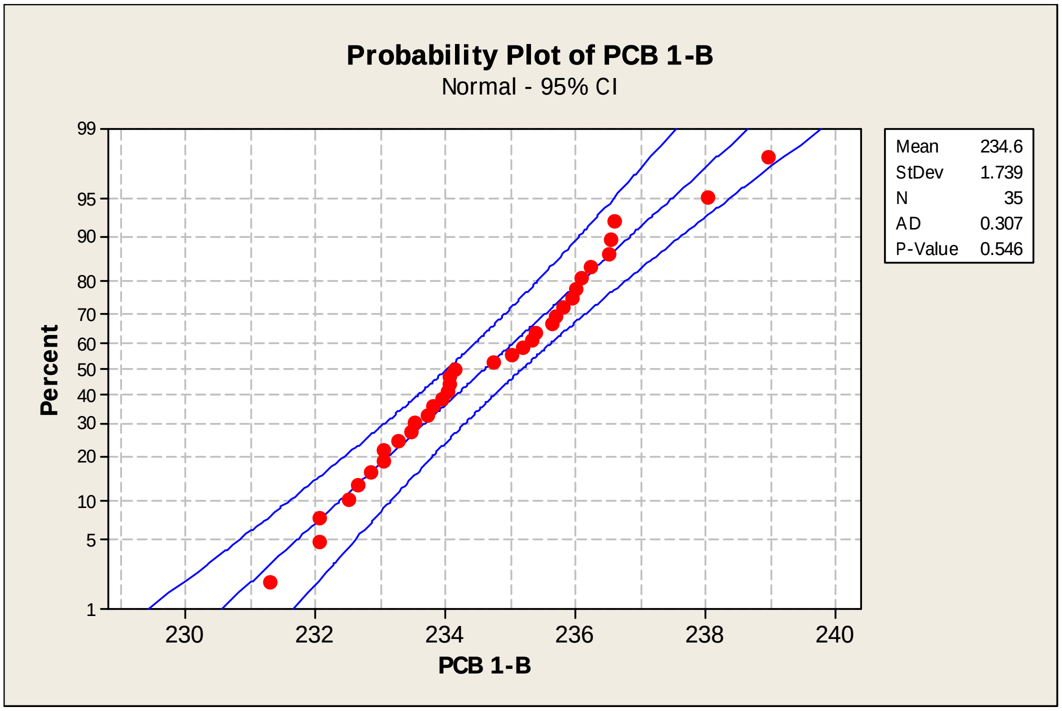
A-4. Multi-Head Placement Machine

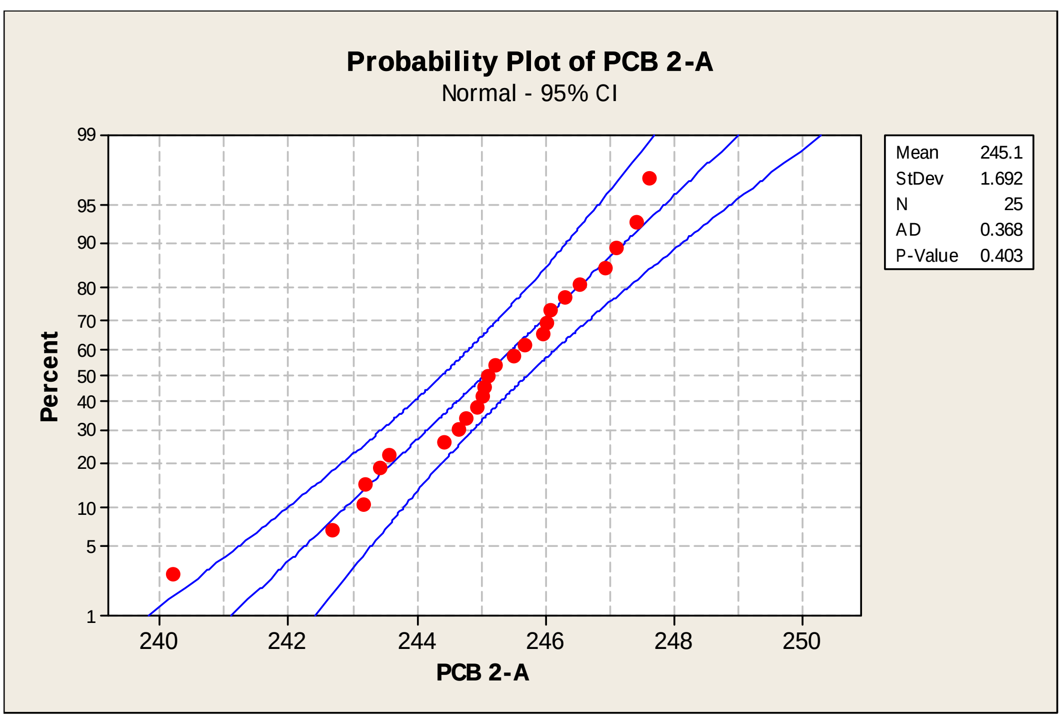
In this machine, the tour of the heads begins by picking up a few SMCs from the feeder simultaneously. Then, the head and the arm travel in the X and Y direction simultaneously and the head positions itself on top of the point where the component will be mounted, and then the head moves down (Z-direction) and mounts the component on the board then returns to the original position and repeats these steps for the next locations on the board that have to be mounted on the same tour. The PCB table also moves in X and Y directions, concurrently with the movements of head and arm. After completing a travel, the head returns to the feeder location to begin another tour, unless nozzle changes are required. The heads of this machine can be similar to the heads of turret type machine. The difference is that it is located on top of the arm. A head is used to grasp a few components from the feeder locations and mount them on the PCB.

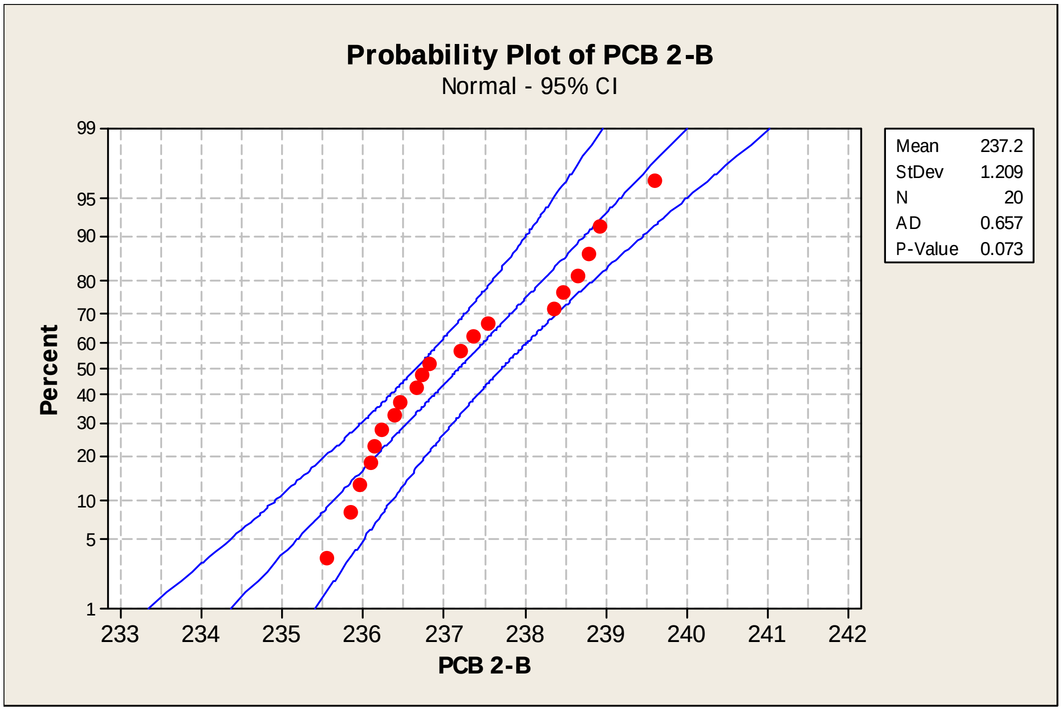
Appendix B: Normal Probability Plots for the Assembly Time

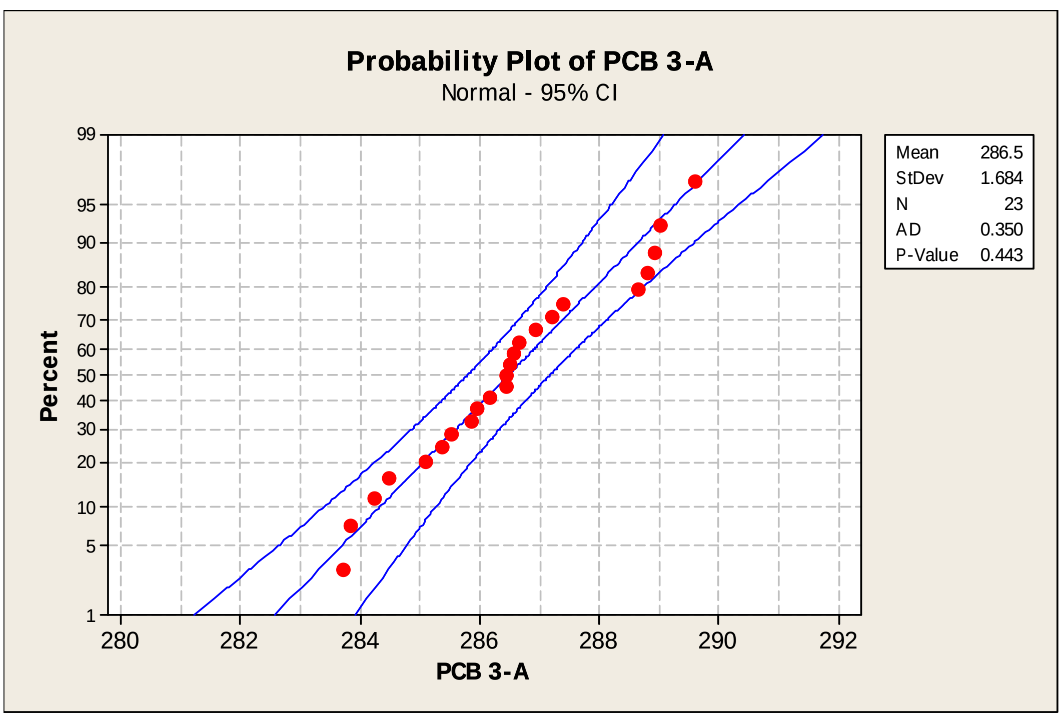
The normal probability plots for the six scenarios show normal distributions for the assembly times of the PCBs under study. It validates the assumptions required to perform a T-test.

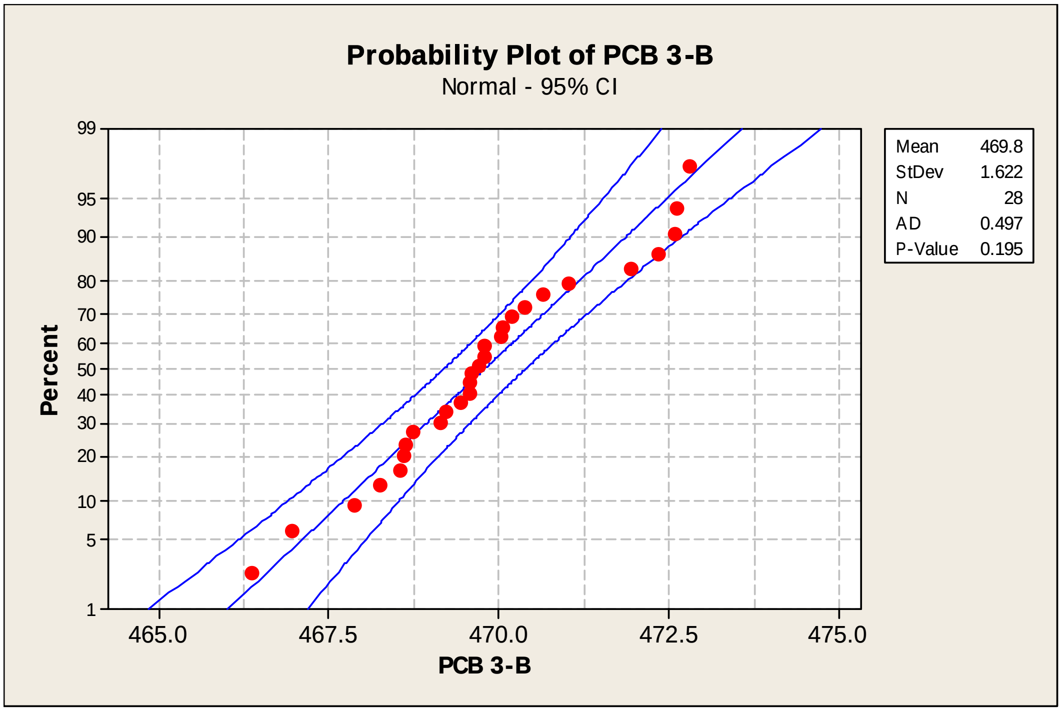



Probability Plot of PCB 1-B
Normal - 95% CI
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
230
232
234
236
238
240
PCB 1-B
Mean 234.6
StDev 1.739
N 35
AD 0.307
P-Value 0.546


Probability Plot of PCB 2-A
Normal - 95% CI
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
240
242
244
246
248
250
PCB 2-A
Mean 245.1
StDev 1.692
N 25
AD 0.368
P-Value 0.403


Probability Plot of PCB 2-B
Normal - 95% CI
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
233
234
235
236
237
238
239
240
241
242
PCB 2-B
Mean 237.2
StDev 1.209
N 20
AD 0.657
P-Value 0.073


Probability Plot of PCB 3-A
Normal - 95% CI
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
280
282
284
286
288
290
292
PCB 3-A
Mean 286.5
StDev 1.684
N 23
AD 0.350
P-Value 0.443


Probability Plot of PCB 3-B
Normal - 95% CI
Percent
PCB 3-B
99
95
90
80
70
60
50
40
30
20
10
5
1
465.0
467.5
470.0
472.5
475.0
Mean 469.8
StDev 1.622
N 28
AD 0.497
P-Value 0.195