Refinement, Implementation and Validation of Assembly Cost Model for Printed Circuit Assemblies

by

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ABSTRACT

This research presents the development of a software application that implemented the generalization of a model to estimate the cost of electronic products that are being developed. The generalized cost model described the typical processes found in the electronics manufacturing industry. The proposed application allows users to define facilities, processes and products, calculate its cost and evaluate design alternatives in terms of cost. The application also contains also a default (virtual) facility with the typical processes of the electronics industry to make preliminary cost calculations of products. A relational database was designed to manage the information provided by users. The software was developed in Microsoft Visual Basic.NET®. A validation of the model was performed using four products from a local electronic company. A discrete event simulation model was also generated to evaluate the precision of the model and its application.

RESUMEN

Esta investigación presenta el desarrollo de una aplicación de computadora donde se implementó la generalización de un modelo para estimar el costo de productos electrónicos nuevos siendo desarrollados. El modelo de costo generalizado describió los procesos típicos encontrados en la industria de la manufactura electrónica. La aplicación propuesta permite a los usuarios definir facilidades, procesos y productos, calcular su costo y evaluar alternativas de diseño en términos de costo. La aplicación también contiene a una facilidad predefinida (virtual) con los procesos típicos encontrados en la industria electrónica, para calcular preliminarmente el costo de productos. Una base de datos relacional fue diseñada para manejar la información provista por los usuarios. La aplicación fue desarrollada en Microsoft Visual Studio.NET®. Una validación del modelo fue hecha usando cuatro productos de una compañía local de productos electrónicos. Un modelo de simulación de eventos discretos fue también generado para evaluar la precisión del modelo y de la aplicación.

To my father Geovanie,
my grandmother Nelida
and my girlfriend Laura,
and those people who helped me with
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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

The cost of a product is essential for the competitive position of the organization that manufactures it. Probably the most challenging cost analysis is related to a product that has not been manufactured. The difficulty of making estimations of products not yet manufactured is that there are elements that need to be unavoidably forecasted. Other difficulty in estimating the cost of a new design is that most prospective products to be made are unique; that is, similar products have not been made in the past under the same conditions. "Due to this, outcome data that can be used in estimating the cost directly and without modification often do not exist" [6].

"It has been pointed out by several electronic researchers that 85% of a product cost is already committed through decisions made during the product design stage even though only 5% of the total development costs have been expended" [14-16]. Since it is critical that a product be well designed to avoid high costs after implementation, efforts must be made to ensure efficient designs of electronic products.

With this in mind, in 2001, the Center for Power Electronics Systems (CPES) sponsored a project called Development of Cost Models for Electronic Assemblies [1]; its main purpose was to construct a cost model that could be used to estimate the cost of electronic assemblies from the early stages of product conception, to guide research and development efforts. This model assumed a generic fabrication/assembly sequence and described how resources are typically consumed and costs incurred throughout the electronic assembly and fabrication processes. This model was completely formulated

[2], but was only crudely implemented using an Excel spreadsheet, and needed more validation.

This project deals mostly with the development of a software application to implement the model by *Mendez [1 and 2]* to estimate the cost of an electronic product and to evaluate the feasibility of design alternatives in terms of cost. The first step was the revision of the assembly cost model by *Mendez* in order to generalize it and simplify it. Once the generalization of the assembly cost model was made, a software application was developed that implements it in a user friendly environment. An attempt was done to validate the revised cost model through several examples obtained from assembly companies, comparing the cost estimates provided by the companies with the estimates resulting from the revised cost model. Also, a simulation model was developed to further study the validity of the revised cost model. This cost model implementation will help electronic designers to calculate the cost of a new electronic product and to study the impact and feasibility of different design alternatives in terms of cost.

CHAPTER 2: LITERATURE REVIEW

Mendez [1 and 2] presented a thesis and paper report that documents the research done as part of a project to develop a cost model that can be used to estimate the cost of the new power electronics systems and products that are being developed. This research addressed a need for cost models to be used as a decision making tool from the early stages of the conception of the device to guide the research and development process.

The main motivation of *Mendez* was power electronics products, but an examination of this type of product revealed that they share the basic characteristics of any modern electronic product, this is, a printed circuit board (PCB) with electronic components that are soldered to it. Given that assumption, *Mendez* developed a cost model for the board level fabrication and assembly of electronics products assuming a typical and generic fabrication/assembly sequence and processes. This sequence included all of the typical processes for the fabrication and assembly of a PCB-based electronic product. The processes identified were the ones used in the assembly of through-hole technology (THT) components, surface mount technology (SMT) components, chip on board wire-bonded components, or any combination of them. Also, it included assembly of components on one-sided or two-sided PCB.

The model described how resources are consumed and costs incurred in a typical electronics assembly operation. The resources and costs included in the model were direct labor, materials and components, equipment, support personnel, utilities, and space. Each assembly and PCB manufacturing process step was analyzed to understand how resources were consumed and costs allocated to every board produced. Numerous, but simple mathematical equations were developed to model this type of resource consumption and then estimate the total unit cost.

The *Mendez* model seems to be the most detailed work that has been made so far to estimate the cost of electronic assemblies. It provides the following factors that have not been considered so far by any cost model in the literature examined:

- All the SMT and THT assembly processes were detailed and described.
- One-sided or two-sided boards can be considered in the model
- Overhead cost can be calculated and is included in the model.
- Every process is explained in detail.

A cost modeling of electronics assembly operations was discussed by *Theng [3]*. He presented station by station assembly cost equations for the estimation of total assembly cost of a seven station printed wiring board (PWB) assembly. *Theng*, also demonstrated the equations for the average production time of the assemblies at these stations. The total manufacturing cost equation in his model included three elements, which are inventory cost, assembly cost and test and rework associated cost. The cost model developed in this paper can be used by a design team to evaluate the associated manufacturing cost for design alternatives in concurrent engineering processes.

The assembly equations proposed by *Theng* were very similar to those in the *Mendez [1]* model. Interesting costs considered in *Theng*'s model were the inventory cost of components and the rework of operations. Although these costs may not be of interest for a designer, they could be of interest for a process engineer or a planner that would like to estimate the inventory cost of the components at the facility and knows the defect rate of the electronic components or electronic boards. The inclusion of these costs in a model could motivate process engineers and planners to collaborate with design engineers in the redesign of electronic components.

Nagarajan [4 and 5] presented a thesis and paper report that contains a computer aided cost estimation (CACE) system. Such system was developed to compare the costs of assembling a board with peripherally leaded devices such as Quad Flat Pack (QFP) or a Tape Automated Bonding (TAB) component with the costs of assembling a board with functionally equivalent Ball Grid Arrays (BGA) or Direct Chip Attach (DCA) devices. The CACE system permitted the user to execute “what if” analyses, allowing the user to recognize the key cost drivers. Also, the CACE system had the capability to read CAD drawings and incorporated Design for Manufacture (DFM) principles through interactive visual design to measure the effects of design changes when alternate packaging formats were studied. The final assembly cost per unit was the metric he used for cost comparison. The cost factors considered in the model were: equipment, material, labor, board, component, rework/ repair, cleaning and floor space. In addition, throughput variables (cycle times, production hours, etc.) were also incorporated in the CACE system, to the above factors.

The cost model application developed by *Nagarajan* was a great achievement because it included features such as reading CAD drawings; making comparisons between the use of different technologies and the inclusion of several cost factors that were included in *Mendez* model also. The only limitation of its cost model application was that it only considered the existing technologies available so far to manufacture electronic components. Is not clear how *Nagarajan* makes the association between the types of components being studied on a particular product and the processes to locate or deal with those components.

A development of an activity-based cost estimating system to help designers in computing the manufacturing cost of a printed circuit board assembly at the early concept stage of design was developed by *Ong N.S [7]*. Activities were identified, quantified and the costs allocated based on the amount and type of activities used by the printed circuit assembly (PCA). The activity costs were established using activity charts, worksheets and a cost build-up table. *Ong* stated that the cost estimating system developed will allow designers to identify those problematic activities that incur substantial cost so that efforts can then be made in reducing these costs. Therefore, by providing early manufacturing cost information during the design cycle, considerable improvements in productivity and manufacturing can be achieved.

The model developed by *N.S Ong* was very similar to the approach used by *Mendez* but he did not detail the processes and their equations as explicitly as *Mendez*. Although this was a spreadsheet model, it was a good and simple tool to estimate the cost of PCA's.

Giachetti and Arango Juan [8] presented an activity-based printed circuit assembly (PCA) cost estimation model. Such model estimated PCB fabrication cost based on the design parameters. The activities were defined so that the design decisions become the cost drivers and thus enable the cost estimation model to be utilized early in the design process when sufficient time remains to make design changes. The cost model was used to rapidly compare different PCA design alternatives, let the designers assess the impact of their decisions on the final cost, and aid them in generating lower cost alternatives. An analysis of the cost model reveals important relationships between design parameters and cost. The model developed by *Giachetti and Arango* is very similar to the work of *Mendez* but there was no description of the equations used to calculate cost and only a spreadsheet model was developed to calculate the cost of a product.

Castillo C. and Malavé C.O [9] developed a system that was intended to provide the designers with the opportunity considerate manufacturing in the early design stages of a PCA. The model suggested by them consisted of a knowledge-based system for the automatic generation of PCA alternative designs. Their system decomposed an existing design and presented other design alternatives equivalent to the design under consideration. They had a dual purpose with their system. First, different, but equivalent, PCA designs could be evaluated for manufacturability to aid the designer to make the final PCB design replacement board or a spare without going the entire design process. Second, a PCB design-specific module can be produced and kept on hand to be utilized in cases where there is a need to find a substitution board or a spare without going through the entire design process.

The knowledge based system developed by *Castillo and Malavé* was good because tried to replace the existing components used in a board design and make the equivalent necessary replacements to make a more competitive design in terms of cost and efficiency. Although the improvements at a PCA can be made, this article was focused only in the improvement of existing PCA designs as a concurrent engineering strategy and not on designs not previously considered.

The concept of flexible costing in Flexible Manufacturing Systems (FMS's) was presented by *Koltai, Lozano and Onieva [10]*. They proposed a method that changes the overhead allocation, based on the production plan outcomes and on the process simulated performance. FMS's are designed to integrate the flexibility of job shops and the efficiency of mass production systems. Product costing techniques need to adjust to this new technological environment. At one side, the high production overhead cost of these systems requires a particular consideration to overhead allocation. In contrast, the frequently changing setup configuration and production plans require a regular recalculation of overhead allocation and an *a priori* evaluation of the estimated production cost. In FMS's the same product can be produced along diverse paths, in different product mixes, and in diverse setup configurations. This flexibility of the production system must be reproduced in the costing system as well. The flexible costing system established in the paper connects production planning and the *a priori* estimation of the performance of the system with the costing process. The method applies Activity Based Costing (ABC) with the assistance of a production planning model and a discrete event simulation model that permitted a regular update of the overhead allocation bases and rates. Consequently, it is possible to reproduce the alterations in the FMS operation into the production cost. The system proposed is a good one because it combined discrete event system simulation of the processes being studied as an input to calculate the cost of products.

Arieh [11] presented a hybrid cost estimation system for rotational parts that used a combination of the variant approach with explicit calculations. The variant approach is employed by them to retrieve machining parameters from a database of early period parameters. These parameters were extracted from many Numerical Control (NC) programs that were used by their industrial partner. The parameters reflect the optimal machining circumstances on a particular NC machine, using a diversity of materials and tools available on the machine. The cost estimation developed considers the components geometry and design features such as tolerance, which affect the detailed set-up and machining plan. Thus, in order to estimate the cost, the system develops a set-up plan for chucking the parts and changing tools. In addition, the system considers the parts deflection in order to verify or correct the cutting parameters. This information is used to calculate the total machining time of the part and thus its cost.

Although the approach of *Arieh* is for machined parts, it is a good one because it explores the capabilities of using two of the three types of cost estimation which are: estimation based on past experience (variant cost estimation), estimation based on explicit cost computations, and parametric cost estimation.

CHAPTER 3: REVISION OF MENDEZ'S MODEL

Mendez [1] developed a cost model for the image level assembly of electronics products assuming a typical and generic assembly sequence and processes. These sequences included all typical processes for the assembly of a PCB-based electronic product. The processes identified were the ones used in the assembly of through hole technology (THT) components, surface mount technology (SMT) components, chip on board wire-bonded components, or any combination of them. Also, it included assembly of components on one-sided or two-sided PCB.

The cost model developed by *Mendez* (see Figure 1) was developed with the power electronics product developer as the main user. Nevertheless, the user needs in this area are very similar to those of the developer of any other type of electronic product. This person will develop a series of product specifications. Given those specifications, the cost model proposed can be used as a tool to estimate the cost of the product considering how it is manufactured. The basic product specifications to provide include: a bill of materials (BOM), the printed circuit board (PCB) characteristics (size and the expected market demand). The resulting cost estimates can be used to compare one design alternative versus another without actually having to build a unit of the product.

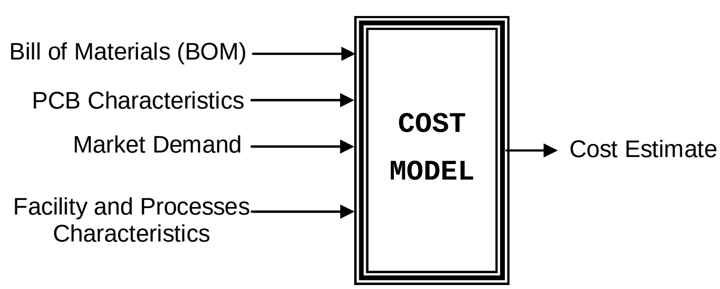


Figure 1 Cost Model Overview

(Reproduced with permission from "Development of Cost Model for Power Electronic Assemblies, *Mendez* M., University of Puerto Rico – Mayagüez Campus, 1998, ME Thesis.)

The *Mendez* cost model assumed that an electronic product consists essentially of a PCB with electronic components soldered to it. It was assumed that this kind of assembly will follow a series of generally sequential steps. In each step of the assembly sequence, resources will be consumed and hence cost will be incurred (see Figure 2)

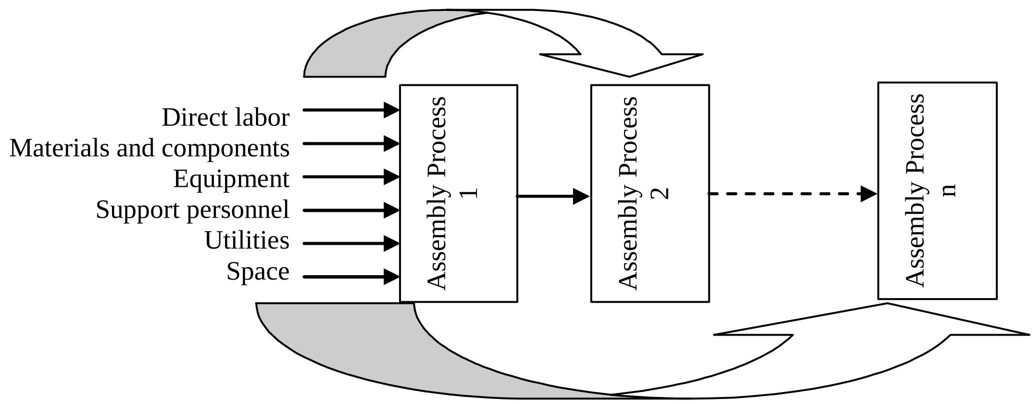


Figure 2 Consumption of resources in each processing step.
(Reproduced with permission from "Development of Cost Model for Power Electronic Assemblies, *Mendez* M., University of Puerto Rico – Mayagüez Campus, 1998, ME Thesis.)

The resources and costs included in the model were direct labor, materials and components, equipment, support personnel, utilities, and space. Each assembly and PCB manufacturing process step was analyzed to understand how the resources were consumed and costs allocated to every board produced. The assembly cost model proposed by *Mendez* [1] included approximately 275 equations and 22 explicitly detailed processes.

Manufacturing Processes Description

A detailed study of the manufacturing processes and typical assembly sequences of electronics products was carried out by *Mendez* research to formulate the mathematical expressions of the cost model. The result of this study was the development of a generic process chart, (see Figure 3).

The study of the manufacturing of electronic products included literature reviews (*Hart [1], Prasad [2], and Hollomon [3]*), plant tours to several electronics assembling plants and PCB fabricators, interviews with engineers, and the investigators experience. Low, medium and high volume assembly plants were studied by *Mendez*. Appendix A contains a brief description of the assembly processes presented in Figure 3.

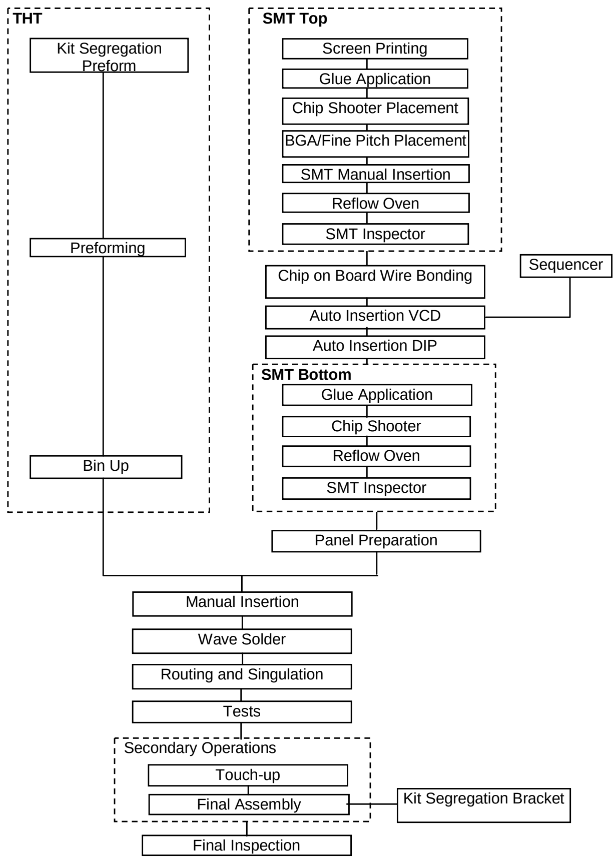


Figure 3 Process chart for assembly sequence
(Reproduced with permission from "Development of Cost Model for Power Electronic Assemblies, *Mendez* M., University of Puerto Rico – Mayagüez Campus, 1998, ME Thesis.

Although *Mendez* model was completely formulated, it contained many equations. The idea behind this research is to generalize and reduce the number of expressions needed to describe the cost of an electronic product. Another purpose of this research is to introduce new equations that could serve to complement the equations presented by *Mendez* that can be used to describe the new processes or technologies being created. This will be done assuming that the new processes or technologies being created could be described with the generalized cost model developed in this research. To do that and obtain a better understanding of the revised cost model, it is necessary to describe the following terms:

1) **Image**- A substrate of epoxy glass, clad metal or other material upon which a pattern of conductive traces is formed to interconnect components.
2) **Panel –** several images joined to be manufactured together.
3) **Part Number**- refers to a unique component or part. A number that is assigned to identify and differentiate parts of a product.
4) **Batch-** refers to the quantity to be made of a particular product. Typically refers to production orders
5) **Efficiency**- It refers to the machine or operator run time versus available time. So, a machine or operator that was down two hours of an eight-hour shift has 75% process efficiency. It is a number > 0 and <= 1.

The cost of the PCB's has been allocated at the image level even though many operations are done in batches of images or in panels with several images per panel.

3.1 Setup time per image in a process

Setup time refers to the time that is spent before actual production occurs It is done to prepare a machine, manual operation or product to be processed. An example of setup time is when rolls of individual part numbers of a product are loaded on a Chip Shooter machine prior to starting the assembly of a batch of boards. All the setup time equations in *Mendez* model, which are presented in Appendix B and the variations of the setup times considered for this research can be generalized in Equation 1:

Equation 1 Setup Time per image in a process

$$TSU_{img} = \frac{TSUF+TSUV*Npn}{Nimg_{pl} * Npl_{bh} *Nplp*Nimgp} *(1+(1-E))$$

where,

TSU_{img} = Setup Time per image
TSUF = Fixed Setup time
TSUV= Variable Setup Time
Npn = Number of different part numbers processed in this given machine
$Nimg_{pl}$ = Number of images per panel
Npl_{bh} = Number of panels per batch
Nplp- Number of panels processed simultaneously
Nimgp – Number of images processed simultaneously
E- Efficiency

With the general Equation 1, the variations presented in Table 1 will allow implementing the Setup Time of a process.

Table 1 Variations or special cases of setup time equations

Total Number of boards benefiting from a Setup Occurrence	Comments	Resulting Equivalent Equation	Sample Process where Equation is applied
Complete Production (Batch) with variable setup time for components to be processed	In this variation, Nimgp and Nplp is 1.	$\frac{TSUF+TSUV*Npn}{Nimg_{pl} * Npl_{bh}}$	Chip Shooter Placement
Complete Production (Batch), no variable time	In this variation, Nimgp and Nplp is 1.	$\frac{TSUF}{Nimg_{pl} * Npl_{bh}}$	Reflow Oven
One Panel with several images or boards	In this variation, Npl_{bh} Nimgp and Nplp is 1.	$\frac{TSUF}{Nimg_{pl}}$	Suitable to occur in new processes
One image or board	In this variation, Npl_{bh} Nimgp and Nplp is 1.	TSUF	Final Assembly

Total Number of boards benefiting from a Setup Occurrence	Comments	Resulting Equivalent Equation	Sample Process where Equation is applied
Group of Panels Processed Simultaneously	In this variation, Npl_{bh} and Nimgp is 1.	$\frac{TSUF}{Nimg_{pl} * Nplp}$	Suitable to occur in new processes
Group of Single Images or Boards Processed Simultaneously	In this variation, Npl_{bh} and Nplp is 1.	$\frac{TSUF}{Nimgo}$	Suitable to occur in new processes
Not Apply	In this case, setup is not needed	0	

Note: Efficiency is not stated in this table but it is considered in all the variations

3.2 Loading time per image in a process

Loading time refers to the time that is spent in a process locating a panel or image. An example of a loading time is when a PCB is loaded into Solder Paste Printing machine. All loading time equations in *Mendez* model, which are presented in Appendix B and the variations of the loading times considered for this research are generalized in Equation 2.

Equation 2 Loading time per image in a process

$$TL_{img} = \frac{TL}{Nimg_{pl} * Nplp * Nimgp} * (1 + (1 - E))$$

where,

TL_{img} = Loading time per image
TL = time spent to locate the panel or image to the machine or workstation where it will be processed. This operation can be made manually by an operator or by a machine.
$Nimg_{pl}$ = Number of images per panel
Nplp- Number of panels processed simultaneously
Nimgp – Number of images processed simultaneously
E- Efficiency

With the general Equation 2, the variations presented in Table 2 will allow to implement the loading time of a process.

Table 2 Variations or special cases of loading time equations

Total Number of boards benefiting from a Loading Occurrence	**Comments**	**Resulting Equivalent Equation**	**Sample Process where Equation is applied**
One Panel with several images or boards	In this variation Nimgp and Nplp is 1.	$\frac{TL}{Nimg_{pl}}$	Solder Paste Printing
One image or board	In this variation, Npl_{bh} Nimgp and Nplp is 1.	TL	Circuit Test or Functional Test
Group of Panels Processed Simultaneously	In this variation, Npl_{bh} and Nimgp is 1.	$\frac{TL}{Nimg_{pl} * Nplp}$	Routing and Singulation
Group of Single Images or Boards Processed Simultaneously	In this variation, Npl_{bh} and Nplp is 1.	$\frac{TL}{Nimgp}$	Suitable to occur in new processes
Not Apply	In this case, loading is not made.	0	

Note: Efficiency is not stated in this table but it is considered in all the variations

3.3 Processing time per image

Process time refers to the time that is spent processing a panel or image of a PCB in a machine or manual operation. An example of a process time is when Non Fine Pitch components of a PCB are assembled on a Chip Shooter Placement machine. All process time equations in the *Mendez* model, which are presented in Appendix B and the variations of the process times considered for this research can be generalized in Equation 3.

Equation 3 Process time per image in a process

$$TP_{img} = \frac{TP * \sum_{i=1}^{Npn} QPN_i}{Nimg_{pl} * Npl_{bh} * Nplp * Nimgp} * (1+(1-E))$$

TP_{img} = Process Time per image
TP = time spent by a machine or operator processing a component, panel or image.
$QNPN_i$ = Quantity of a individual part number processed in this process
Npn = Number of part numbers
$Nimg_{pl}$ = Number of images per panel
Npl_{bh} = Number of panels per batch
Nplp- Number of panels processed simultaneously
Nimgp – Number of images processed simultaneously
E- Efficiency

With general Equation 3, the variations presented in Table 3 will allow to estimate the processing time in a process.

Table 3 Variations or special cases of process time equations

Total Number of boards benefiting from a Processing Occurrence	Comments	Resulting Equivalent Equation	Sample Process where Equation is applied
One Panel with several images or boards	In this variation the sum of $QNPN_i$, Npl_{bh} Nimgp and Nplp is 1.	$\frac{TP}{Nimg_{pl}}$	Solder Paste Printing
One image or board	In this variation, Npl_{bh} Nimgp and Nplp is 1.	TP	Circuit Test or Functional Test
Group of Panels Processed Simultaneously	In this variation, Npl_{bh} and Nimgp is 1.	$\frac{TP}{Nimg_{pl} * Nplp}$	Suitable to occur in new processes
Group of Single Images or Boards Processed Simultaneously	In this variation, Npl_{bh} and Nplp is 1.	$\frac{TP}{Nimgp}$	Suitable to occur in new processes
Components to be assembled on an image	In this variation $Nimg_{pl}$, Npl_{bh}, Nimgp and Nplp is 1.	$TP * \sum_{i=1}^{Npn_n} QPN_i$	Chip Shooter

Note: Efficiency is not stated in this table but it is considered in all the variations

A variation to the process time equations previously presented is when the process time depends on the time a panel or image spends on a conveyor. An example of this is when a panel or image is processed on a Reflow Oven process. In this case the process time is calculated using Equation 4 or Equation 5.

Equation 4 Used to calculate the process time per panel of a product being processed on a conveyor

$$TP_{img} = \frac{\frac{CVL}{CVS} + \frac{\left(SD_{pl} + Size_{pl}\right)}{CVS} * \left(Npl_{bh} - 1\right)}{Nimg_{pl} * Npl_{bh}} * (1+(1-E))$$

Equation 5 Used to calculate the process time per image of a product being processed on a conveyor

$$TP_{img} = \frac{\frac{CVL}{CVS} + \frac{\left(SD_{img} + Size_{img}\right)}{CVS} * \left(Npl_{bh} * Nimg_{pl} - 1\right)}{Nimg_{pl} * Npl_{bh}} * (1+(1-E))$$

where,
CVL = Conveyor Length
CVS = Conveyor Speed
SD_{pl}= Separation Distance between panels
SD_{img}= Separation Distance between images
$Size_{pl}$ = Panel Size
$Size_{img}$ = Image Size
$Nimg_{pl}$ = Number of images per panel
Npl_{bh} = Number of panels per batch
E- Efficiency

3.4 Unloading time per image in a process

Unloading time refers to the time that is spent in a process removing a panel or image from a machine or manual operation. An example of an unloading time is when a PCB is unloaded from the Chip Shooter machine.

All unloading time equations in *Mendez* model, which are presented in Appendix B and the variations of the unloading times considered for this research can be generalized in the Equation 6.

Equation 6 Unloading time per image in a process

$$TU_{img} = \frac{TU}{Nimg_{pl} * Nplp*Nimgp} *(1+(1-E))$$

where,
TU_{img} = Unloading Time per image
TU = time spent to removing a panel or image from the machine or workstation where it was processed
Nplp- Number of panels processed simultaneously
Nimgp – Number of images processed simultaneously
E- Efficiency

With general Equation 6, the variations presented in Table 4 will allow the estimation of the unloading time per image in a process.

Table 4 Variations or special cases of unloading time equations

Total Number of boards benefiting from an Unloading Occurrence	Comments	Resulting Equivalent Equation	Sample Process where Equation is applied
One Panel with several images or boards	In this variation, Npl_{bh} Nimgp and Nplp is 1.	$\frac{TU}{Nimg_{pl}}$	Solder Paste Printing
One image or board	In this variation, Npl_{bh} Nimgp and Nplp is 1.	TU	Circuit Test or Functional Test
Group of Panels Processed Simultaneously	In this variation, Npl_{bh} and Nimgp is 1.	$\frac{TU}{Nimg_{pl} *Nplp}$	Suitable to occur in new processes
Group of Single Images or Boards Processed Simultaneously	In this variation, Npl_{bh} and Nplp is 1.	$\frac{TU}{Nimgp}$	Suitable to occur in new processes
Not Apply	In this case, unloading is not made.	0	Sequencer

Note: Efficiency is not stated in this table but it is considered in all the variations

3.5 Travel Time per image in a process

Travel time refers to the time that is spent transporting a panel, image, etc of a PCB from one process to the next. An example of a travel time in the processes is when a PCB is transported from the Solder Paste Printing process to the Chip Shooter Placement machine where the Non Fine Pitch components are assembled on a PCB. All travel time equations in *Mendez* model, which are presented in Appendix B and the variations of the travel times considered for this research can be generalized in the Equation 7.

Equation 7 Travel time per image in a process

$$TTR_{img} = \frac{TTR}{Nimg_{pl} * Npl_{bh} * Nplp * Nimgp} * (1 + (1 - E))$$

where,

TTR_{img} = Travel Time per image
TTR = time spent to move a panel or image from the machine or workstation where it was processed to the next one.
Nplp- Number of panels moved simultaneously
Nimgp – Number of images moved simultaneously
E- Efficiency

With general Equation 7, the variations presented in Table 5 will allow to estimate the travel time per image in a process.

Table 5 Variations or special cases of travel time Equations

Total Number of boards benefiting from a Travel Occurrence	Comments	Resulting Equivalent Equation	Sample Process where Equation is applied
Complete Production (Batch)	In this variation, Nimgp and Nplp is 1.	$\frac{TTR}{Nimg_{pl} * Npl_{bh}}$	Auto Insertion DIP
One Panel with several images or boards	In this variation, Npl_{bh} Nimgp and Nplp is 1.	$\frac{TTR}{Nimg_{pl}}$	Solder Paste Printing

Total Number of boards benefiting from a Travel Occurrence	Comments	Resulting Equivalent Equation	Sample Process where Equation is applied
One image or board	In this variation, Npl_{bh} Nimgp and Nplp is 1.	TTR	Circuit Test or Functional Test
Group of Panels moved Simultaneously	In this variation, Npl_{bh} and Nimgp is 1.	$\frac{TTR}{Nimg_{pl} * Nplp}$	Suitable to occur in new processes
Group of Single Images or Boards moved Simultaneously	In this variation, Npl_{bh} and Nplp is 1.	$\frac{TTR}{Nimgp}$	Suitable to occur in new processes

Note: Efficiency is not stated in this table but it is considered in all the variations

A variation to the travel time equations previously presented is when the travel time depends on the time a panel or image spends on a conveyor. In this case the travel time is calculated using Equation 8 or Equation 9.

Equation 8 Used to calculate the travel time per panel of a product being moved by a conveyor

$$TTR_{img} = \frac{\frac{CVL}{CVS} + \frac{\left(SD_{pl} + Size_{pl}\right)}{CVS} * \left(Npl_{bh} - 1\right)}{Nimg_{pl} * Npl_{bh}} * (1+(1-E))$$

Equation 9 Used to calculate the travel time per image of a product being moved by a conveyor

$$TTR_{img} = \frac{\frac{CVL}{CVS} + \frac{\left(SD_{img} + Size_{img}\right)}{CVS} * \left(Npl_{bh} * Nimg_{pl}\right)}{Npl_{bh}} * (1+(1-E))$$

where,
CVL = Conveyor Length
CVL = Conveyor Length
CVS = Conveyor Speed
SD_{pl}= Separation Distance between panels
SD_{img}= Separation Distance between images
$Size_{pl}$ = Panel Size
$Size_{img}$ = Image Size
$Nimg_{pl}$ = Number of images per panel
Npl_{bh} = Number of panels per batch
E- Efficiency

3.6 Special Events per image in a process

Special Events are events that occur either randomly or at programmed times such as the Cleaning of the Solder Paste Printing machine which occurs after a predetermined number of times or the rework of a panel or image in a Touch-Up Process which occurs randomly and is faulty rate is p. All Special Event equations in the *Mendez* model, which are presented as part of the setup time for the processes Solder Paste Printing and Glue Application in Appendix B and the variations of the Rework times considered for this research can be generalized in Equation 10.

Equation 10 Special events per image in a process

$$TSP_{img} \; \frac{TSP * \sum_{PN_{i=1}}^{PN_n} QPN_i}{Nplo*Nimgo * Nimg_{pl} *p} *(1+(1-E))$$

where,

TSP_{img} = Special Event time per image
TSP = time that it is spent dealing with the occurrence of a special event. An example of a situation could be in Solder Paste Printing process where a cleaning operation takes place usually after a predetermined number of panels or images processed or to model Rework operations due to faulty rate of panels, images or components.
$QNPN_i$ = Quantity of a particular Part Number
Nplo= Number of Panels per Occurrence
Nimgo= Number of Images per Occurrence
p= defective rate of a component, image or panel
E- Efficiency

With the general Equation 10, the variations presented in Table 6 will allow the implementation of the Occurrence Time in *Mendez* model and to include Rework operations to the model.

Table 6 Variations or special cases of special event operations

Total Number of boards benefiting from a Special Event operation	Comments	Resulting Equivalent Equation	Sample Process where Equation is applied
Programmed Special Event to one Panel with several images or boards	In this variation the sum QPN_i, Nimgo, p are 1	$\frac{TSP}{Nplo^{*}\ Nimg_{pl}}$	Solder Paste Printing
Predetermined Special Event to One image or board	In this variation the sum QPN_i, Nplo, $Nimg_{pl}$ and p are 1	$\frac{TSP}{Nimgo}$	Suitable to occur in new processes
Random Special Event to one panel with several images or boards	In this variation the sum QPN_i, Nimgo, p are 1	$\frac{TSP}{Nimg_{pl}{*}Npl_{bh}{*}p}$	Suitable to occur in new processes
Random Special Event to one image or board	In this variation the sum QPN_i, Nimgo are 1	$\frac{TSP}{Nimg_{pl}{*}p}$	Suitable to occur in new processes
Random Special Event to one component board	In this variation the sum QPN_i, Nimgo are 1	$\frac{TSP * \sum_{PN_{i=1}}^{PN_n} QPN_i}{p}$	Chip Shooter Placement

Note: Efficiency is not stated in this table but it is considered in all the variations

3.7 Total Process time per image in a process

The total time per image of a process can be summarized in Equation 11.

Equation 11 Total Process time per image in a process

$$TPT_{img} = TSU_{mg} + TL_{mg} + TP_{mg} + TU_{mg} + TTR_{mg} + \sum_{i=1}^{n} TSP_{img}$$

where,

TPT_{img} = Total Process time per image
TSU_{img} = Setup time per image in a process (refer to section 3.1)
TL_{img} = Loading time per image in a process (refer to section 3.2)
TP_{img}= Process time per image in a process (refer to section 3.3)
TU_{img} =Unloading time per image in a process (refer to section 3.4)
TTR_{img} =Travel time per image in a process (refer to section 3.5)
TSP_{img} =Special Event Time per image in a process (refer to section 3.6)
n = Number of special events in a process

3.8 Number of required machines or operators of a particular process

Once the total time of a process is calculated, *Mendez* model calculated the number of required machines needed for a process using Equation 12, but this is only used to calculate the cost of equipment and to calculate the number of machines required in Routing and Singulation and Tests processes. Equation 13 was used to calculate the number of operators needed in Manual Insertion of Through Hole Components. In the revised model, Equation 12 and Equation 13 are used to calculate the number of machines or operators that are needed on a process based on the demand of the product or the required number of images processed per hour in a process. When calculating the number of required machines or operators, the result is rounded up to the next number to obtain an integer number.

Equation 12 Number of machines or operators of a particular process based on demand requirements

$$Nrmo = Roundup\left[\frac{D_{yr} * TPT_{img}}{\left(Nday_{yr} * Nhrs_{day}\right)}\right]$$

Equation 13 Number of machines or operators of a particular process based on cycle time

$$Nrmo = Roundup\left[\frac{TPT_{img}}{\frac{1}{Nimg_{hr}}}\right]$$

Nrm –Number of required machines or operators for a particular process
D_{yr} – Product annual demand
TPT_{img} –Total process time per image (refer to section 3.7)
$N\mathit{day}_{yr}$ –Number of working days per year
$N\mathit{hrs}_{day}$ –Number of working hours per day
$Nimg_{hr}$ – Number of required images per hour

3.9 Labor Cost

The labor cost can be classified in two ways: Direct and Indirect

- Direct labor refers to the time an operator spends processing an image, panel, batch, etc. in a particular process. It is assumed that in a manual operation an employee participates in almost all the operations of the process.
- Indirect labor refers to the time spent by operators that are required to setup and maintain a group of processes in a facility but that do not participate directly in the assembly of a unit of product.

All labor cost equations in the *Mendez* model, which are presented in Appendix B can be generalized in Equation 14 and Equation 15. It must be emphasized that Equation 15 differs from *Mendez* because the equation proposed in the model does not consider the fact of having unbalanced group of processes.

The direct labor of a process is calculated using Equation 14.

Equation 14 Direct Labor Cost per image in a process

$$DLC_{img} = \sum_{i=0}^{n} OPT(i)_{img} * Rate_{hr} NOP$$

DLC_{img} = Direct labor cost per image in a process
OPT = Time of the (i) operation where labor is required. The operations applicable to each process are: Setup, Loading, Process, Unloading and Travel and Special Events.
$\$Rate_{hr}$ –Average assembly hourly wage rate
NOP= Number of operators required in a process

The indirect labor cost per image in a group of processes is implemented using Equation 15 and is shown below.

Equation 15 Indirect Labor Cost per image in a group of processes

$$ILC_{img} = \max(TPT_{img})_i * NpGroup * \$Rate_{hr} * NO$$

ILC_{img} = Indirect labor cost per image in a group of processes
$(TPT_{img})_i$ –Total process time per image of a process which belongs to the group i.
$\$Rate_{hr}$ –Average assembly hourly wage rate
NpGroup= Number of processes in a particular group who required indirect labor.
NO= Number of operators in that group of processes

3.10 Equipment Cost per image in a process

The equipment cost equations in *Mendez* model, which are presented in Appendix B can be summarized in Equation 16. It should be noted that the cost of equipment is calculated before taxes.

Equation 16 Equipment Cost per image in a process

$$EC_{img} = \frac{IC^*\left[\frac{MARR * (1 + MARR)^{MEL}}{(1 + MARR)^{MEL} - 1}\right] - SV^*\left[\frac{MARR}{(1 + MARR)^{MEL - 1}}\right]}{D_{yr}}$$

where,

EC_{img} = Equipment cost per image
P = the present value is the initial cost (IC) of the machine

F = the future value is the salvage value (SV) of the machine

MARR = the interest rate is the MARR established by the company representing the expected profit percentage from capital investments

MEL= Machine estimated life

IC= Machine initial cost

A/P= Annualize given a present value
MARR= Minimum acceptable rate of return
SV= Machine salvage value
A/F = Annualize given a future value
D_{yr} = Annual demand

3.11 Consumables Material Cost per image in a process

The consumables cost equation in *Mendez* model, which are presented in Appendix B and the variations of the material costs considered for this research can be summarized in Equation 17:

Equation 17 Material Cost per image in a process

$$MaterialC_{img} = \frac{MaterialC * Material * \sum_{i=1}^{NPN} QPN_i}{Nimg_{pl} * Npl_{bh}}$$

where,

$MaterialC_{img}$ = Material Cost per image in a process
MaterialC = Cost of the Material that is used in a process. Its units will depend on the consumption made
Material = Material consumption per image in a particular process
QPN_i = Quantity of a particular Part Number

With the general Equation 17, the variations presented in Table 6 will allow the implementation of the consumables cost.

Table 7 Variations or special cases of consumables material costs

Total Number of boards benefiting from a material consumable Occurrence	**Comments**	**Resulting Equivalent Equation**	**Sample Process where Equation is applied**
Quantity of Part Numbers Processed	In this variation, $Nimg_{pl}$ and Npl_{bh} is 1 and Material consumption is per component.	$MaterialC_{cp} * Material_{cp} ** \sum_{PN_{i=1}}^{PN_i} QPN_i$	Auto Insertion DIP
Batch	In this variation, Material consumption is per component	$\frac{MaterialC_{bh} * Material_{bh}}{Nimg_{pl} * Npl_{bh}}$	Suitable to occur in new processes

Total Number of boards benefiting from a material consumable Occurrence	Comments	Resulting Equivalent Equation	Sample Process where Equation is applied
Panel	In this variation, Npl_{bh} is 1 and Material consumption is per component is per panel	$\frac{MaterialC_{pl} * Material_{pl}}{Nimg_{pl}}$	Suitable to occur in new processes
Image	In this variation, $Nimg_{pl}$ and Npl_{bh} is 1 and Material consumption is per image	$MaterialC_{img} * Material_{img}$	Suitable to occur in new processes
Not Apply	In this case, material is not needed	0	Suitable to occur in new processes

3.12 Utilities Cost

A major overhead cost is related to utilities consumption. It is assumed that the consumption of utilities is directly proportional to the time that a board requires in a process. In *Mendez* model, the utilities considered were Electricity, Water and Nitrogen. All the utilities in *Mendez* model, which are presented in Appendix B can be summarized in Equation 18.

Equation 18 Utility Cost per image

$$UtilityC_{img} = Utility\ Consumption * UtilityC * \sum_{i=0}^{n} OPT(i)_{img}$$

where,

Utility Cost $_{img}$ = Utility Cost per image in a process
Utility Consumption = Utility consumption in units.
UtilityC= Utility cost per hour
OPT = Time of the (i) operation where the utility is used. The operations applicable to each process are: Setup, Loading, Process, Unloading and Travel.

3.13 Space Cost

There are some overhead expenses that are either fixed amounts or variable amounts not assigned directly to any product. In order to be able to allocate this cost to every unit produced, a space allocation cost was proposed in *Mendez* model. The typical overhead costs identified under this category were the following: heating, ventilation and air conditioning, illumination and building rent. Considering the space required by each of these processes, the cost allocation can be made.

The space for each process was expressed as the required area for a process. If the process uses machines, the space per machine is needed. If the process is manual, the required space by operator is needed. A space allowance factor related to aisles and space between areas must be used when calculating the total required area for all processes.

Finally, the total required square feet per process, the cost per square feet of each overhead cost identified above, and the annual demand are needed for the formulation of the space dependent overhead cost per board in a process. This formulation does not include the required space for other areas such as offices, warehouses, etc. The space costs equation from *Mendez* model, which are presented in Appendix B can be summarized in Equation 19.

Equation 19 Space Cost per image in a process

$$\text{SpaceC}_{\text{img}} = \frac{\left[\text{Space}*(1+\text{SpaceFactor})\right]\left(\sum_{i=0}^{n}\$\text{SOE}_i\right)}{D_{yr}}$$

where,

$\text{SpaceC}_{\text{img}}$ = Space cost per image in a process
Space = Number of Square feet used by a process.
Factor= Space (aisles, etc. allowance factor)

$\$SOE_i$ = Cost of the (i) overhead expense justified by space use.
D_{yr} = Annual demand

3.14 Components and Image Cost

The components cost and image cost equations in *Mendez* model can be summarized in Equation 20, Equation 21 and Equation 22. These equations were the same used in *Mendez* model.

Equation 20 Total Components Cost per image

$$TCC_{img} = \sum_{i=1}^{NPN} TPNC_i$$

Equation 21 Total Part number i cost

$$TPNC_i = QPN_i * PNC_i$$

Equation 22 Image Cost

$$TIC_{img} = \frac{TPC_{pl}}{Nimg_{pl}}$$

where,

TCC_{img} = Total Components Cost per image
$TPNC_i$ = Total Part number *i* cost
PNC_i = Part number *i* cost
QPN_i = Quantity of Part Number *i*
NPN = Number of components part numbers
PNC_i = Cost per component of part number *i*
TIC_{img}=Total Image cost
TPC_{pl} = Panel Cost
Nimgpl = Number of images per panel

3.15 Manufacturing Lead Time and Support Personnel Cost per image

Support Personnel Cost refers to the cost that is allocated to a product to account for the time that Administrative Personnel, Engineers, etc. dedicate to the assembly of the

PCB's. The calculation of the Support Personnel Cost was made using the equation provided in *Mendez* model, which are presented in Appendix B and can be summarized in Equation 23. To calculate this cost, the lead time of a product is first calculated and then Equation 23 is implemented. In simple terms, lead time is calculated as the time it takes from start to finish to manufacture one unit of product.

Equation 23 Support Personnel Cost per image

$$TSUPC_{img} = \left(\frac{AvgSUPC_{yr} * Ntse}{D_{yr}} \right) * \left(MLT_{\frac{hrs}{img}} \right)$$

where,

$TSUPC_{img}$ = Total support personnel cost per image

Ntse= Number of technical support employees of the facility

$MLT_{hrs}/_{img}$ = Manufacturing lead time per image in hours

AvgSUPC = Average support personnel cost per year

3.16 Total Product Cost

$$TP\$ = \sum DLC_{img} + \sum ILC_{img} + \sum EC_{img} + \sum MaterialC_{img} + \sum UtilityC_{img} + \sum SpaceC_{img} + TCC_{img} + TIC_{img} + TSUPC_{img}$$

where,

DLC_{img} = Direct labor cost per image in a process (refer to section 3.9)
ILC_{img} = Indirect labor cost per group of processes (refer to section 3.9)
EC_{img} = Equipment cost per image (refer to section 3.10)
$MaterialC_{img}$ = Material Cost per image in a process (refer to section 3.11)

Utility Cost $_{img}$ = Utility Cost per image in a process (refer to section 3.12)

$SpaceC_{img}$ = Space cost per image in a process (refer to section 3.13)
TCC_{img} = Total Components Cost per image (refer to section 3.14)
TIC_{img}=Total Image cost (refer to section 3.1.15)
$TSUPC_{img}$ = Total support personnel cost per image (refer to section 3.16)

4.0 APPLICATION CONCEPTUAL STRUCTURE AND DATABASE DESIGN

The initial motivation of this research was to generalize the cost model application of *Mendez* and generate a computer application to estimate the cost of the new power electronics systems and products that are being developed assuming that the new technologies could be described with the generalized model developed in this research. Chapter 3 presented the generalization of Mendez model and in this chapter the conceptual structure of the application developed will be explained. To do that and obtain a better understanding of the conceptual structure of the application, it is necessary to describe the following terms:

1) **Manufacturing facility –**refers to a physical place where there are processes to manufacture product(s).

2) **Processes**- individual activities or steps needed to manufacture products. Processes are contained within a determined facility.

3) **Part Number**- refers to a unique component or part. A number that is assigned to identify and differentiate parts of a product.

4) **Product-** any finished item ready to be used for its intended purpose. It is composed of several components of part numbers.

5) **Component type-** designation that reflects the characteristics of a component and its assembly requirements. It is a method to associate part numbers to processes.

The basic requirements of the cost model application to be developed consider the following issues.

1) **User creation –** The reason to create users in an application is to secure the information and analysis made by each user in the application. Before a user can access the application it needs to be registered. The information gathered includes a username and a password. The application will have two types of users. The first one of them is a Product Developer/ Designer and the other is a Process Engineer. The difference between each user is that a Product Developer/Designer is usually interested in the cost estimation of new designs that are being generated while a process engineer is usually seeking how to calculate the cost of the existing products in its facility and how to improve the efficiency of its processes to reduce the cost of its products.

2) **Default facility –** a default facility refers to a generic or virtual facility containing the typical processes found on the electronics industry to estimate the cost of new electronic designs. The reason to create a default facility is to allow users the cost estimation of products without having a real facility defined. The processes considered for the default facility will be those contained in the *Mendez* assembly cost model. These processes are detailed in Appendix A. The costs and times included on the facility must be typical to represent the actual electronics industry.

3) **Facility creation-** the application has been prepared to permit the creation of new facilities. This feature is useful for the electronic designer when there is knowledge of a specific facility where the assembly may take place. It will provide a more accurate cost estimate of the products being developed. This feature will also allow process engineers of a facility to register the real facility in the application and calculate the cost of assembling products in this particular facility. This may be very useful to a process engineer because it allows the evaluation of the activities in the processes of a particular facility and focus on those that could reduce the cost of a product. The feature could also benefit electronic designers, planners and people from the top level of a company to evaluate the facility that could manufacture new designs at the lowest cost.
4) **Processes creation –** the application will provide the capability to add new processes to the application. All the research made so far has not considered the situation when new technologies or processes are created to manufacture and estimate the cost of electronic products. The application also has by default the typical processes found on the electronics industry that were discussed in *Mendez* model and were described in Appendix A.
5) **Components Catalog –** the application will contain a components catalog that will allow users to register part numbers in the application. Once the part numbers are registered, they can be used in product designs to calculate cost.

To implement the requirements presented above, it was necessary to design a database. Its purpose was to maintain data grouped, organized and stored in a safe place.

A relational database is easy to operate and install making it simple to be integrated with other database management systems (DBMS). For the purpose of this project, the database was developed in Microsoft Access 2003. Although there are other DBMS such as Microsoft SQL Server or Oracle that are more robust and powerful that MS Access, these are considerably more expensive and required extensive operational knowledge.

The relationship diagram of the designed database is shown in **Figure 4**. The structure of the tables and the relationship among them are explained next. The database has been designed to facilitate data management and become a valuable information holder. The structure of the database was constructed using the relational database model. This model offers independence for managing and organizing data in the system, because it can alter the structure of the data without altering the programs, and facilitates the exchange of information through tables. In general, 21 tables were built into a database. The content and information management is described in detail next. Each table and its attributes are explained below and the fields that are not familiar are defined.

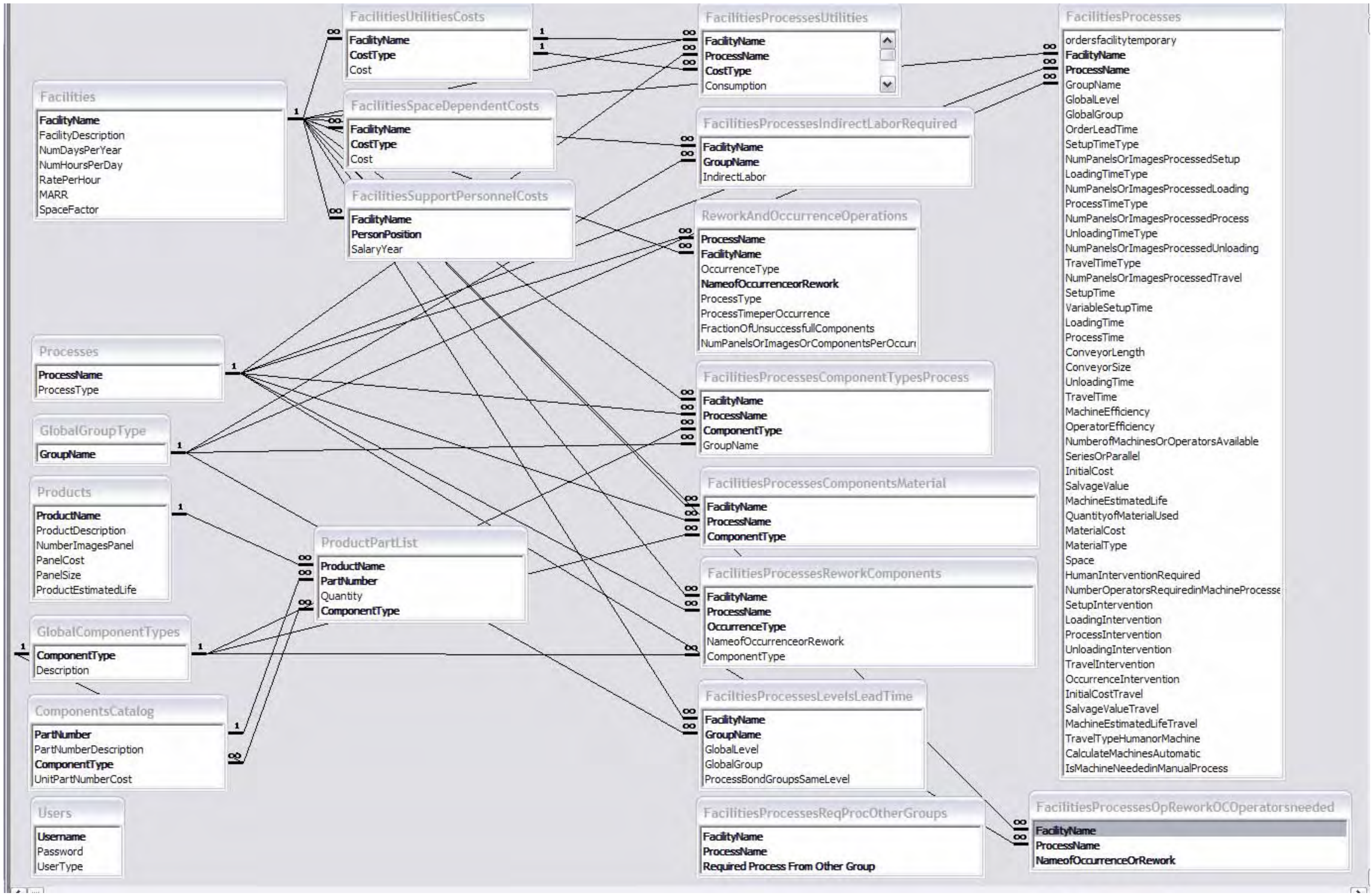


Figure 4 Entity Relationship Diagram of Designed Database

4.1 Users table

This table contains the registered users of the application and its design is shown in Table 8.

Table 8 Design of Users table

Primary Key?	Field Name	Data Type	Description
Yes	Username	Text	This field contains the username of a user.
Yes	Password	Text	This field contains the password of a user.
No	User Type	Text	The types of user available are: Product Developer/Designer or Process Engineer

A snapshot of this table is shown in Table 9.

Table 9 Users Table

Users		
Username	**Password**	**User Type**
GEO	123	PRODUCT DEVELOPER/DESIGNER
GEO2	1234	PROCESS ENGINEER
LAURA	LAURA	PRODUCT DEVELOPER/DESIGNER

4.2 Facilities table

This table contains the general characteristics of a facility. The default facility of the application is already defined. Its design is shown on Table 10.

Table 10 Design of Facilities table

Primary Key?	Field Name	Data Type	Description
Yes	Facility Name	Text	This field contains the name of a facility.
No	Facility description	Text	This field contains the description of a facility.
No	Num Days Per Year	Integer Number	It refers to the number of working days per year. This field cannot have a number greater than 365 or less than 1.

Primary Key?	Field Name	Data Type	Description
No	Num Hours Per Day	Double Number	It refers to the number of working hours per day. It must be greater than 0 and at most 24.
No	Rate Per Hour	Double Number	Average rate of operators (in $)
No	MARR	Double Number	It refers to the Minimum Attractive Rate of Return. Is a number greater than 0 and less or equal to 1.
No	Space factor	Double Number	The space factor is used to allocate aisle space, etc of the facility to each process. It is a percentage allocated to each process to account for spaces that are not directly related to a particular process.

A snapshot showing part of this table is on Table 11.

Table 11 Part of the facilities table

Facilities						
Facility Name	**Facility Description**	**Num Days Per Year**	**Num Hours Per Day**	**Rate Per Hour**	**MARR**	**Space Factor**
ABC	COMPUTERS	248	8	7.44	0.15	1
DEFAULT FACILITY	DEFAULT FACILITY	252	8	10	0.15	1

4.3 Facilities Space Dependent Costs table

This table contains the costs of the utilities that are measured in terms of space and that usually cannot be attributed to any product in particular. The typical ones to be used are: Heating and Ventilation, Building and Rent and Illumination. These space dependent costs were the ones considered in *Mendez* research. The design of this table is presented in Table 12.

Table 12 Design of Facilities space dependent costs table

Primary Key?	Field Name	Data Type	Description
Yes	Facility Name	Text	This field contains the name of a facility.
Yes	Cost Type	Text	It refers to the type of cost specified.
No	Cost	Currency	The cost of this field must be specified in dollars/square feet-year. As an example, building rent must be specified in $/square feet-year.

A snapshot of this table is shown in Table 13.

Table 13 Facilities space dependent costs

Facilities Space Dependent Costs		
Facility Name	**Cost Type**	**Cost**
DEFAULT FACILITY	Heating and Air Conditioning	$0.07
DEFAULT FACILITY	Lightning	$0.02

4.4 Facilities Support Personnel Costs table

This table contains the salary of all the support personnel of a facility. These salaries are used to calculate the support personnel cost of a product. The attributes of this table are shown in Table 14.

Table 14 Design of the Facilities Support Personnel table

Primary Key?	Field Name	Data Type	Description
Yes	Facility Name	Text	This field contains the name of a facility.
Yes	Person Position	Text	It refers to the position of the support or administrative employee.
No	Salary Year	Currency	It refers to the annual salary of a support or administrative employee.

A snapshot of this table is shown in Table 15.

Table 15 Support personnel costs

Facilities Support Personnel Costs		
Facility Name	**Person Position**	**Salary Year**
DEFAULT FACILITY	Process Engineer	$50,000.00
DEFAULT FACILITY	Process Technician	$55,000.00
DEFAULT FACILITY	Product Engineer	$50,000.00
DEFAULT FACILITY	Supervisor	$27,000.00

4.5 Facilities Utility Costs table

This table contains all the utility costs of the facility. The utility costs will vary to each facility, the typical ones being: Electricity, Water and Nitrogen. These utilities were the ones considered in *Mendez* research. The attributes of this table are shown in Table 16.

Table 16 Design of Facilities Utility Costs table

Primary Key?	Field Name	Data Type	Description
Yes	Facility Name	Text	This field contains the name of a facility.
Yes	Cost Type	Text	It refers to the type of cost specified.
No	Cost	Currency	This field contains the cost of the utility in $/unit*hour. As an example consider the cost of electricity which is charged in $/kilowatt*hour

A snapshot of this table is shown in Table 17.

Table 17 Facilities utilities table

Facilities Utilities Costs		
Facility Name	**Cost Type**	**Cost**
DEFAULT FACILITY	Electricity	$2.00
DEFAULT FACILITY	Nitrogen	$1.00
DEFAULT FACILITY	Water	$1.00

4.6 Processes table

This table is special because it contains by default all the processes that are found in today's electronic environment and its type. The default facility of the application has these processes defined to calculate the cost of products. Its attributes are explained in Table 18.

Table 18 Design of Processes table

Primary Key?	Field Name	Data Type	Description
Yes	Process Name	Text	This field contains the name of a process.
No	Process Type	Text	This field contains the type of a process. This concept will be explained below.

Process type refers to a method defined in this research to see if the process is manual, done by a machine or a conveyor. Typical examples of these types of processes in the electronics environment are: Manual Insertion of THT, Solder Paste Printing and Reflow Oven, etc. The type of process types available to add are: Conveyor, Machine or Manual. The idea of the process type is to use a specific input form in the application where the proper factors are supplied to the database. A snapshot of this table is presented in Table 19 where all the default processes that are included in the default facility of the application are shown in Table 19.

Table 19 Processes table

Processes	
Process Name	**Process Type**
AUTO INSERTION DIP	MACHINE
AUTO INSERTION VCD	MACHINE
BIN UP	MANUAL
CHIP ON BOARD WIRE BONDING	MACHINE
CHIP SHOOTER	MACHINE
CHIP SHOOTER BOTTOM	MACHINE
CIRCUIT TEST	MACHINE
FINAL ASSEMBLY	MANUAL
FINAL INSPECTION	MANUAL

Processes	
Process Name	**Process Type**
FINE PITCH PLACEMENT	MACHINE
FUNCTIONAL TEST	MACHINE
GLUE APPLICATION	MACHINE
GLUE APPLICATION BOTTOM	MACHINE
KIT SEGREGATION	MANUAL
MANUAL ASSEMBLY OF SMT	MANUAL
MANUAL INSERTION OF THT	MANUAL
PANEL PREPARATION	MANUAL
PREFORMING	MACHINE
REFLOW OVEN BOTTOM	CONVEYOR
REFLOWOVEN	CONVEYOR
ROUTING AND SINGULATION	MACHINE
SEQUENCER	MACHINE
SMT VISUAL INSPECTION	MANUAL
SMT VISUAL INSPECTION BOTTOM	MANUAL
SOLDER PASTE PRINTING	MACHINE
TOUCH UP	MACHINE
WAVE SOLDER	CONVEYOR

4.7 Facilities Processes table

This table contains all the processes contained in a facility. The attributes of the table are specified in Table 20.

Table 20 Design of Facilities Processes table

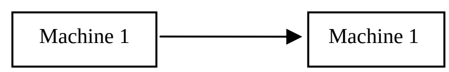
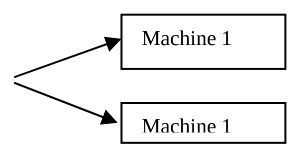
Primary Key?	Field Name	Data Type	Description
Yes	Facility Name	Text	This field contains the name of a facility.
Yes	Process Name	Text	This field contains the name of a process.
No	Group Name	Text	This will be explained in more detail below.
No	Global Groups	Integer Number	This will be explained in more detail below.
No	Level	Integer Number	This will be explained in more detail below.

Primary Key?	Field Name	Data Type	Description
No	Order Lead Time	Integer Number	This field contains the order in which the processes in a global group are carried out. The explanation of why this filed is important will be presented in section 5.15.
No	Setup Time Type	Text	This field is used to specify the setup time variation or special case that applies to a process. Those variations were discussed in Section 3.1
No	Num Panels Or Images Processed Setup	Text	An input that is required if the setup time variation is set to Group of Panels Processed Simultaneously or Group Images Processed Simultaneously. It can contain Integer numbers and the text “Not Apply”. It refers to the number of panels or images that are processed in the setup activity simultaneously.
No	Loading Time Type	Text	This field is used to specify the loading time variation or special case that applies to a process. Those variations were discussed in Section 3.2
No	Num Panels Or Images Processed Loading	Text	An input that is required if the loading time variation is set to Group of Panels Processed Simultaneously or Group Images Processed Simultaneously. It can contain Integer numbers and the text “Not Apply”. It refers to the number of panels or images that are processed in the loading activity simultaneously.
No	Process Time Type	Text	This field is used to specify the process time variation or special case that applies to a process. Those variations were discussed in Section 3.3.
No	Num Panels Or Images Processed Process	Text	An input that is required if the process time variation is set to Group of Panels Processed Simultaneously or Group Images Processed Simultaneously. It can contain Integer numbers and the text “Not Apply”. It refers to the number of panels or images that are processes in the process activity simultaneously.

Primary Key?	Field Name	Data Type	Description
No	Unloading Time Type	Text	This field is used to specify the unloading time variation or special case that applies to a process. Those variations were discussed in Section 3.4
No	Num Panels Or Images Processed Unloading	Text	An input that is required if the unloading time variation is set to Group of Panels Processed Simultaneously or Group Images Processed Simultaneously. It can contain Integer numbers and the text "Not Apply". It refers to the number of panels or images that are processes in the unloading activity simultaneously.
No	Travel Time Type	Text	This field is used to specify the travel time variation or special case that applies to a process. Those variations were discussed in Section 3.5. It refers to the number of panels or images that are processed in the travel activity simultaneously.
No	Num Panels Or Images Processed Travel	Text	An input that is required if the travel time variation is set to Group of Panels Processed Simultaneously or Group Images Processed Simultaneously. It can contain Integer numbers and the text "Not Apply"
No	Setup Time	Double Number	This field contains the fixed amount of setup time applied to a process if the setup time variation of section 3.1 is not "Not Apply". This field must be specified in minutes if apply.
No	Variable Setup Time	Double Number	This field contains the variable setup time of a process. It applies only when the setup time variation chosen is set to Complete Production (Batch) with variable time for components to be processed. This field must be specified in minutes if apply.
No	Loading Time	Double Number	This field contains the loading time of a process if the loading time variation of section 3.2 is not set to "Not Apply". This field must be specified in minutes if apply.

Primary Key?	Field Name	Data Type	Description
No	Process Time	Double Number	This field contains the process time of a process if the process time variation of section 3.3 is not set to "Not Apply" and the process type on the table "Processes" is not set to "CONVEYOR". This field must be specified in minutes if apply.
No	Conveyor Length	Double Number	This field contains the length of a conveyor if the process type on the table "Processes" is set to "CONVEYOR". This field must be specified in feet if apply.
No	Conveyor Speed	Double Number	This field contains the speed of a conveyor if the process type on the table "Processes" is set to "CONVEYOR". This field must be specified in feet/minute if apply.
No	Separation Distance Between Panels or Images	Double Number	This field contains the separation distance between panels or images when a panel or image is being processed in a conveyor. This field applies if the process type on the table "Processes" is set to "CONVEYOR".
No	Unloading Time	Double Number	This field contains the unloading time of a process if the loading time variation of section 3.4 is not set to "Not Apply". This field must be specified in minutes if apply.
No	Travel Time	Double Number	This field contains the travel time of a process if the loading time variation of section 3.4 is not set to "Not Apply". This field must be specified in minutes if apply.
No	Separation Distance Between Panels or Images Travel	Double Number	This field contains the separation distance between panels or images when a panel or image is being transferred to another process by a conveyor. This field applies if the travel time variation is from a conveyor.

Primary Key?	Field Name	Data Type	Description
No	Machine Efficiency	Double Number	It is the machine's run time versus available time. So, a machine that was down two hours of an eight-hour shift has a 75% Machine Efficiency. It is a number > 0 and <= 1.
No	Operator Efficiency	Double Number	It is the operator’s production time versus available time. So, an operator that had one hour of lunch of an eight-hour shift has 87.5% operator efficiency. It is a number > 0 and <= 1.
No	Number of Machines Or Operators Available	Text	It refers to the number of operators or machines that are required in a process. The specification depends on which Process Type was specified in the table “Processes”. If Process Type is “MACHINE” or “CONVEYOR”, the number of machines must be specified. If the Process Type is specified as “MANUAL” then the number of operators required must be specified.

Primary Key?	Field Name	Data Type	Description
No	Series Or Parallel	Text	This field is used when the number of machines or operators in a process is greater than one. Only two values can be chosen. These are: Series or Parallel. **SERIES-** refers to machines that are one next to the other as in the following diagram. In this case a unit needs to be processed by the first Machine 1 in order to be processed by the second Machine 1.  **PARALLEL-** it refers to the following diagram. In this case the incoming product can be processed by either one of the Machines 1 
No	Is Machine Needed in Manual Process?	Text	This field contains a "YES" or "NO" text depending on the option chosen by the user. The user must specify if a machine is needed in a process which its "Process Type" was set to "MANUAL" in the table Processes.
No	Initial Cost	Double Number	This field contains the initial cost of a machine in dollars if the process type of a process is set to "MACHINE" or "CONVEYOR" or if the field "Is Machine Needed in Manual Process?" is set to "YES"

Primary Key?	Field Name	Data Type	Description
No	Salvage Value	Double Number	This field contains the salvage value cost of a machine in dollars if the process type of a process is set to "MACHINE" or "CONVEYOR" or if the field "Is Machine Needed in Manual Process?" is set to "YES". Salvage Value It refers to the value of a machine at the end of its useful life.
No	Machine Estimated Life	Double Number	This field contains the machine estimated life of a machine (in years) if the process type of a process is set to "MACHINE" or "CONVEYOR" or if the field "Is Machine Needed in Manual Process?" is set to "YES". Salvage Value It refers to the value of a machine at the end of its useful life.
No	Material Type	Text	This field is used to specify the consumables material cost variation or special case that is applied to a process. Those variations were discussed in section 3.11
No	Material Cost	Double Number	This field contains the cost of material in $/unit if the variation of the equation presented in section 3.11 is not set to "Not Apply". As an example consider the cost of solder paste in the process Solder Paste Printing as $.0065/gram.
No	Quantity of Material Used	Double Number	This field is an input that is required if the consumables material cost of section 3.11 is not "Not Apply". It refers to the quantity of material that is used in a process. As an example, the quantity of solder paste used is .00025 gram/ component.
No	Space	Double Number	This field is required if space dependent costs are defined on the table "Facilities Space Dependent Costs". If required, space must be provided in square feet.

Primary Key?	Field Name	Data Type	Description
No	Human Intervention Required	Text	This field is used to specify the type of labor that is required in a process whose process type in the table Processes is set to “MACHINE” or “CONVEYOR”. This field contains the following options “YES”, “NO”, PARTIAL, INDIRECT and PARTIAL AND INDIRECT. “YES” means that operator(s) are required to operate the machine. “NO” means that operators are not required on this machine. “PARTIAL” means that operator or operators are needed in some of the activities of the process. INDIRECT- this means that operators are required to maintain a group of processes and that this process is included on those. PARTIAL AND INDIRECT- this is a combination of the two options previously presented.
No	Number Operators Required in Machine Processes	Integer Number	This field is required if the Process Type in the table “Processes” is set to “MACHINE” or “CONVEYOR” and the field “Human Intervention Required” in this table is set to “YES”, “PARTIAL” OR “PARTIAL AND INDIRECT”.
No	Setup Intervention	Text	This field is required if the field “Human Intervention Required” in this table is set to “PARTIAL” OR “PARTIAL AND INDIRECT”. It is used as a “YES” or “NO” decision that is used to specify if an operator is required in the setup operation of a process.
No	Loading Intervention	Text	This field is required if the field “Human Intervention Required” in this table is set to “PARTIAL” OR “PARTIAL AND INDIRECT”. It contains a “YES” or “NO” decision that is used to specify if an operator is required in the loading operation of a process.

Primary Key?	Field Name	Data Type	Description
No	Process Intervention	Text	This field is required if the field “Human Intervention Required” in this table is set to “PARTIAL” OR “PARTIAL AND INDIRECT”. It contains a “YES” or “NO” decision that is used to specify if an operator is required in the process operation of a process.
No	Unloading Intervention	Text	This field is required if the field “Human Intervention Required” in this table is set to “PARTIAL” OR “PARTIAL AND INDIRECT”. It contains a “YES” or “NO” decision that is used to specify if an operator is required in the unloading operation of a process.
No	Travel Intervention	Text	This field is required if the field “Human Intervention Required” in this table is set to “PARTIAL” OR “PARTIAL AND INDIRECT”. It contains a “YES” or “NO” decision that is used to specify if an operator is required in the travel operation of a process.
No	Rework or Occurrence Intervention	Text	This field is required if the field “Human Intervention Required” in this table is set to “PARTIAL” OR “PARTIAL AND INDIRECT”. It contains a “YES” or “NO” decision that is used to specify if an operator is required in the special operations of a process. If “YES” is specified, the operations where the operators participate must be specified in the table “Facilities Processes Op Rework OC Operators needed” which will be presented later.
No	Travel Type Human or Machine	Text	This field is used to specify if a machine or operator is needed to move a panel, image, etc of a PCB to another process. This field is required if the travel time variations presented in section 3.5 is not set to “Not Apply”. It will contain the following options: “MACHINE” or “MANUAL”.

Primary Key?	Field Name	Data Type	Description
No	Initial Cost Travel	Double Number	This field contains the initial cost of a machine in dollars if the travel variation of a process is set to “CONVEYOR” or the field “Travel Type Human or Machine” is set to “MACHINE”.
No	Salvage Value Travel	Double Number	This field contains the initial cost of a machine in dollars if the travel variation of a process is set to “CONVEYOR” or the field “Travel Type Human or Machine” is set to “MACHINE”. Salvage Value refers to the value of a machine at the end of its useful life.
No	Machine Estimated Life Travel	Double Number	This field contains the machine estimated life (in years) of a machine if the travel variation of a process is set to “CONVEYOR” or the field “Travel Type Human or Machine” is set to “MACHINE”.
No	Calculate Machines, Conveyors or Operators Automatic	Text	This field contain a “YES” or “NO” decision that if specified to “YES” it is used to calculate the number of machines, conveyors or operators that are required in an operation.

The Group Name, Global Groups, and Level fields will be explained through an example because these concepts have been developed in this research to implement *Mendez* model in a computer application. The concept of a group will be explained first. Suppose that a new facility has been created and that the processes registered in this facility are those shown on Figure 5.

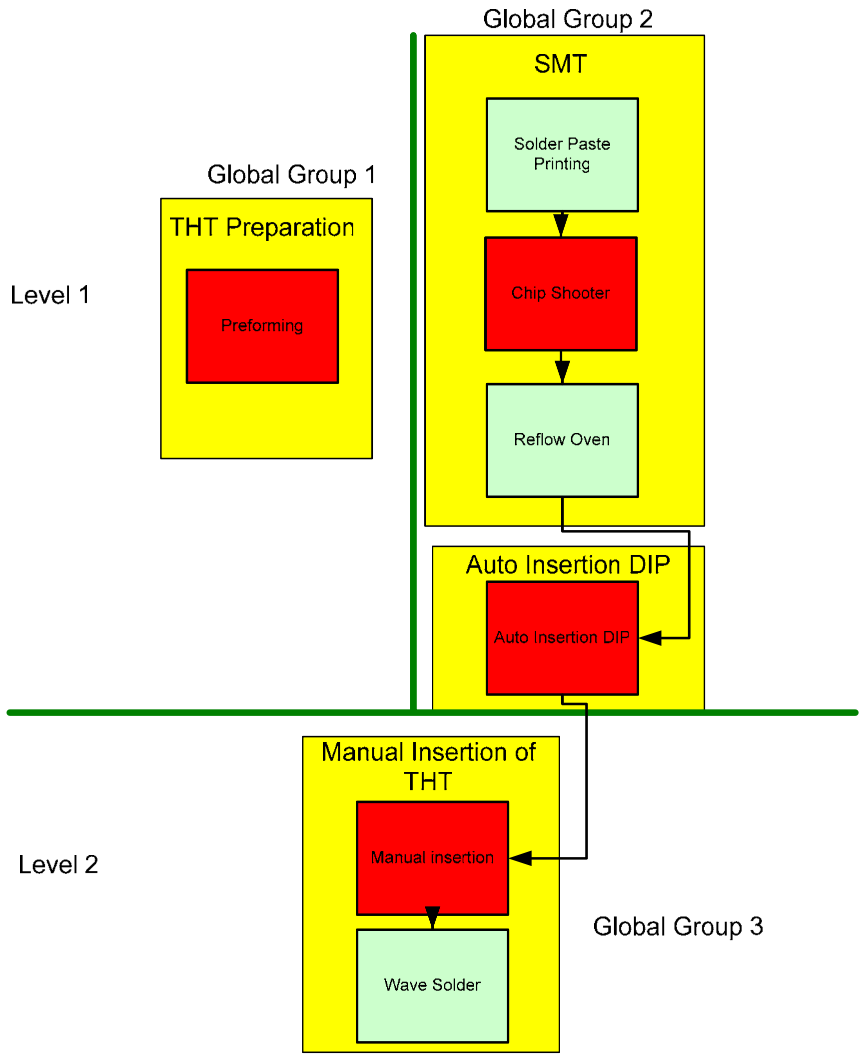


Figure 5 Sample facility to explain field's concept

The processes Preforming, Chip Shooter and Manual Insertion are painted in red because they are the only ones that locate, insert or deal directly with components of a product. It is also assumed that the component types that can be handled in each process respectively are THT, Non Fine Pitch, and THT. Let's suppose also that a product has been designed and the types of part numbers required by this product are THT and Non Fine Pitch. The first thing to do to calculate the cost of a product is to locate those processes needed to assemble these components. The next thing to do is to find the processes that complement these processes. Complementary processes refer to those processes that are needed when a particular process that locate or insert components is needed. The method used to find the complementary processes in the cost model application developed is associating processes by defining groups. In this case, the complementary processes of the Chip Shooter process are Solder Paste Printing and Reflow Oven and are all assembled in a yellow box in Figure 5. with the name SMT. In this case the name SMT refers to the group of processes Solder Paste Printing, Chip Shooter and Reflow Oven.

The second and third concepts to be explained will be Global Groups and Levels. These concepts are introduced in this research to calculate the lead time of a product. In section 3.12 the lead time of a product was needed to calculate the support personnel cost allocated to a product. We will proceed to explain these concepts using Figure 5. It can be seen in Figure 5 that a green horizontal and vertical line divide processes or group of processes. The vertical line represents the division of processes or group of processes that can be made simultaneously. In this case, the maximum of the times in each global group is used to calculate the lead time of a product. Basically the concept of a global group is used to find the maximum time that will take to different group of processes which can be made simultaneously to be included in the lead time of a product. The concept of a level is defined to establish the order in which the sequential order of group of processes is carried out. In Figure 5 the sum of the times at each level represents the lead time of a product.

A snapshot of part of this table is shown in Table 21.

Table 21 Part of the Facilities Processes table

Facilities Processes						
Facility Name	**Process Name**	**Group Name**	**Global Level**	**Global Group**	**Order Lead Time**	**Setup Time Type**
DEFAULT FACILITY	SOLDER PASTE PRINTING	SMT TOP	1	2	0	NOTAPPLY
DEFAULT FACILITY	CHIP SHOOTER	SMT TOP	1	2	2	NOTAPPLY
DEFAULT FACILITY	GLUE APPLICATION	SMT TOP	1	2	1	NOTAPPLY
DEFAULT FACILITY	FINE PITCH PLACEMENT	SMT TOP	1	2	3	NOTAPPLY
DEFAULT FACILITY	MANUAL ASSEMBLY OF SMT	SMT TOP	1	2	4	NOTAPPLY
DEFAULT FACILITY	REFLOWOVEN	SMT TOP	1	2	5	NOTAPPLY
DEFAULT FACILITY	SMT VISUAL INSPECTION	SMT TOP	1	2	6	NOTAPPLY

4.8 Facilities Processes Utilities

This table contains all the utility consumptions of a process that belongs to a particular facility. The attributes of this table are presented in Table 22.

Table 22 Facilities Processes Utilities table

Primary Key?	Field Name	Data Type	Description
Yes	Facility Name	Text	This field contains the name of a facility.
Yes	Process Name	Text	This field contains the name of a process.
No	Cost Type	Text	It refers to the name of the utility in a process.
No	Consumption	Double Number	Refers to the quantity used by a process. As an example, the consumption of electricity in a machine depends on the voltage and current requirements of a machine and it must contain the same units used in the "Facilities Utility Costs" table.

Primary Key?	Field Name	Data Type	Description
No	Setup participation	Text	This field will only have a "YES" or "NO" decision to specify if a utility is required in the setup operation of a process.
No	Loading participation	Text	This field will only have a "YES" or "NO" decision to specify if a utility is required in the loading operation of a process.
No	Process participation	Text	This field will only have a "YES" or "NO" decision to specify if a utility is required in the process operation of a process.
No	Unloading participation	Text	This field will only have a "YES" or "NO" decision to specify if a utility is required in the unloading operation of a process.
No	Travel participation	Text	This field will only have a "YES" or "NO" decision to specify if a utility is required in the travel operation of a process.

A snapshot showing part of this table is shown in Table 23.

Table 23 Facilities Processes Utilities table

Facilities Processes Utilities					
Facility Name	**Process Name**	**Cost Type**	**Consumption**	**Setup Participation**	**Loading Participation**
DEFAULT FACILITY	AUTO INSERTION VCD	Electricity	3	YES	YES
DEFAULT FACILITY	CHIP ON BOARD WIRE BONDING	Electricity	.025	YES	YES
DEFAULT FACILITY	CHIP SHOOTER	Electricity	10	YES	YES
DEFAULT FACILITY	CHIP SHOOTER BOTTOM	Electricity	10	YES	YES

4.9 Facilities Processes Indirect Labor Required table

This table contains all the processes in a facility that requires indirect labor. Indirect labor was defined previously to be the quantity of operators that are assigned to maintain up and running a group of processes. The attributes are shown on Table 24 .

Table 24 Design of the Facilities Processes Indirect Labor Required table

Primary Key?	Field Name	Data Type	Description
Yes	Facility Name	Text	This field contains the name of a facility.
Yes	Group Name	Text	This field contains the name of a process.
No	Indirect Labor	Integer Number	This field refers to the number of operators that are assigned to various processes of a group simultaneously.

A snapshot of this table is shown in Table 25.

Table 25 Facilities processes indirect labor required

Facilities Processes Indirect Labor Required		
Facility Name	**Group Name**	**Indirect Labor**
DEFAULT FACILITY	MANUAL INSERTION	1
DEFAULT FACILITY	SMT TOP	1

5.10 Rework and occurrence operations table

This table contains all the planned and random special events that occur in a process of a facility. The attributes of this table are shown in Table 26.

Table 26 Design of the Rework and occurrence operations table

Primary Key?	Field Name	Data Type	Description
Yes	Facility Name	Text	This field contains the name of a facility.
Yes	Process Name	Text	This field contains the name of a process.
Yes	Name of Occurrence or Rework	Text	This field contains the name of a special event that is applied to a process in a facility.

Primary Key?	Field Name	Data Type	Description
No	Process Type	Text	This field contains the type of a special event that is applied to a process in a facility. The possible values can be “REWORK” or “OCCURRENCE” referring to the Predetermined or Random Special Events discussed in section 3.6.
No	Fraction Of Unsuccessful Components	Double Number	This field is required if the process type field of this table is set to “REWORK”. It refers to the defective rate of a component, image or panel in a product.
No	Num Panels Or Images Or Components Per Occurrence	Integer Number	This field is an input in section 3.6 used only when the special event occurs in panels or images.

A snapshot of part of this table is shown in Table 27.

Table 27 Rework and occurrence operations

Rework and Occurrence Operations					
Process Name	**Facility Name**	**Occurrence Type**	**Name of Occurrence or Rework**	**Process Type**	**Process Time per Occurrence**
GLUE APPLICATION	DEFAULT FACILITY	OCCURRENCE	Cleaning Glue Application Top	PANEL	5

4.11 Facilities Processes Component Types Process table

This table contains all the component types that a process in a facility can locate on an image. The attributes of this table are shown in Table 28.

Table 28 Design of Facilities Processes Component Types Process table

Primary Key?	Field Name	Data Type	Description
Yes	Facility Name	Text	This field contains the name of a facility.
Yes	Process Name	Text	This field contains the name of a process.

Primary Key?	Field Name	Data Type	Description
Yes	Component Type	Text	This field contains the type of component that can be assembled in a process. This concept was discussed previously in section 5.7.
No	Group Name	Text	This field contains the group name of a process in a facility. This concept was discussed previously in section 5.7.

A snapshot of this table is shown in Table 29.

Table 29 Facilities Processes Component Types Process

Facilities Processes Component Types Process			
Facility Name	**Process Name**	**Component Type**	**Group Name**
DEFAULT FACILITY	MANUAL ASSEMBLY OF SMT	SMTMANUAL	SMT TOP
DEFAULT FACILITY	SMT VISUAL INSPECTION	SMTNFP_TOP	SMT TOP

4.12 Facilities Processes Components Material table

This table contains all the type of components that need material in a particular process of a facility if the variation presented in section 3.11 is set to Quantity of Part Numbers Processed. As an example, consider the solder paste that is applied to a product that has SMT components. If a facility contains the process Solder Paste Printing and the cost of material depends on the quantity of components that require solder paste, this table will contain the type of components that require material on this process to allocate its cost. The attributes of this table are shown in Table 30.

Table 30 Design of Facilities Processes Components Material table

Primary Key?	Field Name	Data Type	Description
Yes	Facility Name	Text	This field contains the name of a facility.
Yes	Process Name	Text	This field contains the name of a process.

Primary Key?	Field Name	Data Type	Description
Yes	Component Type	Text	This field contains the type of component that can be assembled in a process. This concept was discussed previously.

A snapshot of this table is shown in Table 31.

Table 31 Facilities Processes Components Material

Facilities Processes Components Material		
Facility Name	**Process Name**	**Component Type**
DEFAULT FACILITY	SEQUENCER	VCD
DEFAULT FACILITY	SOLDER PASTE PRINTING	SMTNFP_TOP

4.13 Facilities Processes Rework Components table

This table contains all the type components that require rework on a particular process of a facility. The attributes of this table are shown in Table 32.

Table 32 Design of Facilities Processes Rework Components table

Primary Key?	Field Name	Data Type	Description
Yes	Facility Name	Text	This field contains the name of a facility.
Yes	Process Name	Text	This field contains the name of a process.
Yes	Name of Occurrence or Rework	Text	This field contains the name of a special event that is applied to a process in a facility.
No	Occurrence Type	Text	This field contains the group name of a process in a facility. This concept was discussed previously in section 5.7.
No	Component Type	Text	This field contains the type of component that can be assembled in a process. This concept was discussed previously in section 5.7.

A snapshot of this table is shown in Table 33.

Table 33 Facilities Processes Rework Components

Facilities Processes Rework Components				
Facility Name	**Process Name**	**Occurrence Type**	**Name of Occurrence or Rework**	**Component Type**
DEFAULT FACILITY	AUTO INSERTION DIP	REWORK	AUTO DIP COMPONENTS	DIP

4.14 Facilities Processes Required Processes from Other Groups table

The reason to create this table will be exposed with an example. Suppose that a facility has been created and that the processes registered are those shown on Figure 6. From the discussion presented in the section 5.7, the only two groups in this facility are: Auto Insertion DIP and Manual Insertion of THT. Let's also suppose that two products have been created and that the types of components of product 1 are THT and DIP. Product 2 only has DIP component types. From the discussion made about groups in the "Facilities Processes" table, product 1 will be processed by all the processes in this facility but product 2 will only be processed by the process Auto Insertion DIP. It is known from the electronics industry that a product that is processed in an Auto Insertion DIP machine is also processed on a Wave Solder machine. In this case, the method of groups to locate complementary processes is not effective in this case because the Wave Solder process is not included in the cost calculation of product 2. To alleviate this problem, this table was created to link processes that locate or deal with components as Auto Insertion DIP with processes like Wave Solder that belong to another group.

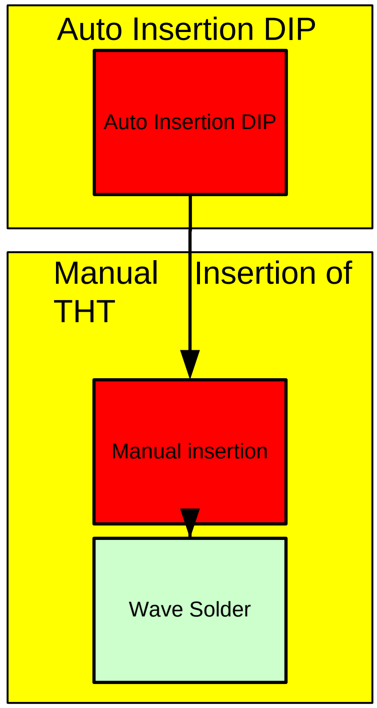


Figure 6 Explanation of the concept "Required processes from other groups".

Once the concept has been explained, Table 34 contains the attributes of this table.

Table 34 Design of Facilities Processes Required Processes from Other Groups table

Primary Key?	Field Name	Data Type	Description
Yes	Facility Name	Text	This field contains the name of a facility.
Yes	Process Name	Text	This field contains the name of a process.
Yes	Required Process from Other Group	Text	The explanation of this field will be made below.

A snapshot of this table is shown in Table 1.

Table 35 Facilities Processes Req. Proc Other Groups table

Facilities Processes Req. Proc Other Groups		
Facility Name	**Process Name**	**Required Process From Other Group**
ABC	AUTO INSERTION DIP	WAVE SOLDER
DEFAULT FACILITY	AUTO INSERTION DIP	WAVESOLDER
DEFAULT FACILITY	AUTO INSERTION VCD	WAVESOLDER

4.15 Facilities Processes Levels table

The reason to create this table will be explained with an example. Suppose again that a new facility has been created and that the processes in a level of the facility are those shown on Figure 7. It can be seen in this figure that the process Sequencer and the processes in the group SMT can be made simultaneously and then a product will be processed in Auto Insertion VCD. This kind of situations are important be considered because the lead time of a product can be affected. This table has been created to consider this kind of situations. The procedure to consider this kind of situations is to link a global group of processes with processes from another global group. Considering the facility used to explain the concept, the global group Sequencer must be linked with the process Auto Insertion VCD and the order of the processes in each global group must be specified to make the correct calculation of the lead time of a product. The order of the processes is contained in the Facilities Processes table. To see how the calculations are affected, if the lead time is calculated using the maximum time of each global group, the results will be incorrect. The correct from to calculate the lead time of a product in this situation is to take the maximum time between the Sequencer and SMT groups and then add the time a product is processed in Auto Insertion VCD to calculate the lead time of a product on that level.

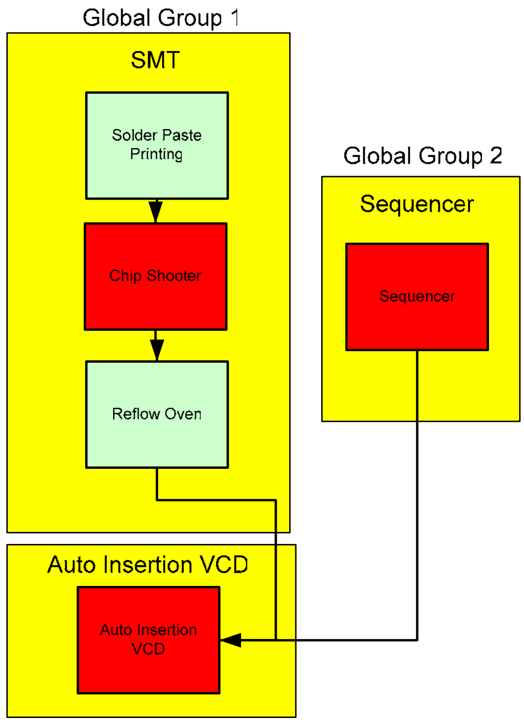


Figure 7 Explanation of Process bond between global groups concept

Once the concept has been explained, Table 36 contains the attributes of this table.

Table 36 Design of the Facilities Processes Levels table

Primary Key?	Field Name	Data Type	Description
Yes	Facility Name	Text	This field contains the name of a facility.
Yes	Process Name	Text	This field contains the name of a process.
Yes	Group Name	Text	The explanation of this field was made in Facilities Processes table.
Yes	Level	Text	The explanation of this field was made in Facilities Processes table.
No	Global Group	Text	The explanation of this field was made in Facilities Processes table.
No	Process Bond Groups Same Level	Text	The explanation of this field will be made below.

A snapshot of this table is shown in Table 37.

Table 37 Facilities Processes Levels Lead Time table

Facilities Processes Levels Lead Time				
Facility Name	**Group Name**	**Global Level**	**Global Group**	**Process Bond Groups Same Level**
DEFAULT FACILITY	AUTO INSERTION DIP	1	2	NOTAPPLY
DEFAULT FACILITY	AUTO INSERTION VCD	1	2	NOTAPPLY
DEFAULT FACILITY	MANUAL INSERTION	2	4	NOTAPPLY
DEFAULT FACILITY	REQUIRED OPERATIONS	2	4	NOTAPPLY
DEFAULT FACILITY	SEQUENCER	1	3	AUTO INSERTION VCD
DEFAULT FACILITY	SMT BOTTOM	1	2	NOTAPPLY
DEFAULT FACILITY	SMT TOP	1	2	NOTAPPLY
DEFAULT FACILITY	THT	1	1	NOTAPPLY
DEFAULT FACILITY	WIRE BONDING	1	2	NOTAPPLY

4.16 Global Group Type table

This table contains all the groups defined. The concept of groups was defined in the table in section 5.7. The attributes of this table are shown in Table 38.

Table 38 Design of Global Group Type table

Primary Key?	Field Name	Data Type	Description
Yes	Group Name	Text	This field contains all the groups defined to associate processes.

A snapshot of this table is shown in Table 39.

Table 39 Global Group Type table

Global Group Type
Group Name
AUTO INSERTION DIP
AUTO INSERTION VCD
COATING PROCESS AND OVEN
FINAL ASSEMBLY
MANUAL INSERTION
REQUIRED OPERATIONS
SEQUENCER
SMT BOTTOM
SMT TOP
THT

This table contains a special group defined with the name "REQUIRED OPERATIONS". This group is highlighted in red in the previous table. This group has been defined as a method to include those operations that are required in all the products being manufactured in a facility but that are not necessarily related to the placement or insertion of components. As an example, it is assumed in the default facility that all the products being manufactured will pass through a circuit and functional test. In this case, the processes called Functional test and Circuit test will belong to the group REQUIRED OPERATIONS.

4.17 Facilities Processes Op Rework OC Operators needed table

This table contains the special events that require labor in a process. The attributes of this table are shown in Table 40.

Table 40 Design of the Facilities Processes Op Rework OC Operators needed table

Facilities Processes Op Rework OC Operators needed		
Facility Name	**Process Name**	**Name of Occurrence Or Rework**
DEFAULT FACILITY	SOLDER PASTE PRINTING	Cleaning

4.18 Products table

This table contains the general characteristics of a product. The attributes of this table are shown in Table 41.

Table 41 Design of the Products table

Primary Key?	Field Name	Data Type	Description
Yes	Product Name	Text	This field contains the name of a product.
No	Product Description	Text	This field contains the description of a product.
No	Number Images Panel	Text	This field contains the number of panels per image in a product.
No	Panel Cost	Text	This field contains the cost of a panel in $.
No	Panel Size (length)	Text	This field contains the size of a panel in feet.
No	Image Size (length)	Text	This field contains the size of a image in feet.

A snapshot of part of this table is presented in Table 42.

Table 42 Snapshot of products table

Product Name	Product Description	Number Images Panel	Panel Cost	Panel Size
A	Computer Board	1	$7.68	1.739
B	Computer Board	4	$1.04	1.0072
C	Computer Board	1	$21.28	.9583
N20	Computer Board	1	$5.00	.6458
ABC	Computer Board	1	$3.45	1.45

4.19 Components Catalog table

This table contain all the part numbers that can be assembled in products, a description and its component type. The concept of component types was introduced in the explanation about groups in the table “Facilities Processes” and it is a method to associate part numbers of an electronic product to processes.

The attributes of this table are shown in Table 43.

Table 43 Design of the Components Catalog table

Primary Key?	Field Name	Data Type	Description
Yes	Part Number	Text	This field contains the number of text assigned to a component.
No	Part Number Description	Text	This field contains the description or specifications of a part number.
No	Component Type	Text	The concept of this field was discussed in the table Facilities Processes
No	Unit Part Number Cost	Text	This field contains the unit cost of a part number in $.

A snapshot of this table is shown in Table 44.

Table 44 Components Catalog table

Components Catalog			
Part Number	**Part Number Description**	**Component Type**	**Unit Part Number Cost**
1508-0033-01	CAP,.1UF,35V MI	DIP	0.0248305
1508-0050-01	CAP ,4700P,100V,1	DIP	0.0342795
1510-0095-01	CAP 10UF,200V,5%	THT	1.909393
1510-0105-01	CAP,5UF,200V,5%	THT2	1.174117
1540-0050-01	CAP,100UF,35V MI	DIP	0.028017
2101-0057-06	TBLK,CPRN,1/4C,S	THT4	2.233777
2103-0115-01	TM,QD,.205X,032	THT	0.022401

4.20 Global Components types table

This table contains all the component types available to associate part numbers to processes. The attributes of this table are shown in Table 45.

Table 45 Design of the Global Components types table

Primary Key?	Field Name	Data Type	Description
Yes	Component Type	Text	The concept of this field was discussed in the table Facilities Processes.
No	Description	Text	This field contains the description of a component type.

A snapshot of this table is shown in Table 46.

Table 46 Global Component Types

Global Component Types	
Component Type	**Description**
BRACKETS OR SOCKETS	Usually assembled in the process Final Assembly
DIP	Usually assembled in the process Auto Insertion DIP
GOLD PLATED PARTS	Usually assembled in the process Panel Preparation
SMTCHIP_BOTTOM	Usually assembled in the process Chip Shooter Bottom
SMTFINEPITCH	Usually assembled in the process BGA/Fine Pitch Placement
SMTMANUAL	Usually assembled in the process SMT Manual Insertion
SMTNFP_TOP	Usually assembled in the process Chip Shooter Top
THT	Usually assembled in the process THT Manual Insertion
THT2	Usually assembled in the process THT Manual Insertion 2
THT3	Usually assembled in the process THT Manual Insertion 3
THT4	Usually assembled in the process THT Manual Insertion 4
VCD	Usually assembled in the process Auto Insertion VCD
WIRE	Usually assembled in the process Chip on Board Wire Bonding

4.21 Product Part List table

This table contains the part numbers required on a product, its quantity, its component type and the product it belongs. The attributes of this table are shown in Table 47.

Table 47 Design of the Product Part List table

Primary Key?	Field Name	Data Type	Description
Yes	Product Name	Text	This field contains the name of a product.
Yes	Part Number	Text	This field contains the number of text assigned to a component.
No	Quantity	Text	This field contains the quantity of a part number that belongs to a product.
Yes	Component Type	Text	The concept of this field was discussed in the table Facilities Processes.

A snapshot of this table is shown in Table 48.

Table 48 Product Part List table

Product Part List			
Product Name	**Part Number**	**Quantity**	**Component Type**
ABC	1508-0033-01	2	DIP
ABC	1508-0050-01	2	DIP
ABC	1510-0095-01	3	THT
ABC	1510-0105-01	1	THT2
ABC	1540-0050-01	2	DIP

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CHAPTER 5: APPLICATION ARCHITECTURE

A cost model application has been developed to implement the revised cost model presented in chapter 3. This cost estimation tool has several modules which have been divided based upon their functionality. Software tools such as Microsoft Visual Basic.Net, Microsoft Access 2003, and Crystal Reports were used to build these modules. The software developed includes in its database, a default (virtual) facility that includes the typical processes used in today's electronic industry. This allows product developer/designers that do not have a particular facility in mind, to estimate the cost of a new design. The default facility included in the application has the capability to expand itself depending on the volume required of a product. This means that it will calculate the number of machines or operators required in an operation based on the demand of a product. This capability tries to improve the conditions of a facility in terms of performance.

The primary objective of this research was to develop an application to help electronic designers, which might not have knowledge of the particular facility in which the product will be assembled, to estimate the cost of a product. It allows design engineers to determine the cost of new designs prior to manufacture and see the impact of design features prior to implementation. In addition, the system developed allows process engineers to work with data from their own facility to get a more accurate and realistic cost estimate. Process engineers of a particular facility can focus on those activities that impact the cost of its products. Cost comparisons of multiple products can also be made simultaneously. Output from the cost estimations or cost comparisons are presented on a Crystal Report that allows you to export them to Microsoft Excel, Microsoft Word, Adobe Acrobat and in Rich Text Format. The next sections of this chapter present the components of the application, an explanation of the application through an example and the implementation details of the application.

5.1 Application Components

The application uses two important components in its structure. These components are: the creation and management of application users, facilities, processes and products through a database and the cost calculation of products using the equations in the cost model presented in Chapter 3. The last two sections of this chapter present an example of the application and the implementation details of the application.

5.1.1 Application Users

The application has been prepared to have two types of users: Product Developers/Designers and Process Engineers. Each type of user has different capabilities while using the software tool.

The capabilities of a Product Developer/ Designer are the following:

- Create, edit or delete products.
- Add, edit or delete part numbers from products.
- Add component types.
- Calculate the cost of products in all the registered facilities or the default facility of the application and evaluate the feasibility of a design in different facilities.
- Edit the Components Catalog of the application.
- Create a product copy.

The capabilities of a process engineer include those of the Product Developer/ Designer, plus the following:

- Create, edit or delete a facility.
- Create, edit or delete processes from a facility.
- Calculate product cost in the facility created.

It can be seen from the previous capabilities presented to each user, that a Product Developer/Designer possesses fewer capabilities than a Process Engineer. The reason of this is that a Product Developer/Designer does not necessarily know the details of the processes in a facility. Figure 8 presents the login process of the users in the application.

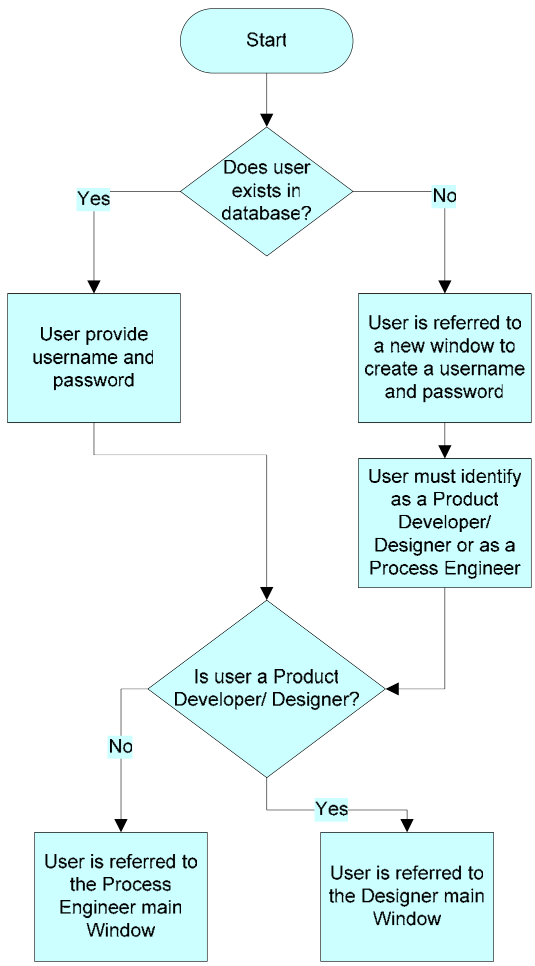

Figure 8 User login process

5.1.2 Creation and management of facilities, processes and products

The application has been prepared to manage the creation and management of facilities, processes and products. The creation of facilities, processes and products is managed through the user interface of the application to maintain integrity in the data being supplied. The data provided by the user is then stored in a database to be used in the cost analysis of products. Figure 9 illustrates the steps in which the creation of a facility is executed.

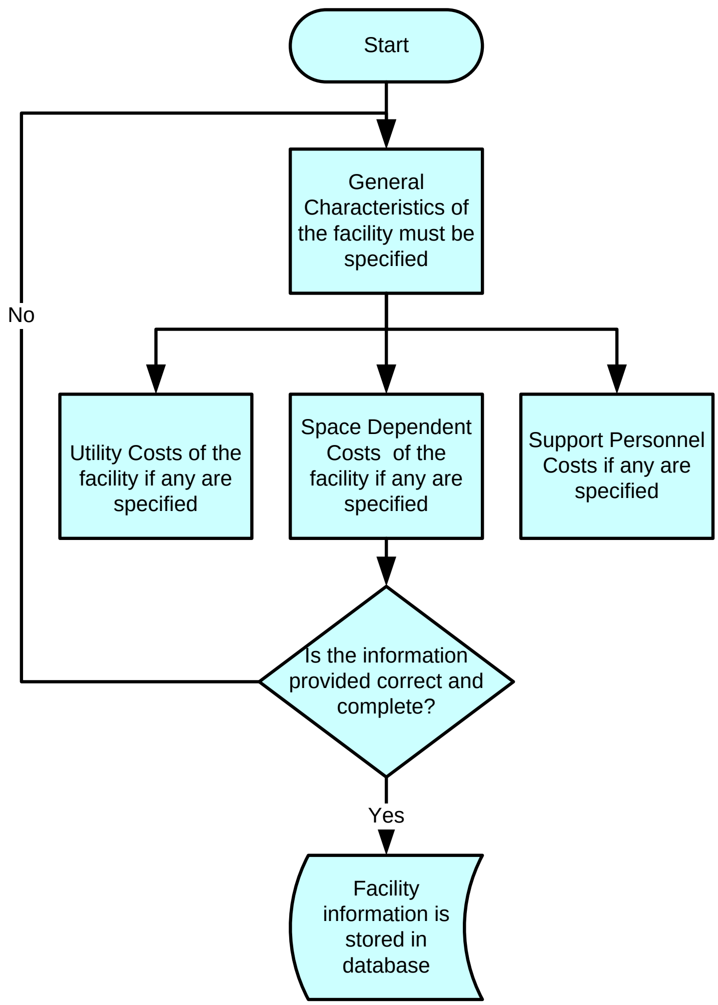

Figure 9 Flowchart of facility creation

Once you create a facility, you must add processes to this facility.

Figure 10 Flowchart of process creation shows how to register a process in a facility.

The steps in

Figure 10 Flowchart of process creation must be repeated to register all the processes of a facility.

If the default facility of the application is to be used instead of a new customized facility, the previous two processes can be skipped (creation of facilities and processes). Once all the processes needed in your facility are registered, the user must specify the level, global groups and the order of the processes in the facility. If there are groups of processes that require indirect labor, or processes that require processes from other groups, it must also be specified. At this point a facility is ready to make cost calculation of products. The next step to be made is the creation of products whose costs are to be estimated. Figure 11 presents the process executed to create a product.

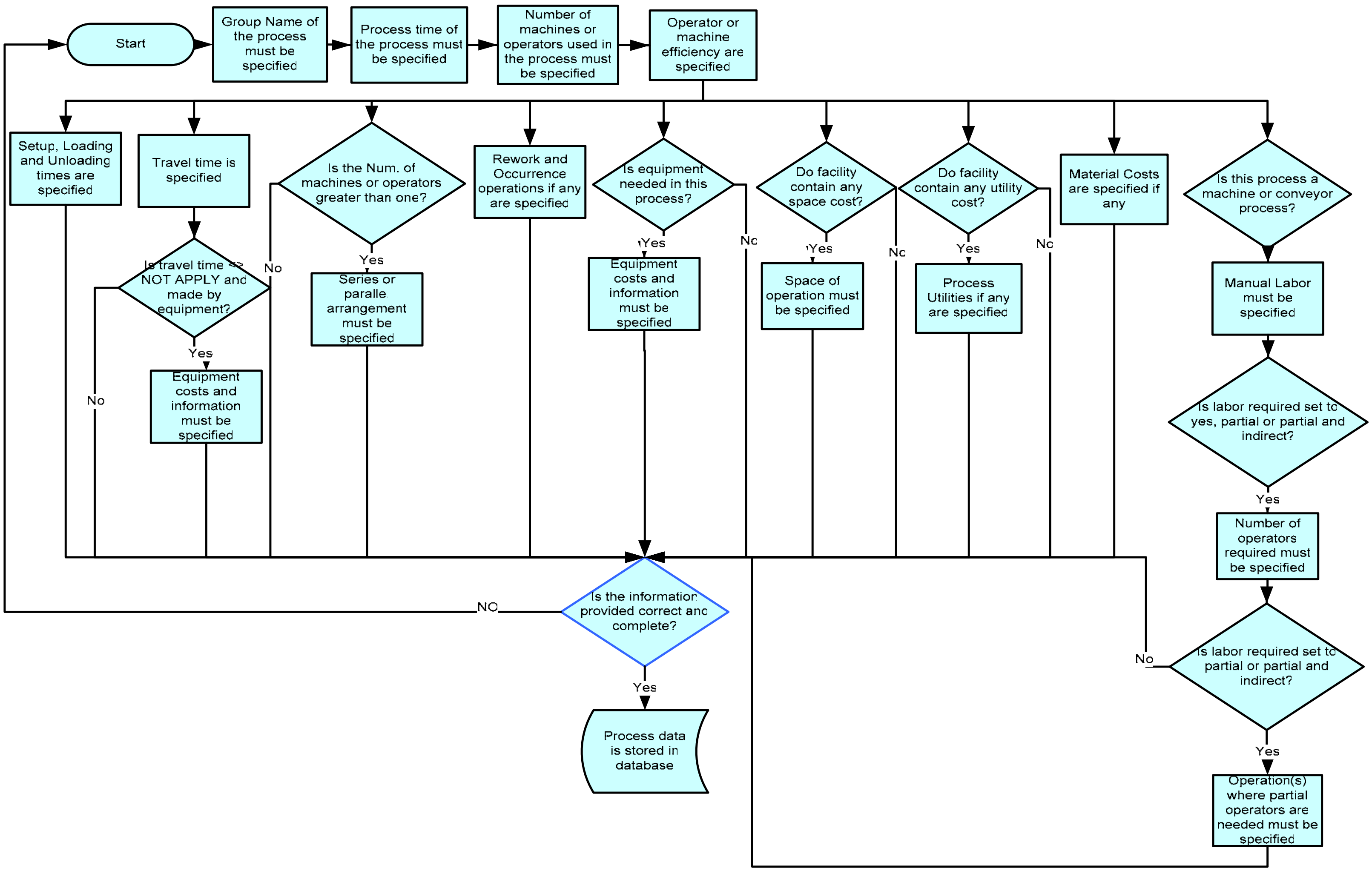

Figure 10 Flowchart of process creation

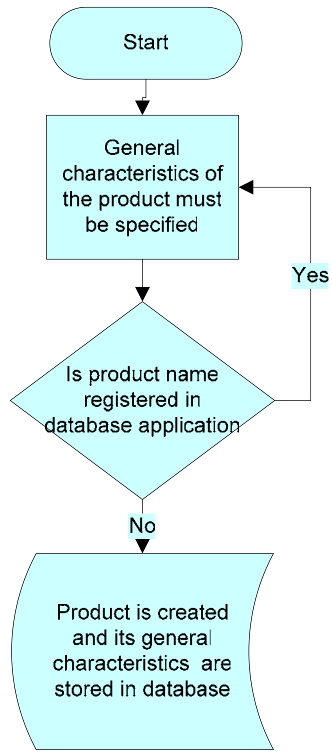

Figure 11 Product creation

Once a product has been created, the next step is the registration of part numbers to a product. Figure 12 presents the registration process of part numbers in a product.

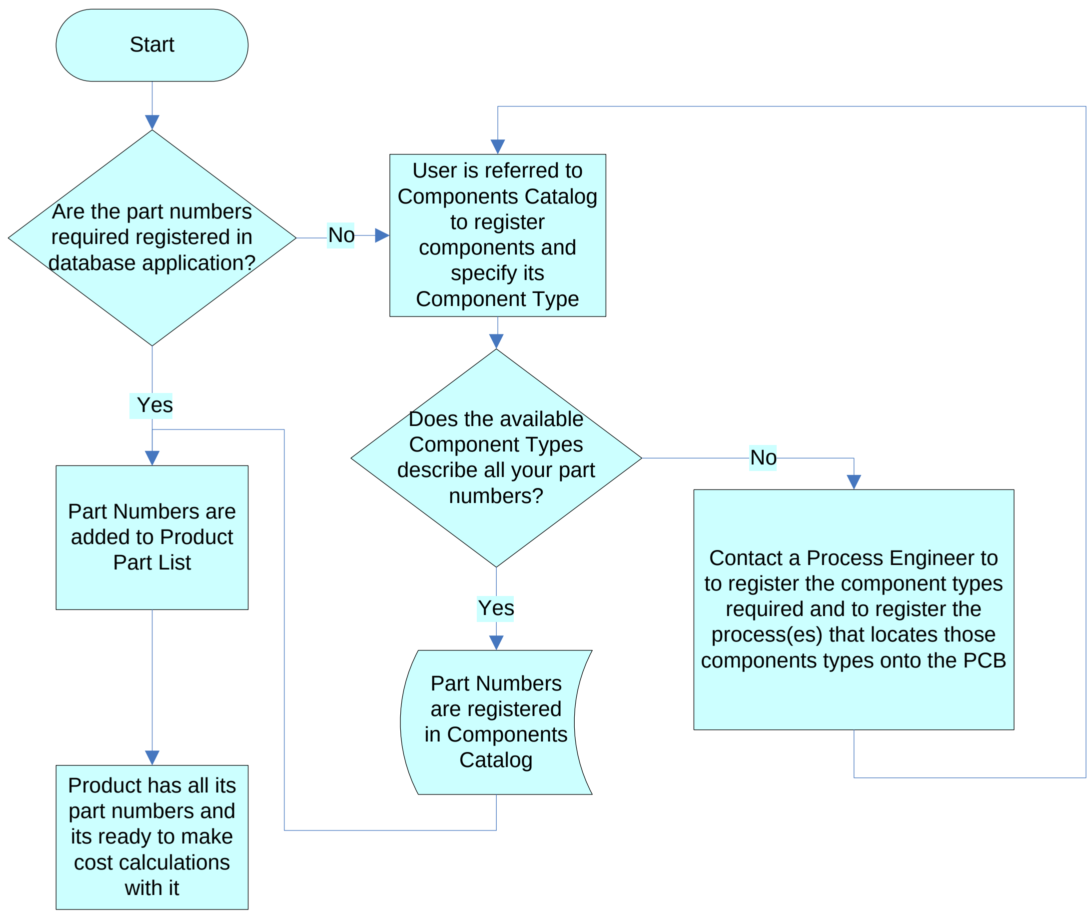

Figure 12 Registration of product part numbers

At this point, the registration of facilities, processes and products has been explained. The next section will explain how the developed application will calculate the cost of a product in a facility.

5.1.3 Cost calculation of products with the revised cost model.

The application developed has been designed to calculate the cost of PCB-based electronic designs. To do that, the revised cost model presented in chapter 3 was implemented. Figure 13 and Figure 14 presents the logic of the routine that is implemented to find the required processes of a facility and the routines implemented to calculate the cost of a product.

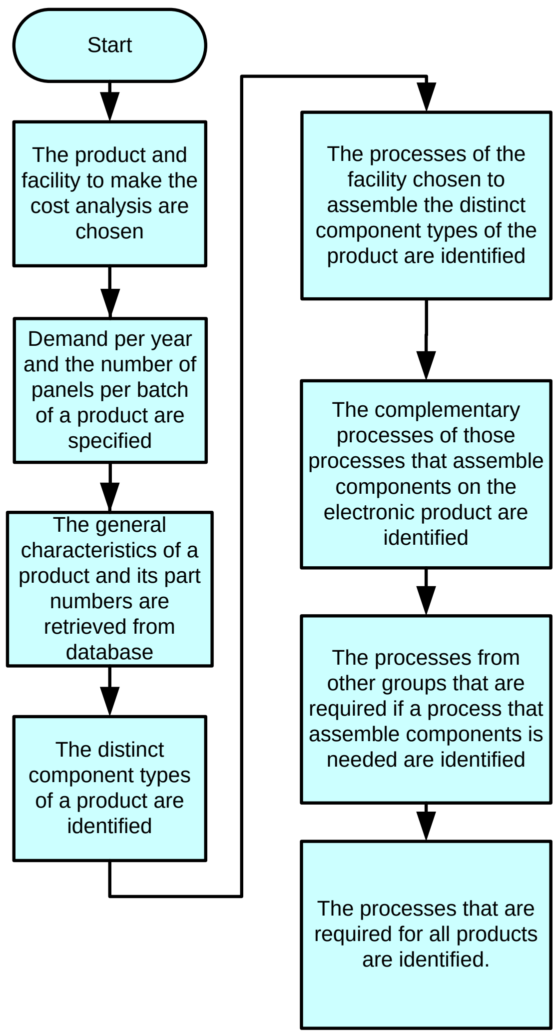

Figure 13 Routine implemented in cost model application to find the processes required to manufacture an electronic product.

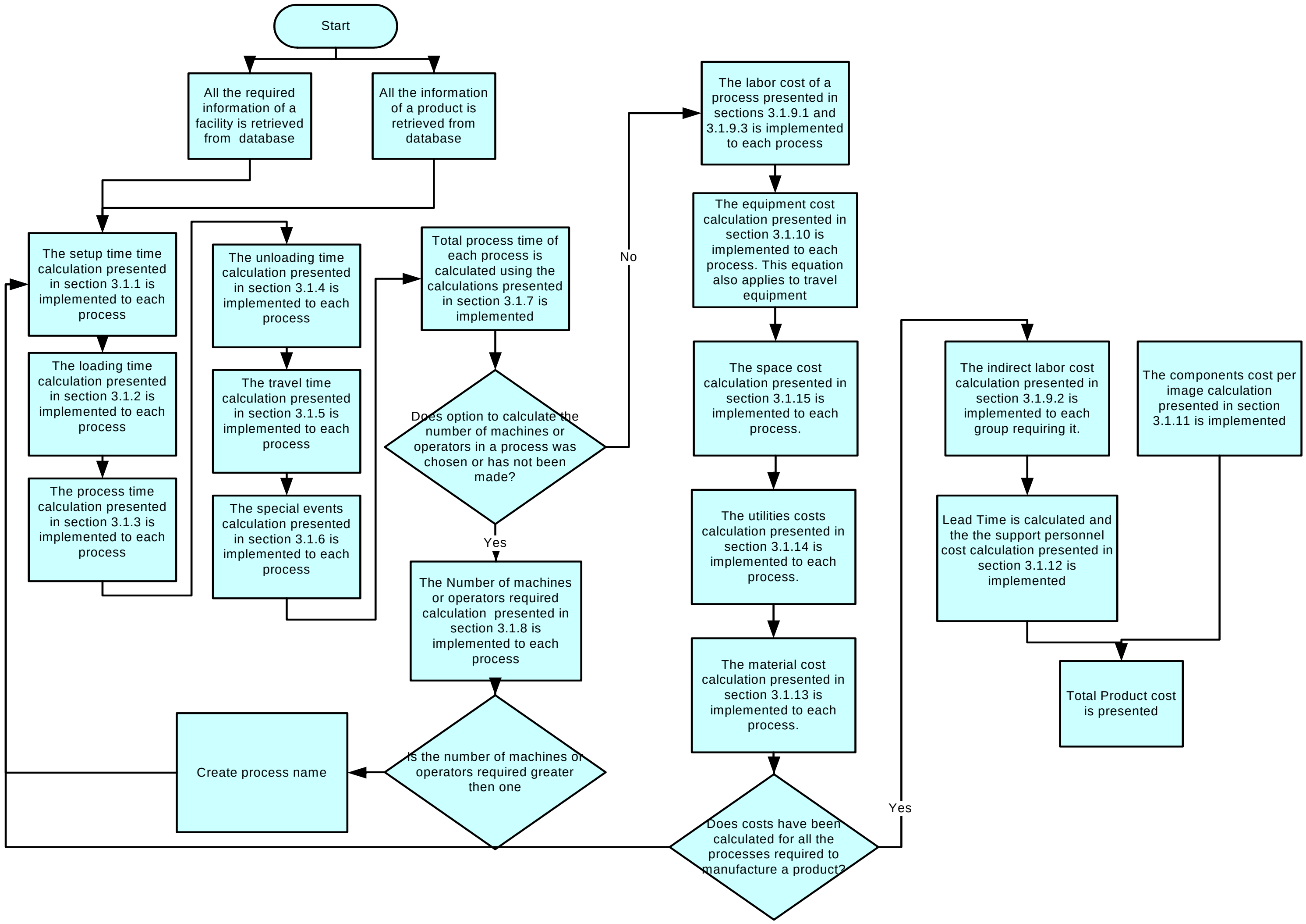

Figure 14 Routines and logic implemented to calculate the cost of an electronic product

At this point, the architecture of the application developed has been shown. The next section will present a detailed example of the application to apply all the concepts previously presented.

5.2 Explanation of application through an example

In this section, the implementation of the revised cost model will be presented through an example. In the example it is assumed that a new facility and product are created to calculate the cost of the product.

Assume that a new facility called ABC is created. The general characteristics of this facility are shown on Table 49 .

Table 49 ABC characteristics

Facility name	Facility description	Number of working days per year	Number of working hours per day	Average rate per hour of operators ($/hour)	Electricity Cost ($/ kilowatt)	Building and Rent Cost ($/square feet)	Space factor	Minimum Attractive rate of return (MARR)
ABC	Computer manufacturer	250	8	10	.12	.50	.2	.15

This new facility has five processes called Preforming, Solder Paste Printing, Chip Shooter, Reflow Oven and Manual Insertion. These processes are typical in the manufacture of electronic products. Figure 15 shows the processes and their sequence.

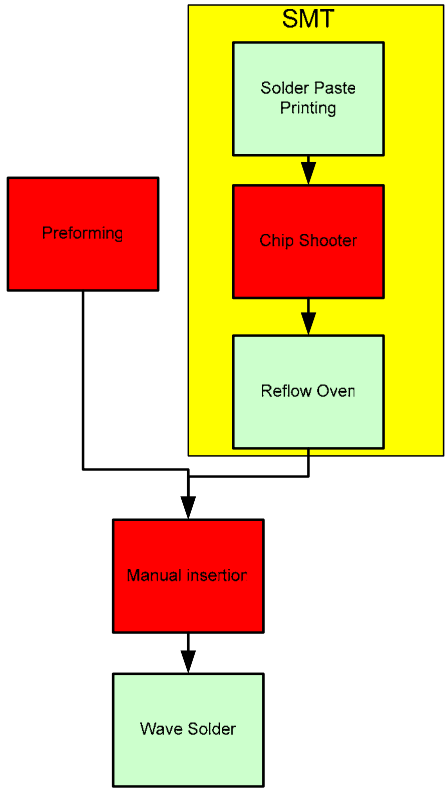

Figure 15 ABC processes

Preforming, Chip Shooter and Manual Insertion are painted in red because they are the only ones in facility ABC that place, insert or deal directly with components in a product. It is also assumed that the component types that can be handled in each process respectively are THT, Non Fine Pitch, and THT. The information assumed for each processes is shown in Table 50.

Table 50 Details of ABC processes

Process Name	Preforming	Solder Paste Printing	Chip Shooter	Reflow Oven	Manual Insertion	Wave Solder
Group Name	**THT Preparation**	**SMT**	**SMT**	**SMT**	**Manual Insertion of THT**	**Manual Insertion of THT**
Setup time	N/A	300 sec/batch	250 sec/batch	200 sec/batch	N/A	275 sec/batch
Process time	5 sec/ component	30 sec/ panel	2 sec/ component	A conveyor is used to process panels and its length is 15 ft, the separation distance between panels is 0 and its speed is 4.5 ft/min	5 sec/ component	A conveyor is used to process panels and its length is 15 ft, the separation distance between panels is 0 and its speed is 4.5 ft/min
Component types that a process can assemble or deal with	THT	N/A	Non fine pitch	N/A	THT	N/A
Travel time	60 sec/batch	A conveyor is used to move panels to the next process and its length is 6 ft, the separation distance between panels is 2 ft and its speed is 30 ft/min	A conveyor is used to move panels to the next process and its length is 6 ft, the separation distance between panels is 2 ft and its speed is 30 ft/min	60 sec/ batch	5 sec/ panel	60 sec/panel

Process Name	Preforming	Solder Paste Printing	Chip Shooter	Reflow Oven	Manual Insertion	Wave Solder
Machine or operator efficiency	.95	.95	.80	1	.90	1
Number of required machines or operators	1	1	1	1	1	1
Are operators or machines in series or parallel?	N/A	N/A	N/A	N/A	N/A	N/A
Initial Cost of Equipment ($)	1000	75,000	250,000	100,000	N/A	50,000
Salvage Value	0	0	0	0	N/A	0
Machine Estimated Life (years)	10	10	10	10	N/A	10
Initial Cost of Equipment in travel operation ($)	N/A	1000	1000	N/A	N/A	N/A
Salvage Value of Equipment in travel operation ($)	N/A	0	0	N/A	N/A	N/A
Machine Estimated Life of Equipment in travel operation (years)	N/A	10	10	N/A	N/A	N/A

Process Name	Preforming	Solder Paste Printing	Chip Shooter	Reflow Oven	Manual Insertion	Wave Solder
Space occupied by operation (square feet)	15	20	20	45	9	45
Electricity consumption (kilowatt/hour)	.25	.25	1	2	N/A	2
Activities where Electricity is required	Process	Setup Process Travel	Setup Process Travel	Setup Process	N/A	Setup Process
Material Cost	N/A	$.0065/gram	N/A	N/A	N/A	N/A
Material consumption	N/A	1/8 gram per component	N/A	N/A	N/A	N/A
Is labor required?	Yes	Indirect[1]	Indirect	Partial. Operator is needed to move batch of panels to next process	Yes	Yes
Number of operators required	1	Will be specified.	Will be specified.	Will be specified.	N/A because process id manual and was specified previously	1

The numbers of operators required to setup and maintain the SMT group of processes is 1. It is also assumed that a new product with the name XYZ has been designed. The general characteristics of this product are presented in Table 51.

[1] **It must be remembered from section 3.1.9.2 that indirect labor refers to the number of operators required to setup and maintain a group of processes.**

Table 51 General characteristics of product XYZ

Product Name	Number of images per panel	Panel Cost ($)	Panel length (feet)
XYZ	1	1.00	1

Let's also assume that this new product has only three part numbers. The three part numbers of the product and its details are shown on Table 52.

Table 52 Product Part List of XYZ

Product Name	Part Number	Quantity	Component Type	Unit Part Number Cost ($)
XYZ	P1	10	Non Fine Pitch	1.00
XYZ	P2	15	Non Fine Pitch	.50
XYZ	P3	10	THT	.10

At this point, the cost calculation of product XYZ can be made in facility ABC. It is assumed that assembly will be carried out in lots of 200 panels and that the demand per year of this product is 10,000 images. To calculate the cost of XYZ product in facility ABC, the first thing to be done is to find the process(es) in the ABC facility that assemble the components of product XYZ. It was stated previously that the only processes that assemble components or deal with components in the facility ABC are Preforming, Chip Shooter and Manual Insertion. So, the first thing to do is to locate the processes needed for these components. The next thing to do is to find the processes that complement these processes. These are the processes that are also needed when a particular process is needed. In this case, the complementary processes of the Chip Shooter process are Solder Paste Printing and Reflow Oven. The method used to find the complementary processes in the cost model application developed is associating processes by defining groups. Let's assume that the processes Solder Paste Printing, Chip Shooter and Reflow Oven belongs to a group called SMT so that when the Chip Shooter is needed, a routine is implemented to find all the processes that belongs to that group to complement this process. Once all the processes needed to manufacture the product XYZ are identified, we proceed to calculate the cost of the product. To calculate the cost of the product, we use the information provided in Table 51 and Table 52. The cost of the product will be divided in five elements as follows:

1) Labor Cost

    Labor Cost will be divided in two:

    1) Direct labor- refers to the labor that is applied on a process when an operator is required to participate in all the operations of a process.
    2) Indirect labor- indirect labor refers to the labor that is applied to a group of processes where operators are assigned to support various processes (usually automated processes) at the same time and not only to one.

2) Equipment Cost
3) Material, Components and Image Cost
4) Overhead Cost

    The overhead cost is divided in three:

    1) Support Personnel Cost- it refers to the cost that is attributed to a unit of product based on the time that support personnel dedicates to the processing of products.
    2) Utilities Cost
    3) Space dependent costs

Each cost is calculated separately. Each of the costs that apply to a particular process will be calculated first and then the overall costs applied to a product will be calculated.

Preforming times and costs

There was no setup, loading, unloading and special operations in this process, so these are set to zero and not presented

$$TP_{img} = \frac{TP * \sum_{PN_{i=1}}^{PN_n} QPN_i}{Nimg_{pl} * Npl_{bh} * Nplp * Nimgp} * (1+(1-E))$$

$$TP_{img} = \left(\frac{5sec}{component} * \frac{10components}{image} * \frac{1min}{60sec} \right) * (1+(1-.95)) = \frac{.874965min}{image}$$

Note: In the previous equation the variables $Nimg_{pl}$, Npl_{bh}, Nplp and Nimgp are set to 1.

$$TTR_{img} = \frac{TTR}{Nimg_{pl} * Npl_{bh} * Nplp * Nimgp}$$

$$TTR_{img} = \left(\frac{\frac{60sec}{batch}}{\frac{1\ image}{panel} * \frac{200\ panel}{batch}} * \frac{1min}{60sec} \right) * (1+(1-.95)) = \frac{.00525min}{image}$$

Note: In the previous equation the variables Nplp and Nimgp are set to 1.

$$TPT_{img} = TSU_{mg} + TL_{mg} + TP_{mg} + TU_{mg} + TTR_{mg} + \sum_{i=1}^{n} TSP_{img}$$

$$TPT_{img} = \frac{.874965min}{image} + \frac{.00525min}{image} = \frac{.880215min}{image}$$

Note: In the previous equation the variables TSU_{img}, TL_{img}, TU_{img} and the sum of TSP are 0.

$$DLC_{img} = \sum_{i=0}^{n} OPT(i)_{img} * Rate_{hr} NOP$$

$$DLC_{img} = \left(\frac{.874965min}{image} + \frac{.00525min}{image} \right) * \left(\frac{\$10}{hr} * \frac{1hr}{60min} \right) * 1\ \ operator\ = \frac{\$\ 0.1467025}{image}$$

Note: In the previous equation the only two operations applicable are process and travel.

$$EC_{img} = \frac{IC*\left[\frac{MARR * (1 + MARR)^{MEL}}{(1 + MARR)^{MEL} - 1}\right] - SV*\left[\frac{MARR}{(1 + MARR)^{MEL - 1}}\right]}{D_{yr}}$$

$$EC_{img} = \frac{\$\,1000*\left[\frac{.15 * (1 + .15)^{10}}{(1 + .15)^{10} - 1}\right] - \$0*\left[\frac{.15}{(1 + .15)^{10 - 1}}\right]}{\frac{10000\ image}{year}} = \frac{\$.019925}{image}$$

The only utility of this process is electricity and its cost is calculated with the utility equation. It should be noted that the only time considered to calculate the electricity cost is the process time because it was stated previously that electricity was only required in the process activity.

$$UtilityC_{img} = Utility\ Consumption * UtilityC*\sum_{i=0}^{n} OPT(i)_{img}$$

$$Elec(\$)_{img} = .25kilowatt*\left(\frac{\$.12}{kilowatt*hr}*\frac{1hr}{60min}\right)*\frac{.874965min}{image} = \frac{\$.000437}{image}$$

$$SpaceC_{img} = \frac{\left[Space*(1+SpaceFactor)\right]\left(\sum_{i=0}^{n}\$SOE_i\right)}{D_{yr}}$$

$$SpaceC_{img} = \frac{\left(15ft^2*(1+.2)\right)*\frac{\$.50}{ft^2*year}}{\frac{10000images}{year}} = \frac{\$.0009}{image}$$

Note: In the previous equation the only space dependent cost allocated are the $.50/ sq^2*year of the facility ABC.

$$\text{Total Process Cost} = \frac{\$\,0.1467025}{\text{image}} + \frac{\$.019925}{\text{image}} + \frac{\$.000437}{\text{image}} + \frac{\$.0009}{\text{image}} = \frac{\$.167965}{\text{image}}$$

Solder Paste Printing times

There are no loading, unloading or special operations in this process, so these are set to zero and not presented.

$$TSU_{img} = \frac{TSUF+TSUV*Npn}{Nimg_{pl} * Npl_{bh} *Nplp*Nimgp}*(1+(1\text{-}E))$$

$$TSU_{img} = \left(\frac{\frac{300sec}{batch}}{\frac{1\ image}{panel} * \frac{200\ panel}{batch}} * \frac{1min}{60sec} \right)*(1+(1\text{-}.95)) = \frac{.02625min}{image}$$

Note: In the previous equation the variables TSUV, Npn are 0 and Nplp and Nimgp are set to 1.

$$TP_{img} = \frac{TP * \sum_{PN_{i=1}}^{PN_n} QPN_i}{Nimg_{pl} * Npl_{bh}*Nplp*Nimgp}*(1+(1\text{-}E))$$

$$TP_{img} = \left(\left(\frac{\frac{30sec}{panel}}{\frac{1\ image}{panel}} \right) * \frac{1min}{60sec} \right)*(1+(1\text{-}.95)) = \frac{.525min}{image}$$

Note: In the previous equation the variables the sum over QPN_i, Npl_{bh}, Nplp and Nimgp are set to 1.

$$TTR_{img} = \frac{\frac{CVL}{CVS} + \frac{\left(SD_{pl} + Size_{pl}\right)}{CVS}*\left(Npl_{bh}\text{-}1\right)}{Nimg_{pl} * Npl_{bh}}*(1+(1\text{-}E))$$

$$TTR_{img} = \left(\frac{\frac{6ft}{\frac{30\ ft}{min}} + \frac{\left(\frac{2\ ft}{panel} + \frac{1\ ft}{panel}\right)}{\frac{30\ ft}{min}} * \left(\frac{200\ panel}{batch} - 1\right)}{\frac{1\ image}{panel} * \frac{200\ panel}{batch}} \right) *(1+(1-.95)) = \frac{.105525min}{image}$$

$$TPT_{img} = TSU_{mg} + TL_{mg} + TP_{mg} + TU_{mg} + TTR_{mg} + \sum_{i=1}^{n} TSP_{img}$$

$$TPT_{img} = \frac{.02625min}{image} + \frac{.525min}{image} + \frac{.105525min}{image} = \frac{.656775min}{image}$$

This process does not contain direct labor. Its labor is indirect and it will be calculated later.

$$EC_{img} = \frac{IC*\left[\frac{MARR * (1 + MARR)^{MEL}}{(1 + MARR)^{MEL} - 1}\right] - SV*\left[\frac{MARR}{(1 + MARR)^{MEL - 1}}\right]}{D_{yr}}$$

$$EC_{img} = \frac{\$\ 75000*\left[\frac{.15 * (1 + .15)^{10}}{(1 + .15)^{10} - 1}\right] - \$0*\left[\frac{.15}{(1 + .15)^{10 - 1}}\right]}{\frac{10000\ image}{year}} = \frac{\$1.49439}{image}$$

The cost of equipment to travel the product from the process Solder Paste Printing to the next process will be calculated now.

$$EC_{img} = \frac{IC*\left[\frac{MARR * (1 + MARR)^{MEL}}{(1 + MARR)^{MEL} - 1}\right] - SV*\left[\frac{MARR}{(1 + MARR)^{MEL - 1}}\right]}{D_{yr}}$$

$$EC_{img} = \frac{\$ 1000*\left[\frac{.15*(1+.15)^{10}}{(1+.15)^{10}-1}\right] - \$0*\left[\frac{.15}{(1+.15)^{10-1}}\right]}{\frac{10000 \text{ image}}{\text{year}}} = \frac{\$.019925}{\text{image}}$$

The only utility of this process is electricity and its cost is calculated with the utility equation. It should be noted that the total time of the process was considered to calculate the electricity cost because electricity is used in all the activities of the process.

$$UtilityC_{img} = \text{Utility Consumption} * UtilityC * \sum_{i=0}^{n} OPT(i)_{img}$$

$$Elec(\$)_{img} = .25\text{kilowatt} * \left(\frac{\$.12}{\text{kilowatt*hr}} * \frac{1\text{hr}}{60\text{min}}\right) * \left(\frac{.656775\text{min}}{\text{image}}\right) = \frac{\$.000328}{\text{image}}$$

$$MaterialC_{img} = \frac{MaterialC * Material * \sum_{i=1}^{NPN} QPN_i}{Nimg_{pl} * Npl_{bh}}$$

$$MaterialC_{img} = \frac{1}{8}\frac{\text{gram}}{\text{component}} * \frac{\$.0065}{\text{gram}} * \frac{25 \text{ component}}{\text{image}} = \frac{\$.020313}{\text{image}}$$

Note: In the previous equation the variables $Nimg_{pl}$, Npl_{bh} are set to 1.

$$SpaceC_{img} = \frac{[Space*(1+SpaceFactor)]\left(\sum_{i=0}^{n} \$SOE_i\right)}{D_{yr}}$$

$$Space\$_{img} = \frac{\left(20ft^2*(1+.2)\right)*\frac{\$.50}{ft^2}}{10000\text{images}} = \frac{\$.0012}{\text{image}}$$

Note: In the previous equation the only space dependent cost allocated are the $.50/ sq^2*year of the facility ABC.

$$\text{Total Process Cost} = \frac{\$1.49439}{\text{image}} + \frac{\$.019925}{\text{image}} + \frac{\$.000328}{\text{image}} + \frac{\$.020313}{\text{image}} + \frac{\$.0012}{\text{image}} = \frac{\$1.536156}{\text{image}}$$

Chip Shooter times

There are no loading, unloading or special operations in this process, so these are set to zero and not presented.

$$TSU_{img}=\frac{TSUF+TSUV*Npn}{Nimg_{pl}\ *\ Npl_{bh}\ *Nplp*Nimgp}*(1+(1-E))$$

$$TSU_{img}=\frac{\frac{250sec}{batch}}{\frac{1\ image}{panel}*\frac{200\ panel}{batch}}*\frac{1min}{60sec}(1+(1-.80))=\frac{.025min}{image}$$

Note: In the previous equation the variables Nplp and Nimgp are set to 1.

$$TP_{img}=\frac{TP*\sum_{PN_{i=1}}^{PN_n}QPN_i}{Nimg_{pl}\ *\ Npl_{bh}*Nplp*Nimgp}*(1+(1-E))$$

$$TP_{img}=\frac{2sec}{component}*\frac{25\ components}{image}*\frac{1min}{60sec}(1+(1-.80))=\frac{.99996min}{image}$$

Note: In the previous equation the variables $Nimg_{pl}$, Npl_{bh}, Nplp and Nimgp are set to 1.

$$TTR_{img}=\frac{\frac{CVL}{CVS}+\frac{\left(SD_{pl}+Size_{pl}\right)}{CVS}*\left(Npl_{bh}-1\right)}{Nimg_{pl}\ *\ Npl_{bh}}*(1+(1-E))$$

$$TTR_{img}=\frac{\frac{6ft}{\frac{30\ ft}{min}}+\frac{\left(\frac{2\ ft}{panel}+\frac{1\ ft}{panel}\right)}{\frac{30\ ft}{min}}*\left(\frac{200\ panel}{batch}-1\right)}{\frac{1\ image}{panel}*\frac{200\ panel}{batch}}(1+(1-.80))=\frac{.1206min}{image}$$

$$TPT_{img}=TSU_{mg}\ +TL_{mg}\ +TP_{mg}\ +TU_{mg}\ +TTR_{mg}\ +\sum_{i=1}^{n}TSP_{img}$$

$$TPT_{img}=\frac{.020833min}{image}+\frac{.8333\ min}{image}+\frac{.1005min}{image}=\frac{1.14556min}{image}$$

This process does not contain direct labor. Its labor is indirect and it will be calculated later.

$$EC_{img} = \frac{IC*\left[\frac{MARR * (1 + MARR)^{MEL}}{(1 + MARR)^{MEL} - 1}\right] - SV*\left[\frac{MARR}{(1 + MARR)^{MEL - 1}}\right]}{D_{yr}}$$

$$EC_{img} = \frac{\$ 250000*\left[\frac{.15 * (1 + .15)^{10}}{(1 + .15)^{10} - 1}\right] - \$0*\left[\frac{.15}{(1 + .15)^{10 - 1}}\right]}{\frac{10000 \text{ image}}{\text{year}}} = \frac{\$4.981302}{\text{image}}$$

The cost of equipment to travel the product from the process Chip Shooter process to the next process will be calculated now.

$$EC_{img} = \frac{IC*\left[\frac{MARR * (1 + MARR)^{MEL}}{(1 + MARR)^{MEL} - 1}\right] - SV*\left[\frac{MARR}{(1 + MARR)^{MEL - 1}}\right]}{D_{yr}}$$

$$EC_{img} = \frac{\$ 1000*\left[\frac{.15 * (1 + .15)^{10}}{(1 + .15)^{10} - 1}\right] - \$0*\left[\frac{.15}{(1 + .15)^{10 - 1}}\right]}{\frac{10000 \text{ image}}{\text{year}}} = \frac{\$.019925}{\text{image}}$$

The only utility of this process is electricity and its cost is calculated with the utility equation. It should be noted that the total time of the process was considered to calculate the electricity cost because electricity is used in all the activities of the process.

$$UtilityC_{img} = \text{Utility Consumption} * UtilityC * \sum_{i=0}^{n} OPT(i)_{img}$$

$$Elec(\$)_{img} = 1 \text{ kilowatt} * \left(\frac{\$.12}{\text{kilowatt*hr}} * \frac{1\text{hr}}{60\text{min}}\right) * \left(\frac{1.14556\text{min}}{\text{image}}\right) = \frac{\$.002291}{\text{image}}$$

$$SpaceC_{img} = \frac{[Space*(1+SpaceFactor)]\left(\sum_{i=0}^{n} \$SOE_i\right)}{D_{yr}}$$

$$Space\$_{img} = \frac{\left(20ft^2*(1+.2)\right)*\frac{\$.50}{ft^2}}{10000images} = \frac{\$.0012}{image}$$

Note: In the previous equation the only space dependent cost allocated are the $.50/ sq^2*year of the facility ABC.

$$\text{Total Process Cost} = \frac{\$4.981302}{image} + \frac{\$.019925}{image} + \frac{\$.002291}{image} + \frac{\$.0012}{image} = \frac{\$5.004718}{image}$$

Reflow Oven times

There are no loading, unloading or special operations in this process, so these are set to zero and not presented.

$$TSU_{img} = \frac{TSUF+TSUV*Npn}{Nimg_{pl} * Npl_{bh} *Nplp*Nimgp}*(1+(1-E))$$

$$TSU_{img} = \frac{\frac{200sec}{batch}}{\frac{1\ image}{panel} * \frac{200\ panel}{batch}} * \frac{1min}{60sec}*(1+(1-1)) = \frac{.016667min}{image}$$

In the previous equation the variables TSUV, Npn are 0 and Nplp and Nimgp are set to 1.

The process time of this process will be calculated using Equation 8 of section 3.3. It should be noted that the reason to use this equation is because the process Reflow Oven is a conveyor process and that panels are processed through the process.

$$TP_{img}=\frac{\frac{CVL}{CVS}+\frac{\left(SD_{pl}+Size_{pl}\right)}{CVS}*\left(Npl_{bh}-1\right)}{Nimg_{pl}*Npl_{bh}}*(1+(1-E))$$

$$TP_{img}=\frac{\frac{\frac{15ft}{4.5\ ft}}{min}+\frac{\left(\frac{0\ ft}{panel}+\frac{1\ ft}{panel}\right)}{\frac{4.5\ ft}{min}}*\left(\frac{200\ panel}{batch}-1\right)}{\frac{1\ image}{panel}*\frac{200\ panel}{batch}}*(1+(1-1))=\frac{.237778min}{image}$$

$$TTR_{img}=\frac{TTR}{Nimg_{pl}*Npl_{bh}*Nplp*Nimgp}*(1+(1-E))$$

$$TTR_{img}=\frac{\frac{60sec}{batch}}{\frac{1\ image}{panel}*\frac{200\ panel}{batch}}*\frac{1min}{60sec}*(1+(1-1))=\frac{.005min}{image}$$

Note: In the previous equation the variables Nplp and Nimgp are set to 1.

$$TPT_{img}=TSU_{mg}+TL_{mg}+TP_{mg}+TU_{mg}+TTR_{mg}+\sum_{i=1}^{n}TSP_{img}$$

$$TPT_{img}=\left(\frac{.016667min}{image}+\frac{.237778min}{image}+\frac{.005min}{image}\right)=\frac{.259445min}{image}$$

This process contains direct labor because an operator is needed to move a batch of panels to the next process and it also contains indirect labor that will be calculated later.

$$DLC_{img}=\sum_{i=0}^{n}OPT(i)_{img}*Rate_{hr}NOP$$

$$DLC_{img}=\left(\frac{.005min}{image}\right)*\left(\frac{\$10}{hr}*\frac{1hr}{60min}\right)*1\ \ operator=\frac{\$\ 0.000833}{image}$$

$$EC_{img} = \frac{IC*\left[\frac{MARR*(1+MARR)^{MEL}}{(1+MARR)^{MEL}-1}\right] - SV*\left[\frac{MARR}{(1+MARR)^{MEL-1}}\right]}{D_{yr}}$$

$$EC_{img} = \frac{\$\,100000*\left[\frac{.15*(1+.15)^{10}}{(1+.15)^{10}-1}\right] - \$0*\left[\frac{.15}{(1+.15)^{10-1}}\right]}{\frac{10000\ image}{year}} = \frac{\$1.992521}{image}$$

The only utility of this process is electricity and its cost is calculated with the utility equation. It should be noted that times used to calculate the electricity cost are the setup and process activities of the process because electricity is used in these activities.

$$UtilityC_{img} = Utility\ Consumption * UtilityC * \sum_{i=0}^{n} OPT(i)_{img}$$

$$Elec(\$)_{img} = 2kilowatt * \left(\frac{\$.12}{kilowatt*hr} * \frac{1hr}{60min}\right) * \left(\frac{.016667min}{image} + \frac{.237778min}{image}\right) = \frac{\$.001018}{image}$$

$$SpaceC_{img} = \frac{[Space*(1+SpaceFactor)]\left(\sum_{i=0}^{n} \$SOE_i\right)}{D_{yr}}$$

$$Space\$_{img} = \frac{\left(45ft^2*(1+.2)\right)*\frac{\$.50}{ft^2*year}}{\frac{10000images}{year}} = \frac{\$.0027}{image}$$

Note: In the previous equation the only space dependent cost allocated are the \$.50/ sq^2*year of the facility ABC.

$$Total\ Process\ Cost = \frac{\$\,0.000833}{image} + \frac{\$1.992521}{image} + \frac{\$.001018}{image} + \frac{\$.0027}{image} = \frac{\$1.997072}{image}$$

Manual Insertion times

There are no setup, loading, unloading or special operations in this process, so these are set to zero and not presented.

$$TP_{img} = \frac{TP * \sum_{PN_{i=1}}^{PN_n} QPN_i}{Nimg_{pl} * Npl_{bh} * Nplp * Nimgp} * (1+(1-E))$$

$$TP_{img} = \frac{5sec}{component} * \frac{10\ components}{image} * \frac{1min}{60sec} * (1+(1-.90)) = \frac{.91663min}{image}$$

In the previous equation the variables $Nimg_{pl}$, Npl_{bh}, Nplp and Nimgp are set to 1.

$$TTR_{img} = \frac{TTR}{Nimg_{pl} * Npl_{bh} * Nplp * Nimgp} * (1+(1-E))$$

$$TTR_{img} = \frac{\frac{5sec}{panel}}{\frac{1\,image}{panel}} * \frac{1\min}{60\sec} * (1+(1-.90)) = \frac{.091663\min}{image}$$

Note: In the previous equation the variables Npl_{bh}, Nplp and Nimgp are set to 1.

$$TPT_{img} = TSU_{mg} + TL_{mg} + TP_{mg} + TU_{mg} + TTR_{mg} + \sum_{i=1}^{n} TSP_{img}$$

$$TPT_{img} = \frac{.91663\min}{image} + \frac{.091663\min}{image} = \frac{1.008329\min}{image}$$

$$DLC_{img} = \sum_{i=0}^{n} OPT(i)_{img} * Rate_{hr} NOP$$

$$DLC_{img} = \frac{.91663\min}{image} + \frac{.091663\min}{image} * \left(\frac{\$10}{hr} * \frac{1hr}{60\min}\right) * 1\ operator = \frac{\$\ .168055}{image}$$

$$SpaceC_{img} = \frac{[Space*(1+SpaceFactor)]\left(\sum_{i=0}^{n} \$SOE_i\right)}{D_{yr}}$$

$$\text{Space\$}_{img} = \frac{\left(9ft^2 * (1+.2)\right) * \frac{\$.50}{ft^2 * year}}{\frac{10000 \text{ images}}{year}} = \frac{\$.00054}{image}$$

Note: In the previous equation the only space dependent cost allocated are the \$.50/ sq^2*year of the facility ABC.

$$\text{Total Process Cost} = \frac{\$\ .168055}{image} + \frac{\$.00054}{image} = \frac{\$.168595}{image}$$

Wave Solder times

There are no loading, unloading or special operations in this process, so these are set to zero and not presented.

$$TSU_{img} = \frac{TSUF + TSUV * Npn}{Nimg_{pl} * Npl_{bh} * Nplp * Nimgp} * (1+(1-E))$$

$$TSU_{img} = \frac{\frac{275sec}{batch}}{\frac{1 \text{ image}}{panel} * \frac{200 \text{ panel}}{batch}} * \frac{1min}{60sec} = \frac{.022917min}{image}$$

Note: In the previous equation the variables Nplp and Nimgp are set to 1.

The process time of this process will be calculated using Equation 8 of section 3.3. It should be noted that the reason to use this equation is because the process Reflow Oven is a conveyor process and that panels are processed through the process.

$$TP_{img} = \frac{\frac{CVL}{CVS} + \frac{\left(SD_{pl} + Size_{pl}\right)}{CVS} * \left(Npl_{bh} - 1\right)}{Nimg_{pl} * Npl_{bh}} * (1+(1-E))$$

$$TP_{img} = \frac{\frac{15ft}{\frac{4.5\ ft}{min}} + \frac{\left(\frac{0\ ft}{panel} + \frac{1\ ft}{panel}\right)}{\frac{4.5\ ft}{min}} * \left(\frac{200\ panel}{batch} - 1\right)}{\frac{1\ image}{panel} * \frac{200\ panel}{batch}} * (1+(1-1)) = \frac{.237778min}{image}$$

$$TTR_{img} = \frac{TTR}{Nimg_{pl} * Npl_{bh} * Nplp * Nimgp} * (1+(1-E))$$

$$TTR_{img} = \frac{\frac{60sec}{panel}}{\frac{1\ image}{panel}} * \frac{1min}{60sec} * (1+(1-1)) = \frac{1min}{image}$$

Note: In the previous equation the variables Npl_{bh}, Nplp and Nimgp are set to 1.

$$TPT_{img} = TSU_{mg} + TL_{mg} + TP_{mg} + TU_{mg} + TTR_{mg} + \sum_{i=1}^{n} TSP_{img}$$

$$TPT_{img} = \left(\frac{.022917min}{image} + \frac{.237778min}{image} + \frac{1min}{image}\right) = \frac{1.260695min}{image}$$

$$DLC_{img} = \sum_{i=0}^{n} OPT(i)_{img} * Rate_{hr} NOP$$

$$DLC_{img} = \left(\frac{.022917min}{image} + \frac{.237778min}{image} + \frac{1\ min}{image}\right) * \left(\frac{\$10}{hr} * \frac{1hr}{60min}\right) * 1\ \text{operator} = \frac{\$\ .210116}{image}$$

$$EC_{img} = \frac{IC * \left[\frac{MARR * (1 + MARR)^{MEL}}{(1 + MARR)^{MEL} - 1}\right] - SV * \left[\frac{MARR}{(1 + MARR)^{MEL - 1}}\right]}{D_{yr}}$$

$$EC_{img} = \frac{\$\ 50000 * \left[\frac{.15 * (1 + .15)^{10}}{(1 + .15)^{10} - 1}\right] - \$0 * \left[\frac{.15}{(1 + .15)^{10 - 1}}\right]}{\frac{10000\ image}{year}} = \frac{\$.99626}{image}$$

The only utility of this process is electricity and its cost is calculated with the utility equation.

$$\text{UtilityCost (\$)}_{img} = \text{Utility Consumption} * \text{Utility Cost (\$)} * \sum_{i=0}^{n} \text{OPT(i)}_{img}$$

$$\text{Elec(\$)}_{img} = 2\text{kilowatt} * \left(\frac{\$.12}{\text{kilowatt*hr}} * \frac{1\text{hr}}{60\text{min}} \right) * \left(\frac{.022917\text{min}}{\text{image}} + \frac{.237778\text{min}}{\text{image}} \right) = \frac{\$.001043}{\text{image}}$$

$$\text{SpaceC}_{img} = \frac{[\text{Space}*(1+\text{SpaceFactor})]\left(\sum_{i=0}^{n} \$\text{SOE}_i \right)}{D_{yr}}$$

$$\text{Space\$}_{img} = \frac{\left(45\text{ft}^2*(1+.2)\right) * \frac{\$.50}{\text{ft}^2*\text{year}}}{\frac{10000\text{images}}{\text{year}}} = \frac{\$.0027}{\text{image}}$$

Note: In the previous equation the only space dependent cost allocated are the $.50/ sq^2*year of the facility ABC.

$$\text{Total Process Cost} = \frac{\$\ .210116}{\text{image}} + \frac{\$.99626}{\text{image}} + \frac{\$.001043}{\text{image}} + \frac{\$.0027}{\text{image}} = \frac{\$1.210119}{\text{image}}$$

Once all the costs of the processes have been calculated, the indirect labor will be calculated. Indirect labor refers to the quantity of labor that is applied to a group of processes that require labor mostly for support activities. As an example, consider a group of processes in which an operator needs to setup and maintain the machines of that group. Due to the fact that this operator is not assigned to a machine or process directly, the labor required in each process is distributed along the machines with the Equation 15 of Section 3.9.3. In this example the indirect labor cost of the SMT processes group is as follow:

$$ILC_{img} = \max(TPT_{img})_i * NpGroup * \$Rate_{hr}$$

Cost of Indirect labor in SMT =

$$\max\left(\frac{.656775\text{min}}{\text{image}}, \frac{1.14556\text{min}}{\text{image}}, \frac{.259445\text{min}}{\text{image}}\right) * 3 * \left(\frac{\$10}{\text{hr}} * \frac{1\text{hr}}{60\text{min}}\right) * 1 \text{ operators} = \frac{\$.57278}{\text{image}}$$

Components and Image Cost

$$TCC_{img} = \sum_{i=1}^{NPN} TPNC_i$$

$$TPN_i = QPN_i * PNC_i$$

Components Cost of XYZ =

$$\frac{\$1.00}{\text{component}} * \frac{10 \text{ component}}{\text{image}} + \frac{\$.50}{\text{component}} * \frac{15 \text{ component}}{\text{image}} + \frac{\$.10}{\text{component}} * \frac{10 \text{ component}}{\text{image}} = \frac{\$18.50}{\text{image}}$$

$$TIC_{img} = \frac{TPC_{pl}}{Nimg_{pl}}$$

$$\text{Image Cost} = \frac{\frac{\$1.00}{\text{panel}}}{\frac{1\text{image}}{\text{panel}}} = \frac{\$1.00}{\text{image}}$$

Support Personnel Cost

One of the most difficult costs to allocate to a product is the support personnel cost. The reason is that the time that support personnel dedicate to the processing of a particular product is not easy to measure. We will use Equation 23 to calculate the support personnel cost per image. To calculate the support personnel cost of the product XYZ, we will first calculate the lead time of the product and then proceed to implement Equation 23.

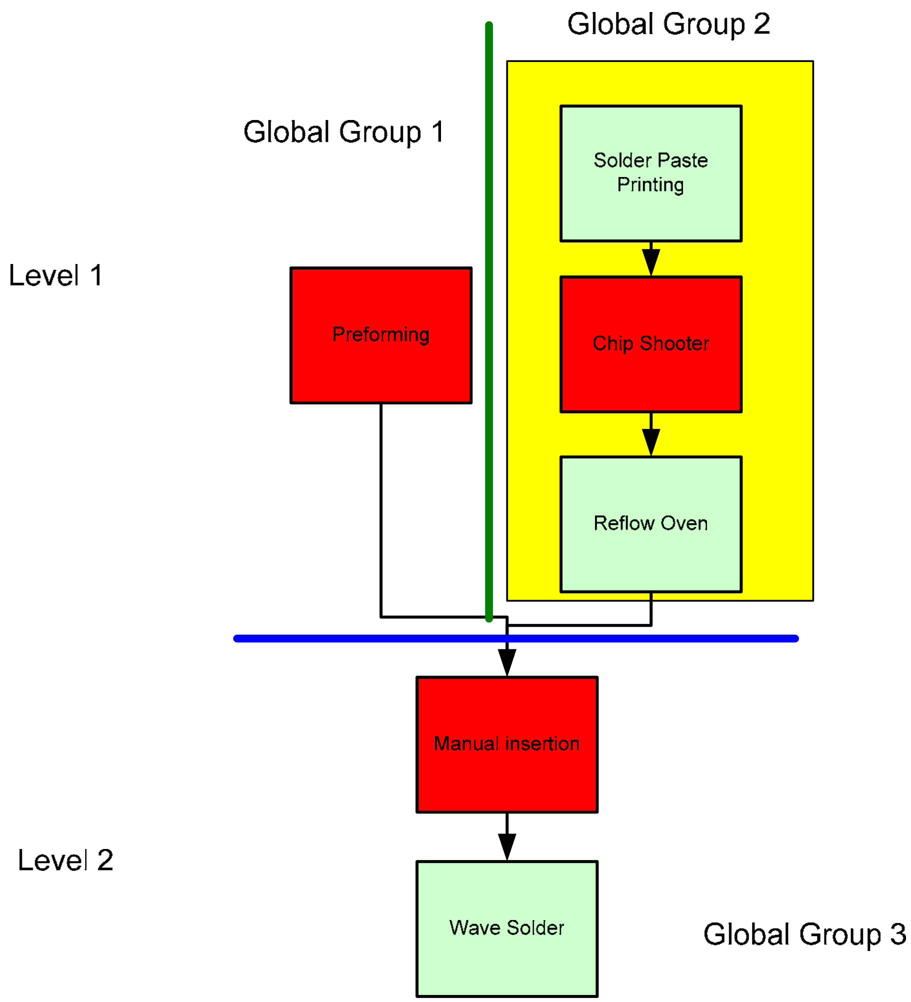

Figure 16 ABC Processes with Levels and Global Groups

Let us calculate the lead time of product XYZ to understand better the concept of levels and global groups. As you can see from Figure 16, the global groups and levels are divided as follows:

Global Group 1

- Preforming(PRE)

Global Group 2

- Solder Paste Printing (SPP)

- Chip Shooter (CS)
- Reflow Oven (RO)

Global Group 3

- Manual Insertion (MI)
- Wave Solder (WS)

Level 1

- Preforming (Pre)
- Solder Paste Printing (SPP)
- Chip Shooter (CS)
- Reflow Oven (RO)

Level 2

- Manual Insertion (MI)
- Wave Solder (WS)

To calculate the Lead Time of the product, the cycle time of the Global Groups need to be calculated.

Cycle time of Global Group 1= TPT of PRE

$$= \frac{.880215 \text{ min}}{\text{mage}}$$

Cycle time of Global Group 2= (max (TPT of SPP, TPT of CS, TPT of RO)) * NGM

$$= \left(\max \left(\frac{.656775\text{min}}{\text{image}}, \frac{1.14556\text{min}}{\text{image}}, \frac{.259445\text{min}}{\text{image}} \right) \right) *3 = \frac{3.43668\text{min}}{\text{image}}$$

Note: NGM means Number of machines in this group.

Cycle time of Global Group 3 = (max (TPT of MI, TPT of WS)) * NMG

$$= \left(\max \left(\frac{1.008329 \text{ min}}{\text{mage}}, \frac{1.260695\text{min}}{\text{image}} \right) \right) * 2 = \frac{2.52139\text{min}}{\text{image}}$$

Now that the cycle times of the groups have been calculated, proceed to calculate the level times. To do that, we will proceed to calculate the lead time as follows:

Level 1 Time = max (Cycle time of Global Group 1, Cycle time of Global Group 2)

$$= \max \left(\frac{.880215 \text{ min}}{\text{mage}}, \frac{3.43668\text{min}}{\text{image}} \right) = \frac{3.43668\text{min}}{\text{image}}$$

Level 2 Time = Cycle time of Global Group 3

$$= \frac{2.52139\text{min}}{\text{image}}$$

Lead Time of the Product = Level 1 Time + Level 2 Time

$$\frac{3.43668\text{min}}{\text{image}} + \frac{2.52139\text{min}}{\text{image}} = \frac{5.95807\text{min}}{\text{image}}$$

Once it is known the lead time of the product, the calculation of the support personnel cost will be made. It will also be assumed that the support personnel of the facility ABC and the salary of each person are as shown on Table 53.

Table 53 Salaries of Support Personnel in ABC facility

Person Position	Salary ($)
Product Engineer	70,000
Process Engineer	60,000
Average of the salaries	**65,000**

Now that we have all the needed information, the support personnel cost of the product ABC is calculated using Equation 23 which is shown below.

$$TSUPC_{img} = \left(\frac{AvgSUPC_{yr} * Ntse}{D_{yr}} \right) * \left(MLT_{\frac{hrs}{img}} \right)$$

$$T\$SUP_{img} = \left(\frac{\frac{\$65000}{year} * 2}{\frac{10000image}{year}} \right) * \left(\frac{5.95807min}{image} * \frac{1hr}{60min} \right) = \frac{\$1.290915}{image}$$

Once all the costs have been calculated, the total cost is calculated.

Preforming Total Process Cost = $\frac{\$.167965}{image}$

Solder Paste Printing Total Process Cost $= \frac{\$1.536156}{image}$

Chip Shooter Total Process Cost $= \frac{\$5.004718}{image}$

Reflow Oven Total Process Cost $= \frac{\$2.009441}{image}$

Manual Insertion Total Process Cost = $= \frac{\$.168595}{image}$

Wave Solder Total Process Cost = $\frac{\$1.210119}{image}$

Cost of Indirect labor in SMT $\frac{\$1.150141}{image}$

Components Cost of XYZ = $\frac{\$\ 18.50}{image}$

Image Cost = $\frac{\$\ 1.00}{image}$

Support Personnel Cost per image = $\frac{\$1.290915}{image}$

Total Product Cost =

$$= \frac{\$.167965}{\text{image}} + \frac{\$1.536156}{\text{image}} + \frac{\$5.004718}{\text{image}} + \frac{\$1.997072}{\text{image}} + \frac{\$.168595}{\text{image}} + \frac{\$1.210119}{\text{image}} + \frac{\$.57278}{\text{image}} + \frac{\$\ 18.50}{\text{image}} + \frac{\$1.00}{\text{image}} + \frac{\$1.290915}{\text{image}}$$

$$= \frac{\$31.44832}{\text{image}}$$

The example presented previously is a simple example of how the cost application developed works.

5.3 Implementation Details

The cost model proposed is developed using Microsoft Visual Studio.Net. Appendix B contains a user manual for the cost model application developed that guides a product developer to create a new product, add part numbers to it and calculate the cost of this product in the default facility of the application. Appendix C contains also a user manual but this one is prepared for a process engineer interested in the creation of a facility to calculate the cost of its products. Appendix A contains the description of the most relevant routines of the application. Next chapter will present the validation of the cost model application developed and the simulation model developed to evaluate the efficiency of the deterministic estimate given by the cost model application.

CHAPTER 6: TESTING, VALIDATION AND RESULTS

This chapter summarizes the validation of the cost model application developed. The validation was carried out in three steps. The first step consisted in the cost calculation of four products provided by a local electronic manufacturing company using the cost model application with the times and cost information provided by the company. The second step consisted in the cost comparison of the products with a spreadsheet model developed by an engineer of the company with the cost model application. A comparison between the company estimate and the one provided by the application was made to test the application developed. The third step consisted in the generation of a discrete event simulation model. A comparison between the application and the discrete event simulation model was made to evaluate the validity of the cost model. The Company provided the standard time of each operation in their facility used to calculate the cost of each product. Although the initial motivation of the validation was to evaluate all the costs of these products, we only had access to calculate the direct labor cost of the products and their material cost.

6.1 Comparison between company and cost model application developed.

Table 54, Table 55, Table 56 and Table 57 contain the analysis made for the products of the Company. These tables contain the times, direct labor and material cost calculation with the cost model application and also with the spreadsheet model developed by the engineer of the company. The processes needed to manufacture each product are also shown on these tables and an analysis per process of the times is also made to find discrepancies.

Table 54 Product A from the local electronic manufacturer

Product A			
Processes	Application	Company	% Difference
LABELS AREA	0.485050	0.485050	0%
AUTO INSERTION DIP	0.8440	0.8440	0%
AUTO INSERTION VCD	0.5641	0.5641	0%
MANUAL INSERTION OF THT	1.9352	2.0841	0%
MANUAL INSERTION OF THT 2	0.1489		
TOUCH UP	1.5533	1.5533	0%
WAVESOLDER	0.3920	0.8357	72%
ATE TEST	1.0020	1.0020	0%
BENCH TEST	3.0000	3.0000	0%
Total Time (min)	9.9245	10.3682	4%
Direct Labor Cost	1.3630	1.4239	4%
Material Costs	16.6100	16.6100	0%
Product Cost considering only Direct labor and Material	17.9730	18.0339	0.0437

Table 55 Product B from the local electronic manufacturer

Product B			
Processes	Application	Company	% Difference
LABELS AREA	0.485050	0.485050	0%
AUTO INSERTION VCD	0.3969	0.3969	0%
MANUAL INSERTION OF THT	1.1909	1.1909	0%
TOUCH UP	0.6119	0.6119	0%
WAVESOLDER	0.2337	0.8357	113%
ATE TEST	1.0020	1.0020	0%
BENCH TEST	3.0000	3.0000	0%
Total Time (min)	6.9205	7.5225	8%
Direct Labor Cost	0.9504	1.0331	8%
Material Costs	3.2800	3.2800	0%
Product Cost considering only Direct labor and Material	4.2304	4.3131	0.0834

Table 56 Product C from the local electronic manufacturer

Product C			
Processes	Application	Company	% Difference
LABELS AREA	0.970100	0.970100	0%
AUTO INSERTION VCD	3.0920	3.0920	0%
MANUAL INSERTION OF THT	28.5815	29.4747	0%
MANUAL INSERTION OF THT 2	0.5954		
MANUAL INSERTION OF THT 3	0.2977		
TOUCH UP	15.6272	15.6272	0%
WAVESOLDER	0.2232	0.8357	116%
ATE TEST	1.0020	1.0020	0%
BENCH TEST	3.0000	3.0000	0%
Total Time (min)	53.3892	54.0017	1%
Direct Labor Cost	7.3321	7.4162	1%
Material Costs	28.9500	28.9500	0%
Product Cost considering only Direct labor and Material	36.2821	36.3662	0.0114

It can be seen in Table 54,Table 55, and Table 56 that the only discrepancy between the cost model application and the spreadsheet model developed by the engineer of the company is in the time of the process wave solder. The difference in the calculation is because the time of the wave solder process in the cost model application is calculated with Equation 4 of section 3.3. In the spreadsheet model of the engineer, the wave solder time is the same for all the panels passing through the process. This difference logically affects the direct labor cost of the product. Table 57 contains the analysis of the four product of the company considered in the comparison. As opposed to the previous three products where only THT components are required for the products, this product also contains SMT components.

Table 57 Product D from the local electronic manufacturer

Product D			
Processes	Application	Company	% Difference
LABELS AREA	0.485050	0.485050	0%
SOLDER PASTE PRINTING	0.2008	0.2008	0%
CHIP SHOOTER PLACEMENT	3.310800	3.310800	0%
CHIP SHOOTER PLACEMENT 2	3.310800	3.310800	0%
FINE PITCH PLACEMENT	3.8880	3.8880	0%
REFLOW OVEN	1.1075	2.2257	67%
SMT VISUAL INSPECTION	3.5613	3.5613	0%
SOLDER PASTE PRINTING BOTTOM	0.2008	0.2008	0%
CHIP SHOOTER BOTTOM	3.6307	3.6307	0%
CHIP SHOOTER BOTTOM2	3.6307	3.6307	0%
REFLOW OVEN BOTTOM	1.1075	2.2257	67%
SMT VISUAL INSPECTION BOTTOM	3.6132	3.6132	0%
MANUAL INSERTION OF THT	3.1261	37.5132	0%
MANUAL INSERTION OF THT 2	3.5727		
MANUAL INSERTION OF THT 3	3.7216		
MANUAL INSERTION OF THT 4	3.4238		
MANUAL INSERTION OF THT 5	3.1261		
MANUAL INSERTION OF THT 6	2.9772		
MANUAL INSERTION OF THT 7	3.8704		
MANUAL INSERTION OF THT 8	4.3170		
MANUAL INSERTION OF THT 9	2.828378		
MANUAL INSERTION OF THT 10	3.2750		
MANUAL INSERTION OF THT 11	3.2750		
TOUCH UP	11.8616	11.8616	0%
WAVESOLDER	0.4485	0.8357	60%
ATE TEST	1.0020	1.0020	0%
BENCH TEST	3.0000	3.0000	0%
Sum of the times where Direct Labor is required	61.484933		
Average time in SMT Top	3.927649	N/A	N/A
Average time in SMT Bottom	3.655415	N/A	N/A
Total Time (min)	69.0680	84.4960	20%
Direct Labor Cost	10.5267	11.6041	10%
Material Costs	263.5056	263.5056	0.00%
Product Cost considering only Direct labor and Material	274.0324	275.1097	0.39%

In Table 57, two differences affect the estimate of the time and labor cost of the product. In this product, there are differences again in the times of the conveyor processes which are: Reflow Oven, Reflow Oven Bottom and Wave Solder. The other difference to be noted is that in the company model, to obtain the direct labor cost of the product, the sum of the times of the operations is used to calculate the labor cost while in the cost model application the calculations are made different. The reason to be made different is because in the SMT Top and Bottom lines, an operator is not assigned to each of the machine of the line. In these lines, there are two operators to maintain a complete line and the cost of labor in these lines is calculated using Equation 15 from section 3.9.2 and this logically affects the labor cost of the product.

6.2 Comparison between cost model application discrete event simulation

The idea behind the creation of a discrete event simulation model was to evaluate the precision of the cost estimate provided by application developed. The reason to point this is because although a comparison was made in the previous section to evaluate the cost model application with the spreadsheet model developed by the company, there is no way to know which of the models is closer to the reality. Knowing this, a discrete event simulation model was developed to examine in detail what happens in the production floor to take this as the best representation of the reality.

In the simulation model, the company standard times were used as mean values to adjust triangular distributions to represent the service times at each operation, assuming the mean value as the mode and adding a variability of more or less 20% to the mean to represent the minimum, and maximum. The discrete event simulation model contained all the processes of the Company needed to manufacture the product under study. Figure 17 shows the logic and animation of the simulation model developed. The product analyzed in this phase was presented in Table 57. The simulation was replicated ten times assuming that batches of 200 images were assembled in each replication and statistics about the ten replications were generated. Table 58 presents the comparison between the simulation model and the application in terms of time, which is the variable that could take variability in the cost estimate of a product. The content of the table is as follows:

1) The first column contains the name of each process in the facility.
2) The second column contains the time estimate given by the application for each process.
3) The third and fifth column contain the 95% lower and upper bound of a confidence interval generated by the simulation model for the ten replications that were carried out.
4) The fourth column the mean value of the time generated by the simulation model for the ten replications that were carried out.
5) The sixth column is used to specify if the time estimate provided by the application is inside the intervals calculated in the simulation model.
6) The seventh and eighth columns contain the minimum and maximum average of the ten replications of the simulation model.
7) The ninth and tenth column present the minimum and maximum value of the reported for each process in all the replications made in the simulation.

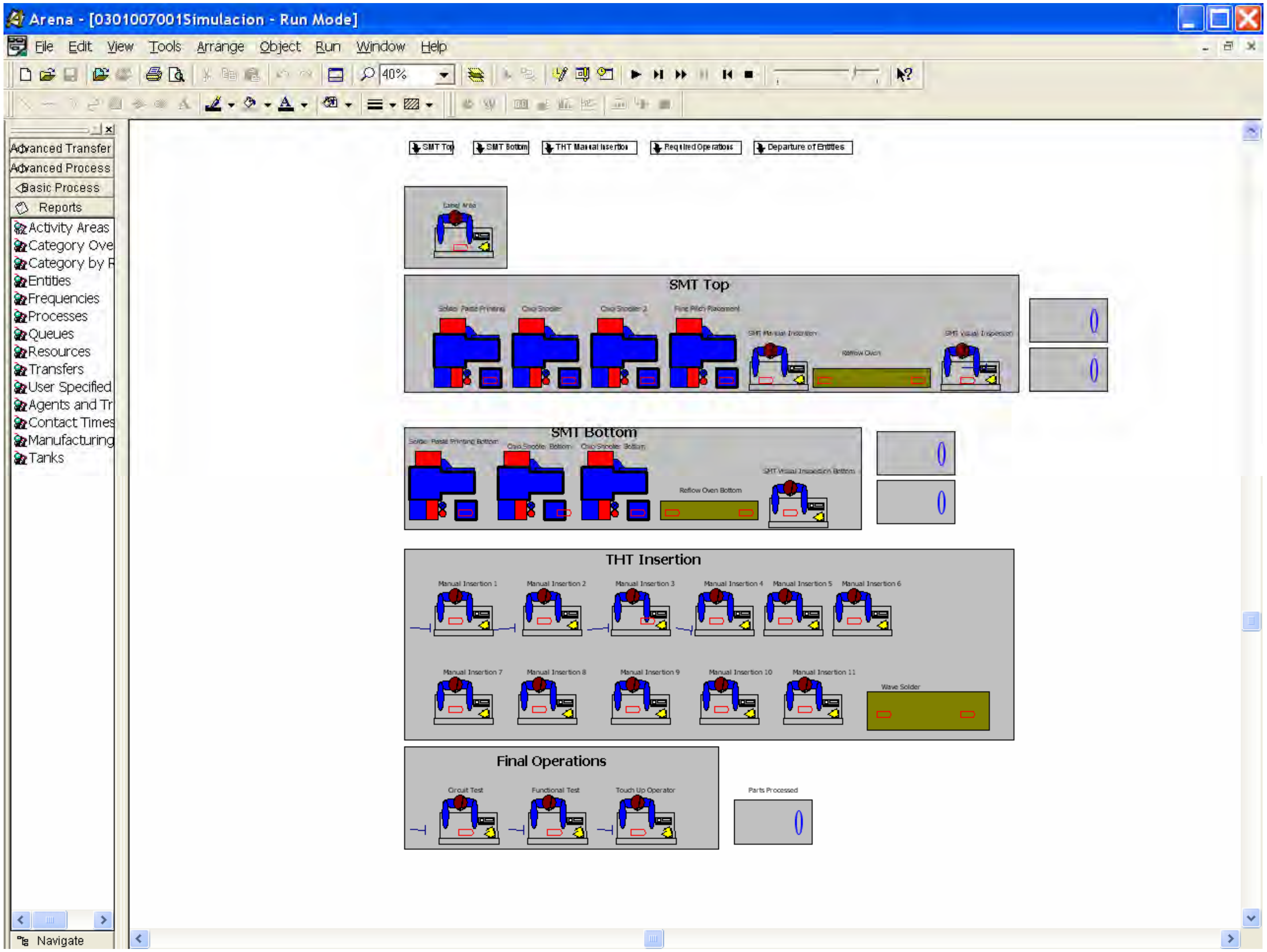

Figure 17 Simulation model developed to evaluate the efficiency of the cost model application developed

Table 58 Comparison between cost model application estimate and simulation model

Processes	Application	95 % CI Lower Bound	Mean	95 % CI Upper Bound	Is application estimate within interval ?	Minimum Average of the 10 replications	Maximum Average of the 10 replications	Minimum Value	Maximum Value
LABELS AREA	0.485	0.485	0.485	0.485	NO	0.479	0.489	0.000	0.572
SOLDER PASTE PRINTING	0.201	0.201	0.201	0.201	NO	0.199	0.203	0.000	0.218
CHIP SHOOTER PLACEMENT	3.311	3.304	3.304	3.314	YES	3.280	3.328	0.000	3.738
CHIP SHOOTER PLACEMENT 2	3.311	3.308	3.308	3.318	YES	3.293	3.319	0.000	3.568
FINE PITCH PLACEMENT	3.888	4.502	4.502	4.682	NO	4.250	4.922	0.000	5.425
REFLOW OVEN	1.107	5.919	5.919	5.919	NO	5.917	5.921	0.000	5.962
SMT VISUAL INSPECTION	3.561	3.627	3.627	3.647	NO	3.584	3.689	0.000	4.007
SOLDER PASTE PRINTING BOTTOM	0.201	0.201	0.201	0.201	NO	0.198	0.201	0.000	0.233
CHIP SHOOTER BOTTOM	3.631	3.610	3.610	3.630	NO	3.571	3.658	0.000	4.113
CHIP SHOOTER BOTTOM2	3.631	3.908	3.908	3.968	NO	3.778	4.048	0.000	4.569
REFLOW OVEN BOTTOM	1.107	5.929	5.929	5.929	NO	5.928	5.930	0.000	5.962
SMT VISUAL INSPECTION BOTTOM	3.613	3.879	3.879	3.919	NO	3.801	4.005	0.000	4.595
MANUAL INSERTION OF THT	3.126	3.120	3.120	3.140	YES	3.093	3.152	0.000	3.562
MANUAL INSERTION OF THT 2	3.573	6.957	6.957	7.027	NO	6.760	7.092	0.000	7.184
MANUAL INSERTION OF THT 3	3.722	6.967	6.967	7.087	NO	6.647	7.139	0.000	7.320
MANUAL INSERTION OF THT 4	3.424	3.521	3.521	3.551	NO	3.455	3.567	0.000	3.921
MANUAL INSERTION OF THT 5	3.126	3.130	3.130	3.150	NO	3.084	3.162	0.000	3.538
MANUAL INSERTION OF THT 6	2.977	2.968	2.968	2.978	YES	2.940	3.006	0.000	3.359
MANUAL INSERTION OF THT 7	3.870	7.121	7.121	7.241	NO	6.827	7.391	0.000	7.619
MANUAL INSERTION OF THT 8	4.317	8.233	8.233	8.303	NO	8.085	8.398	0.000	8.625
MANUAL INSERTION OF THT 9	2.828	2.780	2.780	2.790	NO	2.762	2.808	0.000	3.100
MANUAL INSERTION OF THT 10	3.275	3.236	3.236	3.256	NO	3.202	3.277	0.000	3.777
MANUAL INSERTION OF THT 11	3.275	3.241	3.241	3.261	NO	3.168	3.289	0.000	3.810
WAVESOLDER	0.449	3.376	3.376	3.376	NO	3.374	3.378	0.000	3.434
TOUCH UP	11.862	12.090	12.090	12.170	NO	11.891	12.241	0.000	14.428
ATE TEST	1.002	0.981	0.981	0.981	NO	0.974	0.987	0.000	1.102
BENCH TEST	3.000	2.945	2.945	2.955	NO	2.911	2.968	0.000	3.335
Average time in SMT Top	3.928	5.825	5.825	5.825	NO	5.818	5.834	0.000	5.969
Average time in SMT Bottom	3.655	5.806	5.806	5.806	NO	5.798	5.815	0.000	5.978
Total Time (min)	69.068	86.930	86.930	87.160	NO	86.338	87.571	0.000	88.998
Direct Labor Cost of Product $	9.485	11.938	11.938	11.970	NO	11.857	12.026	0.000	12.222

From Table 58, the following observation can be made.

1) Examination of the application estimate against the confidence intervals calculated for each process shows that only four processes fall inside the intervals.
2) Few processes fall between the minimum and maximum average of the replications.
3) All the values provided by the application are inside the minimum and maximum of the ten replications.
4) It should be noted that exist great differences between the times provided by the application and the simulation in the following processes: Reflow Oven, Reflow Oven Bottom and Wave Solder. These differences affect dramatically the total time of the product and logically the labor cost of the product. The percent difference in the total time and direct labor of the product is 23%.

From the previous results, it can be concluded that the application developed underestimate the labor cost of the product. The reason for this can be greatly influenced by the difference in the times of the conveyor of the facility.

CHAPTER 7: CONCLUSIONS, CONTRIBUTIONS AND FUTURE WORK

7.1 Conclusions

The main contribution of this project is the development of a computer based application to help electronic designers and process engineers to estimate the cost of new, improved or existing electronic products.

The project was accomplished in five stages. The first stage included the revision and generalization of the cost model developed by *Mendez*. The second stage was the explanation of the conceptual structure of the application. The third stage was the development of the database created to manage and store the information of facilities, processes and products needed to calculate the cost of products. The fourth stage was the implementation of the model. The fifth stage was the validation of the cost model application developed.

The designed application uses a graphical user interface allowing a friendly interaction between the model and the end user, converting it in a useful tool, easy to operate and understand. The mechanisms incorporated into the application include the creation of products and facilities to calculate its cost and it also allows calculating the cost of products in a default facility defined in the application.

With the purpose of validating the application, four products from a local electronic manufacturer were used to calculate its cost. A comparison between the cost spreadsheet model developed by the company to estimate the cost of its products and the cost reported by application was made and the discrepancies between models were discussed.

A discrete event simulation model was also constructed to evaluate the precision of the cost model application developed. In this analysis, the times of the conveyor were found as the main difference that affects the estimate provided by the application and although the percent difference between the estimates was 23%, the cost model application developed could be used as a tool to estimate the cost of its designs knowing that this estimate could vary. Although exist differences between the simulation model and the cost model application developed, the application developed provides an easy, fast and cheap estimate of the cost of an electronic product.

7.2 Contributions of this research

1) The *Mendez* cost model has been generalized and simplified.
2) The generalized model has been implemented in a computer application to estimate the cost of electronic designs.
3) It was demonstrated that the application developed produces very similar results to those obtained by a specific model developed by a company to calculate the cost of its products.
4) The limitations of the model were understood when it was compared with a simple simulation model. Although there were differences between the simulation model and the cost model application developed, the tool provided an easy, fast and cheap estimate of the cost of an electronic product.

7.3 Future research

As future research, the following thins must be done.

1. A standard case study must be generated to prove the cost model proposed.
2. It is also imperative to collect data from different companies of the industry to generate a standard data set that could represent typical industry values of the default (virtual) facility of the application.
3. A standard should be generated to characterize the assembly requirements of all the components in the electronics industry and design a database to maintain the characterization, required drawings or specifications of these components.
4. If such effort is made, a designer using the standard database could generate its designs in a CAD program and obtain a cost estimate of the designs being generated if the developed application in this research is complemented in an integrated application.
5. The model and its application should have the ability to account for possible random variations in the processes. The times in the processes of a facility are not always the same and logically the total cost of a product is affected by this. A better result should be an interval instead of a point estimate. Due to the inherent uncertainty this would be a more realistic way to represent the cost of a product.

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APPENDIXES

APPENDIX A. BRIEF DESCRIPTION OF THE TYPICAL ASSEMBLY PROCESSES IN TODAY'S ELECTRONIC INDUSTRY

This appendix contains a brief description of the typical assembly processes in today's electronic industry. It was reproduced with permission from "Development of Cost Model for Power Electronic Assemblies, *Mendez* M., University of Puerto Rico – Mayagüez Campus, 1998, ME Thesis.

Assembly processes of electronics products

THT (Through Hole Technology)

a. Kit Segregation – This operation is composed of two sub-operations: preparing THT components to be preformed, and preparing any brackets included in any assembly process.
b. Preforming – Some of the THT components require a special treatment, like bending or cutting its legs, before being manually inserted on the PCB. The preforming process is done manually and/or with special simple machines designed for specific components. In this operation, the components are usually taken from bags placed on the Kit Segregation racks and processed in the appropriate machine.
c. Bin-Up – The THT components to be manually assembled are classified and placed in the manual insertion bins. This includes the identification of the part numbers to be processed and placing the components (from preforming or not) in the bins. The bins are usually placed on a rack for the manual insertion area.

d. Sequencer – This operation requires the use of a machine that prepares a tape of THT components on the specified sequence to be assembled using the Auto Insertion Variable Center Distance (VCD) process.

e. Auto Insertion VCD – In this operation, the THT components previously prepared in Sequencer are automatically inserted on the board.

f. Auto Insertion Dual In-line Package (DIP) – In this operation, the THT dual in-line packages (DIP) are automatically inserted on the board.

SMT (Surface Mount Technology)

g. Solder Paste Printing – a machine that applies solder paste to the board on the specified locations where SMT components are going to be placed performs this operation.

h. Glue Application – A machine applies glue to the board on the specified locations where chips that will be wire bonded later are going to be placed. This operation may be performed for top and bottom sides of a two-sided board.

i. Chip Shooter Placement – In this operation a placement machine automatically places the small, usually leadless SMT components on the board. This operation may be performed for top and bottom sides of two-sided boards.

j. Fine Pitch Placement – In this operation a placement machine automatically places large components with many closely spaced connections such as ball grid array (BGA) packages on the board.

k. Manual Assembly of SMT – In this operation, SMT components that for any reason cannot be placed automatically on the component placement machines (usually connectors) are placed manually on the board.

l. Reflow – In this operation a reflow oven melts the solder paste to adhere the SMT components to the board. This operation may be performed for top and bottom sides of the two-sided board.

m. SMT Visual Inspection – A visual inspection is performed to the already soldered SMT components in order to find functional and cosmetic defects on the solder and/or components placed. This operation is performed for top and bottom sides of two-sided boards.

2) **Chip on Board Wire Bonding –** In this operation a machine is used to automatically placed wires to silicon chip types of components while bonding them to the board.

3) **Panel Preparation –** In this operation some sensitive areas of the boards are protected in order to process it through a Wave Solder machine later.

4) **Manual Insertion of THT –** This is an operation with multiple sequential stations where most of the THT components that were previously placed in the bins, are manually assembled.

5) **Wave Solder –** In this operation a machine solders the THT components to the board.

6) **Routing and Singulation –** During this process a machine is used to divide a PCB panel into multiple individual and identical boards.

7) **Tests –** In this area, two types of tests are typically performed to the boards. The first one is the electrical in-circuit test where each component of the board is tested individually. The second one is the functional test where the entire assembly is electrically tested simulating the intended function of the board.

8) **Touch-up –** In this operation the THT components soldered by the Wave Solder are inspected and repaired if necessary, for functional or cosmetic reasons.

9) **Final Assembly –** In this operation mechanical components that do not require soldering (brackets, screws, sockets, labels, etc.) are assembled on the board.

10) **Final Inspection –** In this area a final inspection is performed to the board to ensure customer specifications are met.

APPENDIX B. EQUATIONS FROM *MENDEZ* ASSEMBLY COST MODEL

This appendix contains the equations of *Mendez* assembly cost model which were generalized in this research. The material was reproduced with permission from "Development of Cost Model for Power Electronic Assemblies, *Mendez* M., University of Puerto Rico – Mayagüez Campus, 1998, ME Thesis.

Setup time terminology and equations

Setup time terminology	
$TKSprep_{BD}$ –	Time of preparation for kit segregation per board
$TKSprep_{BH}$ –	Time of preparation for kit segregation per batch
$TSUpref_{BD}$ –	Preforming setup time per board
$TSUpref_{BH}$ –	Preforming setup time per batch
$TSUbin_{BD}$ –	Bin-up setup time per board
$TSUbin_{BH}$ –	Bin-up setup time per batch
$TSUseq_{BD}$ –	Sequencer setup time per board
$Treels_{PN}$ –	Time to change reels per part number
$N\textit{pn}vcd_{BD}$ –	Number of radial THT (VCD) part numbers per board
$TSUvcd_{BH}$ –	Auto insertion VCD setup time per batch
$TSUdip_{BD}$ –	Auto insertion DIP setup time per board
$TSUdip_{BH}$ –	Auto insertion DIP setup time per batch
$TSUscpr_{BD}$ –	Screen printing setup time per board
$TSUIscpr_{BH}$ –	Initial screen printing setup time per batch
$TCLscpr_{OCC}$ –	Screen printing cleaning time per occurrence
$N\textit{pl}scpr_{OCC}$ –	Number of panels processed per screen printing cleaning occurrence
$TSUglap_{BD}$ –	Glue application setup time (top) per board
$TSUglapb_{BD}$ –	Glue application setup time (bottom) per board
$TSUIglap_{BH}$ –	Initial glue application setup time (top) per batch
$TSUIglapb_{BH}$ –	Initial glue application setup time (bottom) per batch
$TCLglap_{OCC}$ –	Glue application cleaning time per occurrence
$N\textit{pl}glap_{OCC}$ –	Number of panels processed per glue application cleaning occurrence
$TSUchshb_{BD}$ –	Chip shooter setup time (bottom) per board
$TSUIchsh_{BH}$ –	Initial chip shooter setup time (top) per batch
$TSUIchshb_{BH}$ –	Initial chip shooter setup time (bottom) per batch
$TRPchsh_{PN}$ –	Chip shooter reels pick up time per part number
$N\textit{pn}nfptop_{BH}$ –	Number of SMT non fine pitch part numbers to be placed on top of batch

Setup time terminology	
$TRCchsh_{PN}$ –	Chip shooter reel change time per part number
$N\mathit{pn}nfpbot_{BH}$ –	Number of SMT non fine pitch part numbers to be placed on bottom of batch
$TSUfipi_{BD}$ –	Fine pitch setup time per board
$TSUIfipi_{BH}$ –	Initial fine pitch setup time per batch
$TRPfipi_{PN}$ –	Fine pitch reels pick up time per part number
$N\mathit{pn}fp_{BD}$ –	Number of SMT fine pitch part numbers per board
$TRCfipi_{PN}$ –	Fine pitch reel change time per part number
$TSUref_{BD}$ –	Reflow setup time (top) per board
$TSUref_{BH}$ –	Reflow setup time (top) per batch
$TSUbref_{BH}$ –	Reflow setup time (bottom) per batch
$TSUrefb_{BH}$ –	Reflow setup time (bottom) per batch
$TSUwire_{BD}$ –	Wire bonding setup time per board
$TSUwire_{BH}$ –	Wire bonding setup time per batch
$TSUprep_{BD}$ –	Panel preparation setup time per board
$TSUprep_{BH}$ –	Panel preparation setup time per batch
$TSUmantht_{BD}$ –	Manual insertion setup time allocated per board
$TSUmantht_{BH}$ –	Manual insertion setup time per batch
$TSUwave_{BD}$ –	Wave solder initial setup time per board
$TSUwave_{BH}$ –	Wave solder initial setup time per batch
$TSUrsg_{BD}$ –	Routing and singulation setup time per board
$TSUrsg_{BH}$ –	Routing and singulation setup time per batch
$TSUtests_{BD}$ –	Tests setup time per board
$TSUcircuit_{BH}$ –	In-circuit test setup time per batch
$N\mathit{bd}_{PL}$ –	Number of boards per panel
$N\mathit{pl}_{BH}$ –	Number of panels per batch

Setup Time equations	
Kit Segregation	$TKSprep_{BD} = \frac{TKSprep_{BH}}{Nbd_{PL} * Npl_{BH}}$
Preforming	$TSUpref_{BD} = \frac{TSUpref_{BH}}{Nbd_{PL} * Npl_{BH}}$
Bin Up	$TSUbin_{BD} = \frac{TSUbin_{BH}}{Nbd_{PL} * Npl_{BH}}$
Sequencer	$TSUseq_{BD} = \frac{Treels_{PN} * Npnvcd_{BD}}{Nbd_{PL} * Npl_{BH}}$
Auto Insertion VCD	$TSUvcd_{BD} = \frac{TSUvcd_{BH}}{Nbd_{PL} * Npl_{BH}}$
Auto Insertion DIP	$TSUdip_{BD} = \frac{TSUdip_{BH}}{Nbd_{PL} * Npl_{BH}}$

Setup Time equations	
Solder Paste Printing	$TSUscpr_{BD} = \left[\frac{TSUIscpr_{BH}}{Nbd_{PL} * Npl_{BH}} + \frac{\left(TCLscpr_{OCC} / Nplscpr_{OCC}\right)}{Nbd_{PL}} \right]$
Glue Application	$TSUglap_{BD} = \left[\frac{TSUIglap_{BH}}{Nbd_{PL} * Npl_{BH}} + \frac{\left(TCLglap_{OCC} / Nplglap_{OCC}\right)}{Nbd_{PL}} \right]$
Glue Application Bottom	$TSUglapb_{BD} = \left[\frac{TSUIglapb_{BH}}{Nbd_{PL} * Npl_{BH}} + \frac{\left(TCLglap_{OCC} / Nplglap_{OCC}\right)}{Nbd_{PL}} \right]$
Chip Shooter Placement	$TSUchsh_{BD} = \frac{\left[TSUIchsh_{BH} + \left(TRPchsh_{PN} * Npnnfptop_{BH}\right) + \left(TRCchsh_{PN} * Npnnfptop_{BH}\right) \right]}{Nbd_{PL} * Npl_{BH}}$
Chip Shooter Placement Bottom	$TSUchshb_{BD} = \frac{\left[TSUIchshb_{BH} + \left(TRPchsh_{PN} * Npnnfpbot_{BH}\right) + \left(TRCchsh_{PN} * Npnnfpbot_{BH}\right) \right]}{Nbd_{PL} * Npl_{BH}}$
Fine Pitch Placement	$TSUfipi_{BD} = \left[\frac{TSUIfipi_{BH}}{Nbd_{PL} * Npl_{BH}} + \left(TRPfipi_{PN} * Npnfp_{BD}\right) + \left(TRCfipi_{PN} * Npnfp_{BD}\right) \right]$
Reflow Oven	$TSUref_{BD} = \frac{TSUref_{BH}}{Nbd_{PL} * Npl_{BH}}$
Reflow Oven Bottom	$TSUrefb_{BD} = \frac{TSUrefb_{BH}}{Nbd_{PL} * Npl_{BH}}$
Chip On Board Wire Bonding	$TSUwire_{BD} = \frac{TSUwire_{BH}}{Nbd_{PL} * Npl_{BH}}$
Manual Insertion of THT	$TSUmantht_{BD} = \frac{TSUmantht_{BH}}{Nbd_{BH}}$
Wave Solder	$TSUwave_{BD} = \frac{TSUwave_{BH}}{Nbd_{PL} * Npl_{BH}}$

Setup Time equations	
Routing and Singulation	$TSUrsg_{BD} = \frac{TSUrsg_{BH}}{Nbd_{PL} * Npl_{BH}}$
Circuit and Functional Test	$TSUtests_{BD} = \frac{TSUcircuit_{BH} + TSUfunctional_{BH}}{Nbd_{PL} * Npl_{BH}}$

Loading and Unloading time terminology and equations

Terminology	
$TLUvcd_{BD}$ –	Auto insertion VCD loading/unloading time per board
$TLUvcd_{PL}$ –	Auto insertion VCD loading/unloading time per panel
$TLUdip_{BD}$ –	Auto insertion DIP loading/ unloading time per board
$TLUdip_{PL}$ –	Auto insertion DIP loading/ unloading time per panel
$TLsmt_{BD}$ –	SMT processes loading time per board
$TLsmt_{PL}$ –	SMT processes loading time per panel
$TLUsmt_{BD}$ –	SMT processes loading/unloading time per board
$TLUsmt_{PL}$ –	SMT processes loading/unloading time per panel
$TLUsmt_{BD}$ –	SMT processes loading/unloading time per board
$THGvins_{PL}$ –	Time to place panels on rack once inspected
$THGwire_{BD}$ –	Wire bonding handling time per board
$THGwire_{BD}$ –	Wire bonding handling time per board
$THGprep_{BD}$ –	Panel preparation handling time per board
$THGprep_{PL}$ –	Panel preparation handling time per panel
$TLUwave_{BD}$ –	Wave solder loading/unloading time per board
$TLUwave_{PL}$ –	Wave solder loading/unloading time per panel
$TLUrsg_{BD}$ –	Routing and singulation loading/unloading time per board
$TLrsg_{PL}$ –	Routing and singulation loading time per panel
$TUrsg_{BD}$ –	Routing and singulation unloading time per board
$THGtests_{BD}$ –	Tests handling time per board
$THGcircuit_{BD}$ –	In-circuit test handling time per board
$THGfunctional_{BD}$ –	Functional test handling time per board
$THGrkcy_{BD}$ –	Handling time to move board from functional test to the rack or conveyor
$THGtouch_{BD}$ –	Touch-up handling time per board
$THGfinal_{BD}$ –	Final assembly handling time per board
$THGfinins_{BD}$ –	Final inspection handling time per board
$N\mathit{bd}_{PL}$ –	Number of boards per panel
$N\mathit{pl}_{BH}$ –	Number of panels per batch

Loading and Unloading equations	
Auto Insertion VCD	$TLUvcd_{BD} = \frac{2*TLUvcd_{PL}}{Nbd_{PL}}$
Auto Insertion DIP loading and unloading time	$TLUdip_{BD} = \frac{2*TLUdip_{PL}}{Nbd_{PL}}$
SMT processes loading time	$TLsmt_{BD} = \frac{TLsmt_{PL}}{Nbd_{PL}}$
SMT processes loading and unloading time	$TLUsmt_{BD} = \frac{2*TLUsmt_{PL}}{Nbd_{PL}}$
Chip on Board Wire Bonding handling time	$THGwire_{BD} = \frac{2*THGwire_{PL}}{Nbd_{PL}*Npl_{BH}}$
Panel Preparation handling time	$THGprep_{BD} = \frac{2*THGprep_{PL}}{Nbd_{PL}}$
Wave Solder loading and unloading time	$TLUwave_{BD} = \frac{2*TLUwave_{PL}}{Nbd_{PL}}$
Routing and Singulation loading and unloading time	$TLUrsg_{BD} = \frac{TLrsg_{PL}}{Nbd_{PL}} + TUrsg_{BD}$
Circuit Test, Functional Test and Rack Conveyor handling time	$THGtests_{BD} = \begin{bmatrix} THGcircuit_{BD} + \\ THGfunctional_{BD} + \\ THGrkcy_{BD} \end{bmatrix}$
Touch Up handling time	$2 * THGtouch_{BD}$
Final Assembly handling time	$2 * THGfinal_{BD}$
Final Inspection handling time	$2 * THGfinins_{BD}$

Process time Terminology and equations

Terminology	
TPK_{BD} –	Time to prepare a kit per board
$N\mathit{pn}$ –	Number of components part numbers
$Tret\mathit{pn}$ –	Time to retrieve part numbers from rack
$Tcount_{CP}$ –	Time to count per component
$N\mathit{cp}_{PNi}$ –	Number of components per part number *i*
$N\mathit{bd}_{PL}$ –	Number of boards per panel
$N\mathit{pl}_{BH}$ –	Number of panels per batch
$Tpref_{BD}$ –	Time to preform per board
$Tpref_{CP}$ –	Time to preform per component
$Npref\mathit{cp}_{BD}$ –	Number of components to be preformed per board

Terminology	
$Tbin_{BD}$ –	Time to bin-up per board
$Tbin_{CP}$ –	Time to bin-up per component
$N\mathit{cp}_{PN}$ –	Number of components per part number
$N\mathit{pn}$ –	Number of components part numbers
$Tseq_{CP}$ –	Sequencer time per component
$N\mathit{cp}vcd_{BD}$ –	Number of radial THT (VCD) components per board
$Tvcd_{BD}$ –	Auto insertion VCD machine time per board
$Tvcd_{CP}$ –	Auto insertion VCD process time per component
$N\mathit{cp}vcd_{BD}$ –	Number of radial THT (VCD) components per board
$Tdip_{BD}$ –	Auto insertion DIP process time per board
$Tdip_{CP}$ –	Auto insertion DIP process time per component
$N\mathit{cp}dip_{BD}$ –	Number of components to place in auto insertion DIP per board
$Tscpr_{BD}$ –	Screen printing machine time per board
$Tscpr_{PL}$ –	Screen printing machine time per panel
$Tglap_{BD}$ –	Glue application machine time (top) per board
$Tglapb_{BD}$ –	Glue application machine time (bottom) per board
$Tglap_{CP}$ –	Glue application machine time per component
$N\mathit{cp}wrtop_{BD}$ –	Number of SMT non fine pitch components to be wire bonded on top of board
$N\mathit{cp}wrbot_{BD}$ –	Number of SMT non fine pitch components to be wire bonded on bottom of board
$Tchsh_{BD}$ –	Chip shooter machine time (top) per board
$Tchshb_{BD}$ –	Chip shooter machine time (bottom) per board
$Tchsh_{CP}$ –	Chip shooter machine time per component
$N\mathit{cp}nfptop_{BD}$ –	Number of SMT non fine pitch components to be placed on top of board
$N\mathit{cp}nfpbot_{BD}$ –	Number of SMT non fine pitch components to be placed on bottom of board
$Tfipi_{BD}$ –	Fine pitch machine time per board
$Tfipi_{CP}$ –	Fine pitch machine time per component
$N\mathit{cp}fp_{BD}$ –	Number of SMT fine pitch components per board
$Tmansmt_{BD}$ –	Manual assembly time per board
$Tmansmt_{CP}$ –	Manual assembly time per component
$N\mathit{cp}conn_{BD}$ –	Number of SMT connectors to be assembled manually on board
$Tref_{BD}$ –	Reflow machine time per board
$Tref_{PL1}$ –	Reflow machine time for first panel
$Tref_{PLS}$ –	Reflow machine cycle time
$N\mathit{pl}_{BH}$ –	Number of panels per batch
CVLref –	Reflow conveyor length size
CVSref –	Reflow conveyor speed
$SDref_{PL}$ –	Reflow conveyor separation distance between panels
$Size_{PL}$ –	Assembly panel size (length)
$TTRvins_{PL}$ –	Time to move to visual inspection per panel
$TIsmt_{BD}$ –	Inspection time (top) per board

Terminology	
$TIsmt_{CP}$ –	Inspection time per component
$N\mathit{cp}smttop_{BD}$ –	Number of SMT components to be placed on top of board
$N\mathit{cp}fp_{BD}$ –	Number of SMT fine pitch components per board
$N\mathit{cp}nfptop_{BD}$ –	Number of SMT non fine pitch components to be placed on top of board
$N\mathit{cp}nfpbot_{BD}$ –	Number of SMT non fine pitch components to be placed on bottom of board
$Twire_{BD}$ –	Wire bonding machine time per board
$Twire_{WR}$ –	Wire bonding machine time per wire
$N\mathit{wr}_{BD}$ –	Number of wire bonded connectors per board
$Tprep_{BD}$ –	Panel preparation time per board
$Tprep_{PT}$ –	Panel preparation time per part
$N\mathit{pt}gold_{BD}$ –	Number of gold plated parts on the board
$Tmantht_{CP}$ –	Manual insertion time (hours) per component
$N\mathit{cp}mantht_{BD}$ –	Number of THT radial components to be inserted manually on board
Nstation –	Number of manual insertion stations used
$Tcycle_{BD}$ –	Cycle time per board
$N\mathit{bd}_{HR}$ –	Number of required boards per hour
$Twave_{BD}$ –	Wave solder machine time per board
$Twave_{PL1}$ –	Wave solder machine time for first panel
$Twave_{PLS}$ –	Wave solder machine cycle time
CVLwave –	Wave solder conveyor length size
CVSwave –	Wave solder conveyor speed
$SDwave_{PL}$ –	Wave solder conveyor separation distance between panels
$Size_{PL}$ –	Assembly panel size (length)
$Trsg_{BD}$ –	Routing and singulation machine time per board
$Trsg_{PL}$ –	Routing and singulation time per panel
$Ttests_{BD}$ –	Tests machine time per board
$Tcircuit_{BD}$ –	In-circuit test time per board
$Tfunctional_{BD}$ –	Functional test time per board
$Ttouch_{BD}$ –	Touch-up time per board
$Tfinal_{BD}$ –	Final assembly time per board
$Tfinal_{CP}$ –	Final assembly time per component to be placed in final assembly area
$N\mathit{cp}br_{BD}$ –	Number of brackets or sockets components per board
$Tfinins_{BD}$ –	Final inspection time per board
$N\mathit{bd}_{PL}$ –	Number of boards per panel
$N\mathit{pl}_{BH}$ –	Number of panels per batch

Process time equations	
Kit Segregation	$TPK_{BD}=\frac{Npn*Tretpn}{Nbd_{BH}}+Tcount_{CP}*\sum_{i=1}^{Npn}Ncp_{PN_i}$
Preforming	$Tpref_{BD}=Tpref_{CP}*Nprefcp_{BD}$
Bin Up	$Tbin_{BD}=Tbin_{CP}*Ncp_{PN}*Npn$
Sequencer	$Tseq_{BD}=Tseq_{CP}*Ncpvcd_{BD}$
Auto Insertion VCD	$Tvcd_{BD}=Tvcd_{CP}*Ncpvcd_{BD}$
Auto Insertion DIP	$Tdip_{BD}=Tdip_{CP}*Ncpdip_{BD}$
Solder Paste Printing	$Tscpr_{BD}=\frac{Tscpr_{PL}}{Nbd_{PL}}$
Glue Application	$Tglap_{BD}=Tglap_{CP}*Ncpwrtop_{BD}$
Glue Application Bottom	$Tglapb_{BD}=Tglap_{CP}*Ncpwrbot_{BD}$
Chip Shooter Placement	$Tchsh_{BD}=Tchsh_{CP}*Ncpnfptop_{BD}$
Chip Shooter Placement Bottom	$Tchshb_{BD}=Tchsh_{CP}*Ncpnfpbot_{BD}$
Fine Pitch Placement	$Tfipi_{BD}=Tfipi_{CP}*Ncpfp_{BD}$
Manual Assembly of SMT	$Tmansmt_{BD}=Tmansmt_{CP}*Ncpconn_{BD}$
Reflow Oven or Reflow Oven Bottom	$Tref_{BD}=\frac{Tref_{PL1}+Tref_{PLS}*\left(Npl_{BH}-1\right)}{Nbd_{BH}}$ $Tref_{PL1}=\frac{CVLref}{CVSref}$ $Tref_{PLS}=\frac{\left(SDref_{PL}+Size_{PL}\right)}{CVSref}$
Manual Assembly of SMT	$TIsmt_{BD}=TIsmt_{CP}*Ncpsmttop_{BD}$ $Ncpsmttop_{BD}=Ncpfp_{BD}+Ncpnfptop_{BD}$
Chip on Board Wire Bonding	$Twire_{BD}=Twire_{WR}*Nwr_{BD}$
Panel Preparation	$Tprep_{BD}=Tprep_{PT}*Nptgold_{BD}$
Manual Insertion of THT	$Tmantht_{BD}=Tmantht_{CP}*Ncpmantht_{BD}$
Wave Solder	$Twave_{BD}=\frac{Twave_{PL1}+\left[Twave_{PLS}*\left(Npl_{BH}-1\right)\right]}{Nbd_{BH}}$ $Twave_{PL1}=\frac{CVLwave}{CVSwave}$ $Twave_{PLS}=\frac{\left(SDwave_{PL}+Size_{PL}\right)}{CVSwave}$

Process time equations	
Routing and Singulation	$Trsg_{BD} = \frac{Trsg_{PL}}{Nbd_{PL}}$
Circuit and Functional Test	$Ttests_{BD} = Tcircuit_{BD} + Tfunctional_{BD}$
Touch Up	$Ttouch_{BD}$
Final Assembly	$Tfinal_{BD} = Tfinal_{CP} * Ncpbr_{BD}$
Final Inspection	$Tfinins_{BD}$

Travel time terminology and equations

Terminology	
$TTRpref_{BD}$ –	Time to move kit to preforming area per board
$TTRpref_{BH}$ –	Time to move kit to preforming area per batch
$TTRbin_{BD}$ –	Time to move kit to bin-up area per board
$TTRbin_{BH}$ –	Time to move kit to bin-up area per batch
$TTRmantht_{BD}$ –	Time to move to manual insertion area per board
$TTRmantht_{BH}$ –	Time to move to manual insertion area per batch
$TTRseq_{BD}$ –	Time to move from sequencer to auto insertion VCD area per board
$TTRseq_{BH}$ –	Time to move from sequencer to auto insertion VCD area per batch
$TTRdip_{BD}$ –	Time to move to auto insertion DIP area per board
$TTRdip_{BH}$ –	Time to move to auto insertion DIP area per batch
$TTRaid_{BD}$ –	Time to move to either panel preparation or glue application area per board
$TTRglap_{BH}$ –	Time to move to glue application area per batch
$TTRprep_{BH}$ –	Time to move to panel preparation area per batch
$TTRspga_{BD}$ –	Time to move from screen printing to glue application process per board
$TTRspga_{PL}$ –	Time to move from screen printing to glue application process per panel
$TTRchsh_{BD}$ –	Time to move to chip shooter process per board
$TTRchsh_{PL}$ –	Time to move to chip shooter process per panel
$TTRfipi_{BD}$ –	Time to move to fine pitch process per board
$TTRfipi_{PL}$ –	Time to move to fine pitch process per panel
$TTRmansmt_{BD}$ –	Time to move to manual SMT process per board
$TTRmansmt_{PL}$ –	Time to move to manual SMT process per panel
$TTRref_{BD}$ –	Time to move to manual reflow process per board
$TTRref_{PL}$ –	Time to move to manual reflow process per panel
$TTRvins_{BD}$ –	Time to move to visual inspection per board
$TTRvins_{PL}$ –	Time to move to visual inspection per panel
$TTRprep_{BD}$ –	Total time to move to panel preparation process per board

Terminology	
$TTRvins_{BH}$ –	Time to move from visual inspection to wire bonding per batch
$TTRvinsb_{BH}$ –	Time to move from visual inspection to panel preparation per batch
$TTRvcd_{BD}$ –	Time to move to auto insertion VCD process per board
$TTRvcd_{BH}$ –	Time to move to auto insertion VCD area per batch
$TTRmantht_{BD}$ –	Time to move to manual insertion area per board
$TTRmantht_{BH}$ –	Time to move to manual insertion area per batch
$TTRmiws_{BD}$ –	Time to move to wave solder process per board
$TTRmiws_{BH}$ –	Time to move to wave solder process per batch
$TTRstation_{BD}$ –	Time to move to next manual insertion station per board
$TTRstation_{PL}$ –	Time to move to next manual insertion station per panel
$TTRrsg_{BD}$ –	Time to move to routing and singulation process per board
$TTRrsg_{BH}$ –	Time to move to routing and singulation process per batch
$TTRrsg_{PL}$ –	Time to move to routing and singulation process per panel
$TTRtests_{BD}$ –	Time to move to tests area per board
$TTRtests_{BH}$ –	Time to move to tests area per batch
$TTRtests_{PL}$ –	Time to move to tests area per panel
$TTRtouch_{BD}$ –	Time to move to touch-up area per board
$TTRtouch_{BH}$ –	Time to move to touch-up area per batch
$TTRtouch_{PL}$ –	Time to move to touch-up area per panel
$TTRfinal_{BD}$ –	Time to move to final assembly area per board
$TTRfinal_{BH}$ –	Time to move to final assembly area per batch
$TTRfinins_{BD}$ –	Time to move to final inspection area per board
$TTRfinins_{BH}$ –	Time to move to final inspection area per batch
$N\mathit{bd}_{PL}$ –	Number of boards per panel
$N\mathit{pl}_{BH}$ –	Number of panels per batch

Travel Time equations	
Kit Segregation	$TTRpref_{BD} = \frac{TTRpref_{BH}}{Nbd_{BH}}$
Preforming	$TTRbin_{BD} = \frac{TTRbin_{BH}}{Nbd_{BH}}$
Bin Up	$TTRmantht_{BD} = \frac{TTRmantht_{BH}}{Nbd_{BH}}$
Sequencer	$TTRseq_{BD} = \frac{TTRseq_{BH}}{Nbd_{BH}}$
Auto Insertion VCD	$TTRdip_{BD} = \frac{TTRdip_{BH}}{Nbd_{BH}}$
Auto Insertion DIP	$TTRaid_{BD} = \frac{TTRglap_{BH} * BS + TTRprep_{BH} * (1\text{-}BS)}{Nbd_{BH}}$

Travel Time equations	
Solder Paste Printing	$TTRspga_{BD}=\frac{TTRspga_{PL}}{Nbd_{PL}}$
Chip Shooter Placement	$TTRchsh_{BD}=\frac{TTRchsh_{PL}}{Nbd_{PL}}$
Fine Pitch Placement	$TTRfipi_{BD}=\frac{TTRfipi_{PL}}{Nbd_{PL}}$
Manual Assembly of SMT	$TTRmansmt_{BD}=\frac{TTRmansmt_{PL}}{Nbd_{PL}}$
Reflow Oven	$TTRref_{BD}=\frac{TTRref_{PL}}{Nbd_{PL}}$
SMT Visual Inspection	$TTRwire_{BD}=\frac{THGvins_{PL}}{Nbd_{PL}}+\frac{TTRvins_{BH}}{Nbd_{BH}}$
SMT Visual Inspection Bottom	$TTRprep_{BD}=\frac{THGvins_{PL}}{Nbd_{PL}}+\frac{TTRvinsb_{BH}}{Nbd_{BH}}$
Chip on Board Wire Bonding	$TTRvcd_{BD}=\frac{TTRvcd_{BH}}{Nbd_{BH}}$
Panel Preparation	
Panel Preparation	$TTRmantht_{BD}=\frac{TTRmantht_{BH}}{Nbd_{BH}}$
Manual Insertion of THT	$TTRmiws_{BD}=\frac{TTRmiws_{BH}}{Nbd_{BH}}+TTRstation_{BD}$ $TTRstation_{BD}=\frac{TTRstation_{PL}}{Nbd_{PL}}*Nstation$
Wave Solder	$TTRrsg_{BD}=\frac{TTRrsg_{BH}*CY}{Nbd_{BH}}+\frac{TTRrsg_{PL}*(1-CY)}{Nbd_{PL}}$
Tests	$TTRtests_{BD}=\frac{TTRtests_{BH}*CY}{Nbd_{BH}}+\frac{TTRtests_{PL}*(1-CY)}{Nbd_{PL}}$
Touch Up	$TTRtouch_{BD}=\frac{TTRtouch_{BH}*CY}{Nbd_{BH}}+\frac{TTRtouch_{PL}*(1-CY)}{Nbd_{PL}}$
Final Assembly	$TTRfinal_{BD}=\frac{TTRfinal_{BH}}{Nbd_{BH}}$
Final Inspection	$TTRfinins_{BD}=\frac{TTRfinins_{BH}}{Nbd_{BH}}$

Labor Cost terminology and equations

Labor Cost Terminology	
$DLCks_{bd}$ –	Kit segregation direct labor cost per board
$TTks_{bd}$ –	Total kit segregation time per board
$DLCpf_{BD}$ –	Preforming direct labor cost per board
Tpf_{BD} –	Total preforming time per board
$DLCbu_{bd}$ –	Bin-up direct labor cost per board
$TTbu_{bd}$ –	Total bin-up time per board
$DLCseq_{BD}$ –	Sequencer direct labor cost per board
TSQ_{BD} –	Total sequencer process time per board
$Rate_{HR}$ –	Average assembly hourly wage rate (provided by top management)
$DLCvcd_{BD}$ –	Auto insertion VCD direct labor cost per board
$TAIV_{BD}$ –	Total auto insertion VCD process time per board (refer to equation 2.18)
$DLCdip_{BD}$ –	Auto insertion DIP direct labor cost per board
$TAID_{BD}$ –	Total auto insertion DIP machine time per board (refer to equation 2.23)
$DLCwire_{BD}$ –	Chip-on-board wire bonding direct labor cost per board
TWB_{BD} –	Total wire bonding process time per board
$DLCprep_{BD}$ –	Panel preparation direct labor cost per board
TPP_{BD} –	Total panel preparation time allocated per board (refer to equation 2.82)
$Rate_{HR}$ –	Average assembly hourly wage rate (provided by top management)
$DLCmi_{BD}$ –	Manual insertion direct labor cost per board
TMI_{BD} –	Total manual insertion time allocated per board (refer to equation 2.87)
$DLCwave_{BD}$ –	Wave solder direct labor cost per board
TWS_{BD} –	Total wave solder process time per board
$DLCrsg_{BD}$ –	Routing and singulation direct labor cost per board
$TRSG_{BD}$ –	Total routing and singulation process time per board (refer to equation 2.101)
N*me*route –	Number of required routing and singulation machines
$EFroute_{ME}$ –	Routing and singulation machine efficiency
$DLCtests_{BD}$ –	Tests direct labor cost per board
TTT_{BD} –	Total tests processes time allocated per board
N*me*tests –	Number of required tests machines
$EFtests_{ME}$ –	Tests machine efficiency
$DLCtouch_{BD}$ –	Touch-up direct labor cost per board
TUP_{BD} –	Total touch-up time allocated per board
$DLCfinal_{BD}$ –	Final assembly direct labor cost per board
TFA_{BD} –	Total final assembly time per board
$DLCfinins_{BD}$ –	Final inspection direct labor cost per board

Labor Cost Terminology	
TFI_{BD} –	Total final inspection time per board
D_{YR} –	Annual demand
$N\mathit{day}_{YR}$ –	Number of working days per year
$N\mathit{hrs}_{DAY}$ –	Number of working hours per day
$Rate_{hr}$ –	Average assembly hourly wage rate (provided by top management)

Labor Cost equations	
Kit Segregation	$DLCks_{bd} = TTks_{bd} * Rate_{hr}$
Preforming	$DLCpf_{bd} = TTpf_{bd} * Rate_{hr}$
Bin Up	$DLCbu_{bd} = Tbu_{BD} * Rate_{hr}$
Sequencer	$DLCseq_{BD} = TSQ_{BD} * Rate_{HR}$
Auto Insertion VCD	$DLCvcd_{BD} = TAIV_{BD} * Rate_{HR}$
Auto Insertion DIP	$DLCdip_{BD} = TAID_{BD} * Rate_{HR}$
SMT Top and Bottom	$TP_{BD1} = TP_{BD1top} + TP_{BD1bottom}$ $TP_{BD1top} = \begin{bmatrix} TPscpr_{BD} + TPglap_{BD} + TPchsh_{BD} + \\ TPfipi_{BD} + TMA_{BD} + TPref_{BD} + TVIT_{BD} \end{bmatrix}$ $TP_{BD1bottom} = TPglapb_{BD} + TPchshb_{BD} + TPref_{BD} + TVIB_{BD}$ $TP_{BDS} = TP_{BDStop} + TP_{BDSbottom}$ $TP_{BDStop} = MAX\begin{bmatrix} TPscpr_{BD}, TPglap_{BD}, TPchsh_{BD}, \\ TPfipi_{BD}, TMA_{BD}, TPref_{BD}, TVIT_{BD} \end{bmatrix}$ $TP_{BDSbottom} = MAX\begin{bmatrix} TPglapb_{BD}, TPchshb_{BD}, \\ TPref_{BD}, TVIB_{BD} \end{bmatrix}$ $TPavg_{BD} = \frac{TP_{BD1} + (Nbd_{BH} - 1) * TP_{BDS}}{Nbd_{BH}}$ $DLCsmt_{BD} = \left[\begin{pmatrix} TPavg_{BD} \\ * Nop_{SMT} \end{pmatrix} + \begin{pmatrix} TSUscpr_{BD} + \\ TSUglap_{BD} + \\ TSUchsh_{BD} + \\ TSUfipi_{BD} + \\ TSUref_{BD} + \\ TSUglapb_{BD} + \\ TSUchshb_{BD} + \\ TSUrefb_{BD} \end{pmatrix} \right] * Rate_{HR}$
Chip on Board Wire Bonding	$DLCwire_{BD} = TWB_{BD} * Rate_{HR}$

Labor Cost equations	
Panel Preparation	$DLCprep_{BD} = TPP_{BD} * Rate_{HR}$
Manual Insertion	$DLCmi_{BD} = TMI_{BD} * Rate_{HR}$
Wave Solder	$DLCwave_{BD} = TWS_{BD} * Rate_{HR}$
Routing and Singulation	$DLCrsg_{BD} = \frac{TRSG_{BD}}{Nmeroute} * Rate_{HR}$ $Nmeroute = Roundup\left[\frac{D_{YR} * TRSG_{BD}}{(Nday_{YR} * Nhrs_{DAY} * EFroute_{ME})}\right]$
Tests	$DLCtests_{BD} = \frac{TTT_{BD}}{Nmetests} * Rate_{HR}$ $Nmetests = Roundup\left[\frac{D_{YR} * TTT_{BD}}{(Nday_{YR} * Nhrs_{DAY} * EFtests_{ME})}\right]$
Touch Up	$DLCtouch_{BD} = TUP_{BD} * Rate_{HR}$
Final Assembly	$DLCfinal_{BD} = TFA_{BD} * Rate_{HR}$
Final Inspection	$DLCfinins_{BD} = TFI_{BD} * Rate_{HR}$

Equipment Cost terminology and equations

Equipment Cost terminology	
P –	The present value is the initial cost (IC) of the machine
i –	The interest rate is the MARR established by the company representing the expected profit percentage from capital investments
N –	The product expected life (PEL)
F –	The future value is the salvage value (SV) of the machine
A/P –	Annualize given a present value
A/F –	Annualize given a future value
MARR –	Minimum acceptable rate of return
PEL –	Product estimated life (years)
$N\mathit{day}_{YR}$ –	Number of working days per year
$N\mathit{hrs}_{DAY}$ –	Number of working hours per day
$ECPF_{BD}$ –	Preforming equipment cost per board
ACPF –	Preforming machine annualized cost
N*me*pref –	Number of required preforming machines
$ICpref_{ME}$ –	Preforming machine initial cost
$SVpref_{ME}$ –	Preforming machine salvage value

Equipment Cost terminology	
TPF_{BD} –	Total performing time per board
$EFpref_{ME}$ –	Preforming machine efficiency
$ECAID_{BD}$ –	Auto insertion DIP equipment cost per board
ACAID –	Auto insertion DIP machine annualized cost
N*me*dip –	Number of required Auto insertion DIP machines
$ICdip_{ME}$ –	Auto insertion DIP machine initial cost
$SVdip_{ME}$ –	Auto insertion DIP machine salvage value
$TAID_{BD}$ –	Total auto insertion DIP time per board
$EFdip_{ME}$ –	Auto insertion DIP machine efficiency
$ECSQ_{BD}$ –	Sequencer equipment cost per board
ACSQ –	Sequencer machine annualized cost
N*me*seq –	Number of required sequencer machines
$ICseq_{ME}$ –	Sequencer machine initial cost
$SVseq_{ME}$ –	Sequencer machine salvage value
TSQ_{BD} –	Total sequencer time per board
$EFseq_{ME}$ –	Sequencer machine efficiency
$ECAIV_{BD}$ –	Auto-insertion VCD equipment cost per board
ACAIV –	Auto-insertion VCD machine annualized cost
N*me*vcd –	Number of required auto-insertion VCD machines
$ICvcd_{ME}$ –	Auto-insertion VCD machine initial cost
A/P –	Annualize given a present value
$SVvcd_{ME}$ –	Auto-insertion VCD machine salvage value
A/F –	Annualize given a future value
D_{YR} –	Annual demand
$TAIV_{BD}$ –	Total auto-insertion VCD time per board
$EFvcd_{ME}$ –	Auto-insertion VCD machine efficiency
$ECSP_{BD}$ –	Screen printing equipment cost per board
ACSP –	Screen printing machine annualized cost
N*me*scpr –	Number of required screen printing machines
$ICscpr_{ME}$ –	Screen printing machine initial cost
$SVscpr_{ME}$ –	Screen printing machine salvage value
TSP_{BD} –	Total screen printing time per board
$EFscpr_{ME}$ –	Screen printing machine efficiency
$ECGAT_{BD}$ –	Glue application equipment cost per board
ACGAT –	Glue application machine annualized cost
N*me*glap –	Number of required glue application machines
$ICglap_{ME}$ –	Glue application machine initial cost
PEL –	Product estimated life (years)
$SVglap_{ME}$ –	Glue application machine salvage value
TGA_{BD} –	Total glue application time per board

Equipment Cost terminology	
$TGAT_{BD}$ –	Total glue application time (top) per board
$TGAB_{BD}$ –	Total glue application time (bottom) per board (refer to equation 2.35)
$EFglap_{ME}$ –	Glue application machine efficiency
$ECCS_{BD}$ –	Chip shooter equipment cost per board
ACCS –	Chip shooter machine annualized cost
N*me*chsh –	Number of required chip shooter machines
$ICchsh_{ME}$ –	Chip shooter machine initial cost
$SVchsh_{ME}$ –	Chip shooter machine salvage value
TCS_{BD} –	Total chip shooter time per board
$TCST_{BD}$ –	Total chip shooter time (top) per board
$TCSB_{BD}$ –	Total chip shooter time (bottom) per board
$EFchsh_{ME}$ –	Chip shooter machine efficiency
$ECFP_{BD}$ –	Fine pitch equipment cost per board
ACFP –	Fine pitch machine annualized cost
N*me*fipi –	Number of required fine pitch machines
$ICfipi_{ME}$ –	Fine pitch machine initial cost
$SVfipi_{ME}$ –	Fine pitch machine salvage value
TFP_{BD} –	Total fine pitch time per board
$EFfipi_{ME}$ –	Fine pitch machine efficiency
$ECMA_{BD}$ –	Manual assembly of SMT equipment cost per board
ACMA –	Manual assembly of SMT machine annualized cost
N*me*mansmt –	Number of required manual assembly of SMT machines
$ICmansmt_{ME}$ –	Manual assembly of SMT machine initial cost
$SVmansmt_{ME}$ –	Manual assembly of SMT machine salvage value
TMA_{BD} –	Total manual assembly time of SMT per board (refer to equation 2.57)
$EFmansmt_{ME}$ –	Manual assembly of SMT machine efficiency
$ECRF_{BD}$ –	Reflow oven equipment cost per board
ACRF –	Reflow oven machine annualized cost
N*me*ref –	Number of required reflow oven machines
$ICref_{ME}$ –	Reflow oven machine initial cost
$SVref_{ME}$ –	Reflow oven machine salvage value
$TREF_{BD}$ –	Total reflow oven time per board
TRF_{BD} –	Total reflow oven time (top) per board
$TRFB_{BD}$ –	Total reflow oven time (bottom) per board
$EFref_{ME}$ –	Reflow oven machine efficiency
$ECWB_{BD}$ –	Chip on board wire bonding equipment cost per board
ACWB –	Chip on board wire bonding machine annualized cost
N*me*wire –	Number of required chip on board wire bonding machines
$ICwire_{ME}$ –	Chip on board wire bonding machine initial cost
$SVwire_{ME}$ –	Chip on board wire bonding machine salvage value
D_{YR} –	Annual demand

Equipment Cost terminology	
TWB_{BD} –	Total chip on board wire bonding time per board
$EFwire_{ME}$ –	Chip on board wire bonding machine efficiency
$ECMI_{BD}$ –	Manual insertion of THT equipment cost per board
ACMI –	Manual insertion of THT machine annualized cost
N*me*mantht –	Number of required manual insertion of THT machines
$ICmantht_{ME}$ –	Manual insertion of THT machine initial cost
MARR –	Minimum acceptable rate of return
$SVmantht_{ME}$ –	Manual insertion of THT machine salvage value
TMI_{BD} –	Total manual insertion of THT time per board
$EFmantht_{ME}$ –	Manual insertion of THT machine efficiency
$ECWS_{BD}$ –	Wave solder equipment cost per board
ACWS –	Wave solder machine annualized cost
N*me*wave –	Number of required wave solder machines
$ICwave_{ME}$ –	Wave solder machine initial cost
$SVwave_{ME}$ –	Wave solder machine salvage value
TWS_{BD} –	Total wave solder time per board
$EFwave_{ME}$ –	Wave solder machine efficiency
$ECRSG_{BD}$ –	Routing and singulation equipment cost per board
ACRSG –	Routing and singulation machine annualized cost
N*me*route –	Number of required routing and singulation machines
$ICroute_{ME}$ –	Routing and singulation machine initial cost
$SVroute_{ME}$ –	Routing and singulation machine salvage value
$ECTT_{BD}$ –	Tests equipment cost per board
ACTT –	Tests machine annualized cost
N*me*tests –	Number of required tests machines
$ICtests_{ME}$ –	Tests machine initial cost
$SVtests_{ME}$ –	Tests machine salvage value

Equipment Cost equations	
General equations used to calculate Annualize the present and future value of an investment	$A/P=P*\left[\frac{i(1+i)^N}{(1+i)^N-1}\right]$ $A/F=F*\left[\frac{i}{(1+i)^N-1}\right]$
	$ECPF_{BD}=\frac{ACPF*Nmepref}{D_{YR}}$ $ACPF=\left[\begin{array}{l} ICpref_{ME}(A/P,MARR,PEL)\ - \\ SVpref_{ME}(A/F,MARR,PEL) \end{array}\right]$

Equipment Cost equations	
	$$Nmepref = Roundup\left[\frac{D_{YR}*TPF_{BD}}{(Nday_{YR}*Nhrs_{DAY}*EFpref_{ME})}\right]$$
	$$ECAID_{BD} = \frac{ACAID*Nmedip}{D_{YR}}$$ $$ACAID=\left[\begin{array}{l} ICdip_{ME}(A/P,MARR,PEL)- \\ SVdip_{ME}(A/F,MARR,PEL) \end{array}\right]$$ $$Nmedip = Roundup\left[\frac{D_{YR}*TAID_{BD}}{(Nday_{YR}*Nhrs_{DAY}*EFdip_{ME})}\right]$$
	$$ECSQ_{BD} = \frac{ACSQ*Nmeseq}{D_{YR}}$$ $$ACSQ=\left[\begin{array}{l} ICseq_{ME}(A/P,MARR,PEL)- \\ SVseq_{ME}(A/F,MARR,PEL) \end{array}\right]$$ $$Nmeseq = Roundup\left[\frac{D_{YR}*TSQ_{BD}}{(Nday_{YR}*Nhrs_{DAY}*EFseq_{ME})}\right]$$
	$$ECAIV_{BD} = \frac{ACAIV*Nmevcd}{D_{YR}}$$ $$ACAIV=\left[\begin{array}{l} ICvcd_{ME}(A/P,MARR,PEL)- \\ SVvcd_{ME}(A/F,MARR,PEL) \end{array}\right]$$ $$Nmevcd = Roundup\left[\frac{D_{YR}*TAIV_{BD}}{(Nday_{YR}*Nhrs_{DAY}*EFvcd_{ME})}\right]$$
	$$ECSP_{BD} = \frac{ACSP*Nmescpr}{D_{YR}}$$ $$ACSP=\left[\begin{array}{l} ICscpr_{ME}(A/P,MARR,PEL)- \\ SVscpr_{ME}(A/F,MARR,PEL) \end{array}\right]$$ $$Nmescpr = Roundup\left[\frac{D_{YR}*TSP_{BD}}{(Nday_{YR}*Nhrs_{DAY}*EFscpr_{ME})}\right]$$
	$$ECGAT_{BD} = \frac{ACGAT*Nmeglap}{D_{YR}}$$ $$ACGAT=\left[\begin{array}{l} ICglap_{ME}(A/P,MARR,PEL)- \\ SVglap_{ME}(A/F,MARR,PEL) \end{array}\right]$$ $$TGA_{BD} = TGAT_{BD} + TGAB_{BD}$$

Equipment Cost equations	
	$$Nmeglap=Roundup\left[\frac{D_{YR}*TGA_{BD}}{\left(Nday_{YR}*Nhrs_{DAY}*EFglap_{ME}\right)}\right]$$
	$$ECCS_{BD}=\frac{ACCS*Nmechsh}{D_{YR}}$$ $$ACCS=\begin{bmatrix}ICchsh_{ME}\left(A/P,MARR,PEL\right)-\\SVchsh_{ME}\left(A/F,MARR,PEL\right)\end{bmatrix}$$ $$TCS_{BD}=TCST_{BD}+TCSB_{BD}$$ $$Nmechsh=Roundup\left[\frac{D_{YR}*TCS_{BD}}{\left(Nday_{YR}*Nhrs_{DAY}*EFchsh_{ME}\right)}\right]$$
	$$ECFP_{BD}=\frac{ACFP*Nmefipi}{D_{YR}}$$ $$ACFP=\begin{bmatrix}ICfipi_{ME}\left(A/P,MARR,PEL\right)-\\SVfipi_{ME}\left(A/F,MARR,PEL\right)\end{bmatrix}$$ $$Nmefipi=Roundup\left[\frac{D_{YR}*TFP_{BD}}{\left(Nday_{YR}*Nhrs_{DAY}*EFfipi_{ME}\right)}\right]$$
	$$ECMA_{BD}=\frac{ACMA*Nmemansmt}{D_{YR}}$$ $$ACMA=\begin{bmatrix}ICmansmt_{ME}\left(A/P,MARR,PEL\right)-\\SVmansmt_{ME}\left(A/F,MARR,PEL\right)\end{bmatrix}$$ $$Nmemansmt=Roundup\left[\frac{D_{YR}*TMA_{BD}}{\begin{pmatrix}Nday_{YR}*Nhrs_{DAY}\\*EFmansmt_{ME}\end{pmatrix}}\right]$$
	$$ECRF_{BD}=\frac{ACRF*Nmeref}{D_{YR}}$$ $$ACRF=\begin{bmatrix}ICref_{ME}\left(A/P,MARR,PEL\right)-\\SVref_{ME}\left(A/F,MARR,PEL\right)\end{bmatrix}$$ $$TREF_{BD}=TRF_{BD}+TRFB_{BD}$$ $$Nmeref=Roundup\left[\frac{D_{YR}*TREF_{BD}}{\left(Nday_{YR}*Nhrs_{DAY}*EFref_{ME}\right)}\right]$$
	$$ECWB_{BD}=\frac{ACWB*Nmewire}{D_{YR}}$$

Equipment Cost equations	
	$$ACWB=\left[\begin{array}{l} ICwire_{ME}\left(A/P,MARR,PEL\right)- \\ SVwire_{ME}\left(A/F,MARR,PEL\right) \end{array}\right]$$
	$$Nmewire=Roundup\left[\frac{D_{YR}*TWB_{BD}}{\left(Nday_{YR}*Nhrs_{DAY}*EFwire_{ME}\right)}\right]$$
	$$ECMI_{BD}=\frac{ACMI*Nmemantht}{D_{YR}}$$ $$ACMI=\left[\begin{array}{l} ICmantht_{ME}\left(A/P,MARR,PEL\right)- \\ SVmantht_{ME}\left(A/F,MARR,PEL\right) \end{array}\right]$$ $$Nmemantht=Roundup\left[\frac{D_{YR}*TMI_{BD}}{\left(\begin{array}{c} Nday_{YR}*Nhrs_{DAY} \\ *EFmantht_{ME} \end{array}\right)}\right]$$
	$$ECWS_{BD}=\frac{ACWS*Nmewave}{D_{YR}}$$ $$ACWS=\left[\begin{array}{l} ICwave_{ME}\left(A/P,MARR,PEL\right)- \\ SVwave_{ME}\left(A/F,MARR,PEL\right) \end{array}\right]$$ $$Nmewave=Roundup\left[\frac{D_{YR}*TWS_{BD}}{\left(Nday_{YR}*Nhrs_{DAY}*EFwave_{ME}\right)}\right]$$
	$$ECRSG_{BD}=\frac{ACRSG*Nmeroute}{D_{YR}}$$ $$ACRSG=\left[\begin{array}{l} ICroute_{ME}\left(A/P,MARR,PEL\right)- \\ SVroute_{ME}\left(A/F,MARR,PEL\right) \end{array}\right]$$
	$$ECTT_{BD}=\frac{ACTT*Nmetests}{D_{YR}}$$ $$ACTT=\left[\begin{array}{l} ICtests_{ME}\left(A/P,MARR,PEL\right)- \\ SVtests_{ME}\left(A/F,MARR,PEL\right) \end{array}\right]$$

Material Cost Terminology and Equations

Material Cost terminology	
$TCM\$_{BD}$ –	Total consumable materials' cost per board
$CM\$seq_{BD}$ –	Sequencer consumable material cost per board
$CM\$scpr_{BD}$ –	Screen printing consumable material cost per board
$CM\$glap_{BD}$ –	Glue application consumable material cost per board
$CM\$prep_{BD}$ –	Panel preparation consumable material cost per board
$CM\$wave_{BD}$ –	Wave solder consumable material cost per board
$CM\$all_{BD}$ –	Common materials cost per board
$AVGtape_{CP}$ –	Average length of sequencer tape per component
$N\textit{cp}vcd_{BD}$ –	Number of radial THT (VCD) components
Tape$ –	Sequencer tape cost
$AVGpaste_{CP}$ –	Average quantity of solder paste used per component
$N\textit{cp}smttop_{BD}$ –	Number of SMT components to be placed on top of board
Paste$ –	Screen printing solder paste cost
$AVGglue_{CP}$ –	Average quantity of glue per component
$N\textit{cp}glue_{BD}$ –	Number of components that are glued to the board
Glue$ –	Cost of glue used in glue application
$N\textit{cp}wrtop_{BD}$ –	Number of SMT non fine pitch components to be wire bonded on top of board
$N\textit{cp}wrbot_{BD}$ –	Number of SMT non fine pitch components to be wire bonded on bottom of board
$AVGprtape_{PT}$ –	Average length of protection tape per part to be protected
$N\textit{pt}gold_{BD}$ –	Number of gold plated parts on the board
Prtape$ –	Panel preparation protection tape cost
$AVGsolder_{CP}$ –	Average quantity of solder per component
$N\textit{cp}solder_{BD}$ –	Number of components in wave solder
Solder$ –	Cost of solder used in wave solder
$N\textit{cp}dip_{BD}$ –	Number of axial THT (DIP) components per board
$N\textit{cp}vcd_{BD}$ –	Number of radial THT (VCD) components per board
$N\textit{cp}manth t_{BD}$ –	Number of THT radial components to be inserted manually on board
$AVGall_{BD}$ –	Average quantity of common materials per board
All$ –	Average common materials cost
TMC_{BD} –	Total materials cost per board
$TCP\$_{BD}$ –	Total components cost per board
$TCM\$_{BD}$ –	Total consumable materials' cost per board

Material Cost equations	
	$TCM\$_{BD} = \begin{bmatrix} CM\$seq_{BD} + CM\$scpr_{BD} + CM\$glap_{BD} + \\ CM\$prep_{BD} + CM\$wave_{BD} + CM\$all_{BD} \end{bmatrix}$
	$CM\$seq_{BD} = AVGtape_{CP} * Ncpvcd_{BD} * Tape\$$
	$CM\$scpr_{BD} = AVGpaste_{CP} * Ncpsmttop_{BD} * Paste\$$
	$CM\$glap_{BD} = AVGglue_{CP} * Ncpglue_{BD} * Glue\$$ $Ncpglue_{BD} = Ncpwrtop_{BD} + Ncpwrbot_{BD}$
	$CM\$prep_{BD} = AVGprtape_{PT} * Nptgold_{BD} * Prtape\$$
	$CM\$wave_{BD} = AVGsolder_{CP} * Ncpsolder_{BD} * Solder\$$ $Ncpsolder_{BD} = Ncpdip_{BD} + Ncpvcd_{BD} + Ncpmantht_{BD}$
	$CM\$all_{BD} = AVGall_{BD} * All\$$

Utilities Cost Terminology and Equations

Terminology	
$T\$UTIL_{bd}$ –	Total utilities costs per board
$T\$ELEC_{bd}$ –	Total electricity cost per board
$T\$H2O_{bd}$ –	Total water cost per board
$T\$NITRO_{bd}$ –	Total nitrogen cost per board
$\$ELECpf_{bd}$ –	Electricity cost per board in preforming process
$\$ELECsp_{bd}$ –	Electricity cost per board in screen printing process
$\$ELECgaT_{bd}$ –	Electricity cost per board in glue application (top) process
$\$ELECcsT_{bd}$ –	Electricity cost per board in chip shooter (top) process
$\$ELECfp_{bd}$ –	Electricity cost per board in fine pitch process
$\$ELECroT_{bd}$ –	Electricity cost per board in reflow (top) process
$\$ELECcw_{bd}$ –	Electricity cost per board in wire bonding process
$\$ELECseq_{bd}$ –	Electricity cost per board in sequencer process
$\$ELECvcd_{bd}$ –	Electricity cost per board in auto insertion VCD process
$\$ELECdip_{BD}$ –	Electricity cost per board in auto insertion DIP process
$\$ELECgaB_{bd}$ –	Electricity cost per board in glue application (bottom) process
$\$ELECcsB_{bd}$ –	Electricity cost per board in chip shooter (bottom) process
$\$ELECroB_{bd}$ –	Electricity cost per board in reflow (bottom) process
$\$ELECma_{bd}$ –	Electricity cost per board in manual insertion process
$\$ELECws_{bd}$ –	Electricity cost per board in wave solder process
$\$ELECrs_{bd}$ –	Electricity cost per board in routing and singulation process

Terminology	
$\$ELECtests_{BD}$ –	Electricity cost per board in tests process
$\$H2OroT_{bd}$ –	Water cost per board in reflow (top) process
$\$H2OroB_{bd}$ –	Water cost per board in reflow (bottom) process
$\$NITROroT_{bd}$ –	Nitrogen cost per board in reflow (top) process
$\$NITROroB_{bd}$ –	Nitrogen cost per board in reflow (bottom) process
ELECpref –	Electricity consumption (kilowatt) in preforming process
$\$elec_{KWHR}$ –	Electricity cost per kilowatt hour
$Tpref_{BD}$ –	Preforming time per board
ELECscpr –	Electricity consumption (kilowatt) in screen printing process
$Tscpr_{BD}$ –	Screen printing machine time per board
ELECglap –	Electricity consumption (kilowatt) in glue application process
$Tglap_{BD}$ –	Glue application (top) machine time per board (refer to equation 2.40)
ELECchsh –	Electricity consumption (kilowatt) in chip shooter process
$Tchsh_{BD}$ –	Chip shooter (top) machine time per board
ELECfipi –	Electricity consumption (kilowatt) in fine pitch process
$Tfipi_{BD}$ –	Fine pitch machine time per board
ELECref –	Electricity consumption (kilowatt) in reflow process
$Tref_{BD}$ –	Reflow machine time per board
ELECwire –	Electricity consumption (kilowatt) in wire bonding process
$Twire_{BD}$ –	Wire bonding machine time per board
ELECseq –	Electricity consumption (kilowatt) in sequencer process
$Tseq_{BD}$ –	Sequencer machine time per board
ELECvcd –	Electricity consumption (kilowatt) in auto insertion VCD process
$Tvcd_{BD}$ –	Auto insertion VCD machine time per board
ELECdip –	Electricity consumption (kilowatt) in auto insertion DIP process
$Tdip_{BD}$ –	Auto insertion DIP machine time per board
$Tglapb_{BD}$ –	Glue application (bottom) machine time per board
$Tchshb_{BD}$ –	Chip shooter (bottom) machine time per board
ELECmantht –	Electricity consumption (kilowatt) in manual insertion of SMT process
$Tmantht_{BD}$ –	Manual insertion of THT machine time per board (refer to equation 2.89)
ELECwave –	Electricity consumption (kilowatt) in wave solder process
$Twave_{BD}$ –	Wave solder machine time per board
ELECrsg –	Electricity consumption (kilowatt) in routing and singulation process
$Trsg_{BD}$ –	Routing and singulation machine time per board
ELECtests –	Electricity consumption (kilowatt) in tests process
$Ttests_{BD}$ –	Tests machine time per board
$NITROref_{HR}$ –	Nitrogen consumption (cubic feet per hour) in reflow process
$\$nitro_{CF}$ –	Nitrogen cost per cubic feet
$H2Oref_{HR}$ –	Water consumption (gallons per hour) in reflow process
$\$h2o_{GL}$ –	Water cost per gallon

Utilities Equations	
	$T\$UTIL_{bd} = T\$ELEC_{bd} + T\$H2O_{bd} + T\$NITRO_{bd}$
	$T\$ELEC_{bd} = \begin{bmatrix} \$ELECpf_{bd} + \$ELECsp_{bd} + \\ \$ELECgaT_{bd} + \$ELECcs_{bd} + \\ \$ELECfp_{bd} + \$ELECro_{bd} + \\ \$ELECcw_{bd} + \$ELECseq_{bd} + \\ \$ELECvcd_{bd} + \$ELECdip_{bd} + \\ \$ELECgaB_{bd} + \$ELECcsB_{bd} + \\ \$ELECroB_{bd} + \$ELECma_{bd} + \\ \$ELECws_{bd} + \$ELECrs_{bd} + \\ \$ELECtessssssssts_{bd} \end{bmatrix}$
	$T\$H2O_{bd} = \$H2OroT_{bd} + \$H2OroB_{bd}$
	$T\$NITRO_{bd} = \$NITROroT_{bd} + \$NITROroB_{bd}$
	$\$ELECpf_{bd} = ELECpf * \$elec_{kh} * TTpf_{bd}$
	$\$ELECsp_{bd} = ELECsp * \$elec_{kh} * TTsp_{bd}$
	$\$ELECgaT_{bd} = ELECga * \$elec_{kh} * TTgaT_{bd}$
	$\$ELECcsT_{bd} = ELECcs * \$elec_{kh} * TTcs_{bd}$
	$\$ELECfp_{bd} = ELECfp * \$elec_{kh} * TTfp_{bd}$
	$\$ELECroT_{bd} = ELECro * \$elec_{kh} * TTroT_{bd}$
	$\$ELECcw_{bd} = ELECcw * \$elec_{kh} * TTcw_{bd}$
	$\$ELECseq_{bd} = ELECseq * \$elec_{kh} * TTseq_{bd}$
	$\$ELECvcd_{BD} = ELECvcd * \$elec_{kh} * TTvcd_{bd}$
	$\$ELECdip_{bd} = ELECdip * \$elec_{kh} * TTdip_{bd}$
	$\$ELECgaB_{BD} = ELECga * \$elec_{kh} * TTgaB_{bd}$
	$\$ELECchshb_{BD} = ELECchsh * \$elec_{KWHR} * Tchshb_{BD}$
	$\$ELECrefb_{BD} = ELECref * \$elec_{KWHR} * Tref_{BD}$
	$\$ELECmantht_{BD} = ELECmantht * \$elec_{KWHR} * Tmantht_{BD}$
	$\$ELECwave_{BD} = ELECwave * \$elec_{KWHR} * Twave_{BD}$
	$\$ELECrsg_{BD} = ELECrsg * \$elec_{KWHR} * Trsg_{BD}$
	$\$ELECtests_{BD} = ELECtests * \$elec_{KWHR} * Ttests_{BD}$
	$\$NITROref_{BD} = NITROref_{HR} * \$nitro_{CF} * Tref_{BD}$
	$\$NITROrefb_{BD} = NITROref_{HR} * \$nitro_{CF} * Tref_{BD}$

Utilities Equations	
	$\$H2Oref_{BD} = H2Oref_{HR} * \$h2o_{GL} * Tref_{BD}$
	$\$H2Orefb_{BD} = H2Oref_{HR} * \$h2o_{GL} * Tref_{BD}$

Space Cost Terminology and Equations

Space Terminology	
T$SPACE$_{BD}$ –	Total space dependent overhead cost per board
AREAprocess*i* –	Required area for assembly process *i*
$HVAC –	Heating ventilation and air conditioning cost per square feet per year
$LIGHT –	Lighting cost per square feet per year
$RENT –	Building rent cost per square feet per year
$OTHERS –	Others fixed costs per square feet per year
D_{YR} –	Annual demand
AREAmantht –	Required area for THT manual insertion process
AREAwave –	Required area for wave solder machine
AREArsg –	Required area for routing and singulation machine
AREAtests –	Required area for tests machines
AREAtouch –	Required area for touch-up process
AREAfinal –	Required area for final assembly process
AREAfinins –	Required area for final inspection process
Factor –	Space (aisles, etc.) allowance factor
N*op*kit –	Number of required operators in kit segregation process
SPACE*op*kit –	Required space per kit segregation operator
N*me*pref –	Number of required preforming machines
SPACEpref –	Required space per preforming machine
N*op*bin –	Number of required operators in bin-up process
SPACE*op*bin –	Required space per bin-up operator
N*me*seq –	Number of required sequencer machines
SPACEseq –	Required space per sequencer machine
N*me*vcd –	Number of required auto insertion VCD machines
SPACEvcd –	Required space per auto insertion VCD machine
N*me*dip –	Number of required auto insertion DIP machines
SPACEdip –	Required space per auto insertion DIP machine
AREAscpr –	Required area for screen printing machine
AREAglap –	Required area for glue application machine
AREAchsh –	Required area for chip shooter machine
AREAfipi –	Required area for fine pitch machine
SPACEmansmt –	Required space for SMT manual insertion
AREAref –	Required area for reflow machine
SPACEvins –	Required space for SMT visual inspection

Space Terminology	
N*me*scpr –	Number of required screen printing machines (refer to equation 4.15)
SPACEscpr –	Required space per screen printing machine
N*me*glap –	Number of required glue application machines (refer to equation 4.19)
SPACEglap –	Required space per glue application machine
N*me*chsh –	Number of required chip shooter machines
SPACEchsh –	Required space per chip shooter machine
N*me*fipi –	Number of required fine pitch machines
SPACEfipi –	Required space per fine pitch machine
N*me*ref –	Number of required reflow machines
SPACEref –	Required space per reflow machine
N*me*wire –	Number of required wire bonding machines
SPACEwire –	Required space per wire bonding machine
N*op*prep –	Number of required operators in panel preparation process
SPACE*op*prep –	Required space per panel preparation operator
N*me*mantht –	Number of required manual insertion of THT machines
SPACEmantht –	Required space per manual insertion of THT machine
N*me*wave –	Number of required wave solder machines
SPACEwave –	Required space per wave solder machine
N*me*route –	Number of required routing and singulation machines
SPACErsg –	Required space per routing and singulation machine
N*me*tests –	Number of required tests machines
SPACEtests –	Required space per tests machine
N*op*touch –	Number of required operators in touch-up process
SPACE*op*touch –	Required space per touch-up operator
N*op*final –	Number of required operators in final assembly process
SPACE*op*final –	Required space per final assembly operator
N*op*finins –	Number of required operators in final inspection process
SPACE*op*finins –	Required space per final inspection operator

Space Equations	
	$T\$SPACE_{BD} = \frac{\sum_{i} AREAprocessi * \begin{pmatrix} \$HVAC+ \\ \$LIGHT+ \\ \$RENT+ \\ \$OTHERS \end{pmatrix}}{D_{YR}}$

Space Equations	
	$$\sum_i AREAprocessi = \begin{bmatrix} AREAkit+AREApref+ \\ AREAbin+AREAseq+ \\ AREAvcd+AREAdip+ \\ AREAsmt+AREAwire+ \\ AREAprep+AREAmantht \\ +AREAwave+AREArsg+ \\ AREAtests+AREAtouch+ \\ AREAfinal+AREAfinins \end{bmatrix} *(1+Factor)$$
	$AREAkit=Nopkit*SPACEopkit$
	$AREApref=Nmepref*SPACEpref$
	$AREAbin=Nopbin*SPACEopbin$
	$AREAseq=Nmeseq*SPACEseq$
	$AREAvcd=Nmevcd*SPACEvcd$
	$AREAdip=Nmedip*SPACEdip$
	$$AREAsmt=\begin{bmatrix} AREAscpr+AREAglap+ \\ AREAchsh+AREAfipi+ \\ SPACEmansmt+ \\ AREAref+SPACEvins \end{bmatrix}$$
	$AREAscpr=Nmescpr*SPACEscpr$
	$AREAglap=Nmeglap*SPACEglap$
	$AREAchsh=Nmechsh*SPACEchsh$
	$AREAfipi=Nmefipi*SPACEfipi$
	$AREAref=Nmeref*SPACEref$
	$AREAwire=Nmewire*SPACEwire$
	$AREAprep=Nopprep*SPACEopprep$
	$AREAmantht=Nmemantht*SPACEmantht$
	$AREAwave=Nmewave*SPACEwave$
	$AREArsg=Nmeroute*SPACErsg$
	$AREAtests=Nmetests*SPACEtests$
	$AREAtouch=Noptouch*SPACEoptouch$
	$AREAfinal=Nopfinal*SPACEopfinal$
	$AREAfinins=Nopfinins*SPACEopfinins$

Lead Time and Support Personnel Cost Terminology and Equations

Terminology	
MLT_{BD} –	Manufacturing lead time per board
$TG1_{BD}$ –	Group 1 process time per board (kit segregation, preforming and bin-up)
$TG2_{BD}$ –	Group 2 process time per board (SMT top processes and wire bonding)
$TG3_{BD}$ –	Group 3 process time per board (sequencer)
$TG4_{BD}$ –	Group 4 process time per board (auto insertion VCD, auto insertion DIP, SMT bottom processes and panel preparation)
$TG5_{BD}$ –	Group 5 process time per board (manual insertion, wave solder, routing and singulation, tests, touch up, final assembly and final inspection)
$TTks_{bd}$ –	Total kit segregation time per board
$TTpf_{bd}$ –	Total preforming time per board
$TTbu_{bd}$ –	Total bin-up time per board
$TTsp_{bd}$ –	Total screen printing time per board
$TTgaT_{bd}$ –	Total glue application time (top) per board
$TTcsT_{bd}$ –	Total chip shooter (top) time per board
$TTfp_{bd}$ –	Total fine pitch time per board
$TTma_{bd}$ –	Total manual assembly time per board
$TTroT_{bd}$ –	Total reflow (top) time per board
$TTviT_{bd}$ –	Total visual inspection time (top) per board
$TTcw_{bd}$ –	Total Chip on Board Wire Bonding time per board
$TTseq_{bd}$ –	Total sequencer time per board
$TTvcd_{bd}$ –	Total Auto Insertion VCD time per board
$TTdip_{bd}$ –	Total Auto Insertion DIP time per board
$TTgaB_{bd}$ –	Total glue application time (bottom) per board
$TTcsB_{bd}$ –	Total chip shooter (bottom) time per board
$TTroB_{bd}$ –	Total reflow (bottom) time per board
$TTviB_{bd}$ –	Total visual inspection time (bottom) per board
$TTpp_{bd}$ –	Total panel preparation time per board
$TTmi_{bd}$ –	Total manual insertion time per board
$TTws_{bd}$ –	Total wave solder time per board
$TTrs_{bd}$ –	Total routing and singulation time per board
$TTtests_{BD}$ –	Total tests time per board
$TTtu_{bd}$ –	Total touch-up time per board
$TTfa_{bd}$ –	Total final assembly time per board
$TTfi_{bd}$ –	Total final inspection time per board
$T\$SUP_{bd}$ –	Total support personnel cost per board
$SUPhrs_{hr}$ –	Average support personnel hours per hour of product processing
MLT_{bd} –	Manufacturing lead time per board
$\$SUPavg_{hr}$ –	Average support personnel cost per hour

Manufacturing Lead Time and Support Personnel Cost equation
$MLT_{BD} = MAX\left[TG1_{BD}, \max\begin{pmatrix} TG2_{BD}, \\ TG3_{BD} \end{pmatrix} + TG4_{BD} \right] + TG5_{BD}$
$TG1_{bd} = \left[TTks_{bd} + TTpf_{bd} + TTbu_{bd} \right]$
$TG2_{bd} = \begin{bmatrix} TTsp_{bd} + TTgaT_{bd} + TTcsT_{bd} + TTfp_{bd} \\ + TTma_{bd} + TTro_{bd} + TTvi_{bd} + TTcw_{bd} \end{bmatrix}$
$TG3_{bd} = TTseq_{bd}$
$TG4_{bd} = \begin{bmatrix} TTvcd_{bd} + TTdip_{dip} + TTgaB_{bd} + \\ TTcs_{bd} + TTroB_{bd} + TTvi_{bd} + TTpp_{bd} \end{bmatrix}$
$TG5_{bd} = \begin{bmatrix} TTmi_{bd} + TTws_{bd} + TTrs_{bd} + \\ TTtestsssssss_{bd} + TTtu_{bd} + TTfa_{bd} + TTfi_{bd} \end{bmatrix}$
$T\$SUP_{bd} = SUPhrs_{hr} * MLT_{bd} * \$SUPavg_{hr}$

APPENDIX C. USER MANUAL FOR PRODUCT DEVELOPER / DESIGNER OF THE APPLICATION

Getting Started for Product Developer/Designer

Introduction

- The PCB Assembly Cost Model is an application that complements the research done by *Mendez* to develop cost models that can be used to estimate the cost of new power electronics systems and products that are being developed.
- The project was sponsored by the Center for Power Electronics Systems (CPES).
- This research addressed a need for cost models to be used as a decision making tool from the early stages of the conception of the device to guide the research and development process.
- An examination of power electronics products revealed that they share the basic characteristics of any modern electronic product, this is, a printed circuit board (PCB) with electronic components that are soldered to it. Given that assumption, a cost model was developed for the board level assembly of electronics products assuming a typical and generic assembly sequence and processes. These sequences include all typical processes for the assembly of a PCB-based electronic product. The processes identified are the ones used in the assembly of through hole technology (THT) components, surface mount technology (SMT) components, chip on board wire-bonded components, or any combination of them.

- The cost model was developed with the power electronics product developer as the main user. Nevertheless, the user needs in this area are very similar to those of the developer of any other type of electronic product. Basically, this person will develop a series of product specifications. Given those specifications, the cost model can be used as a tool to estimate the cost of the product considering how it is manufactured. The basic product specifications to provide include: a bill of materials (BOM), the printed circuit board (PCB) characteristics, the expected market demand, and the expected product life. The resulting cost estimates can be used to compare one design alternative versus another without having to build a unit of the product.
- The cost model assumes that an electronic product consists essentially of a PCB with electronic components soldered to it. It is assumed that this kind of assembly will follow a series of generally sequential steps. In each step of the assembly sequence, resources will be consumed and hence cost will be incurred.
- The resources and costs included in the model are direct labor, materials and components, equipment, support personnel, utilities, and space. Each assembly manufacturing process step is analyzed to understand how the resources are consumed and costs allocated to every board produced.
- Once the cost model was developed, CPES was interested in the development of an application that could implement the model developed by *Mendez* to estimate the cost of an electronic product and to evaluate the feasibility of design alternatives in terms of cost.

- The PCB Cost Model application implements a revised version of the cost model developed by *Mendez* and extends its capabilities. Primarily, the cost model was developed thinking on the designer of an electronic product as the only user but its implementation has been improved allowing the creation of custom facilities. This capability allows that a process engineer or planner of a facility can define its own facility to determine the cost of its existing products.

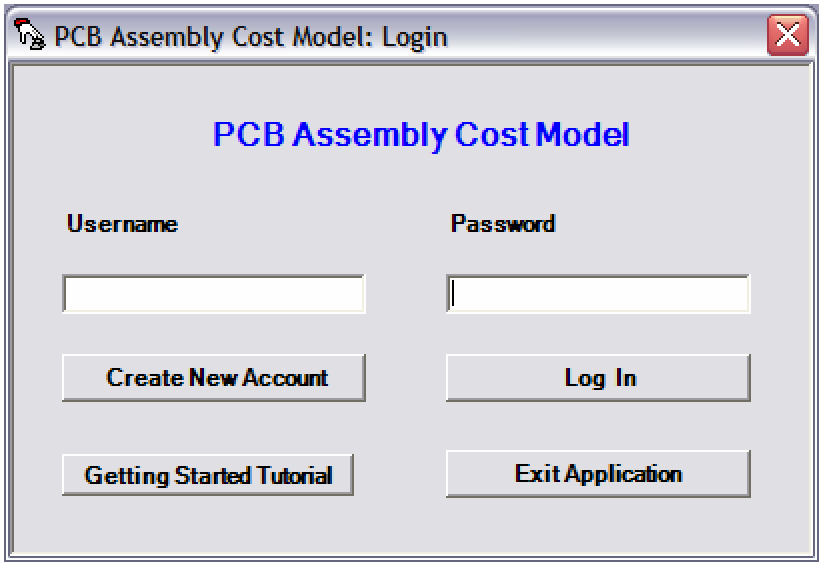
Now that you have an idea of the motivation for the creation of the PCB Cost Model application, we will proceed to explain the capabilities of the PCB Cost Model.

With the PCB Cost Model you can:

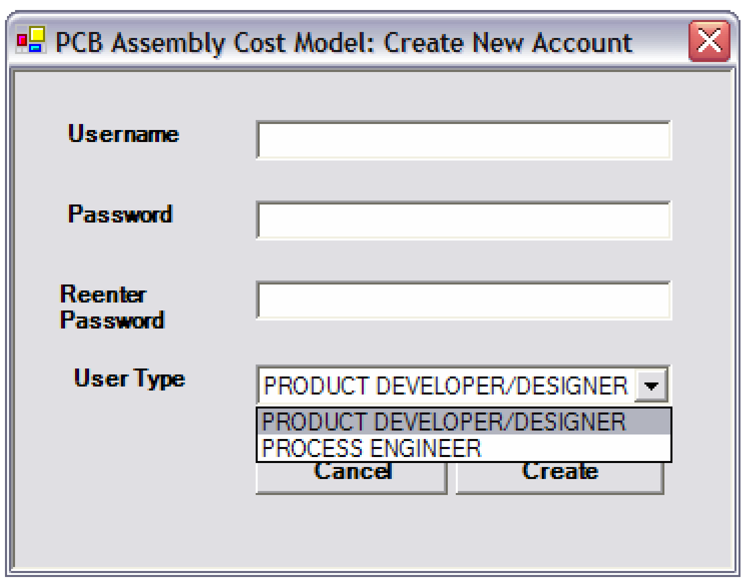
- Estimate the cost of a new electronic design and study the feasibility of alternative designs in terms of cost.
- Estimate the cost of an improved or current electronic design and evaluate the improvements of the designs in terms of cost.
- Estimate the time it will take to manufacture a batch of boards or images in your facility to see if you can meet product demand.
- Visualize the efficiency of your processes and manufacturing lines.

The PCB Cost Model environment

If PCB Cost Model is not already running, start it from the Windows Start menu and navigate to Programs/PCB Cost Model. The PCB Cost Model modeling environment will open with a login window, as shown below.



If you are a new user, you must create a new account to use the PCB Cost Model. When you click in the button "Create New Account", you will be redirected to the form "Create New Account" as shown below.



In this form you provide a username and password to create your new account. Once you provide your username and password, you must identify yourself as the type of user you are in this application. There are two choices in the user type": Product Developer/Designer or Process Engineer.

If you choose Product Developer/Designer you can:

- Create, edit or delete products.
- Add, edit or delete part numbers from your products.
- Add component types.
- Calculate the cost of your products in all the registered facilities in the application evaluate the feasibility of a design in different facilities.
- Edit the Components Catalog of the application.
- Create a product copy.
- Calculate Cost of Product(s) on Default Facility of the application.

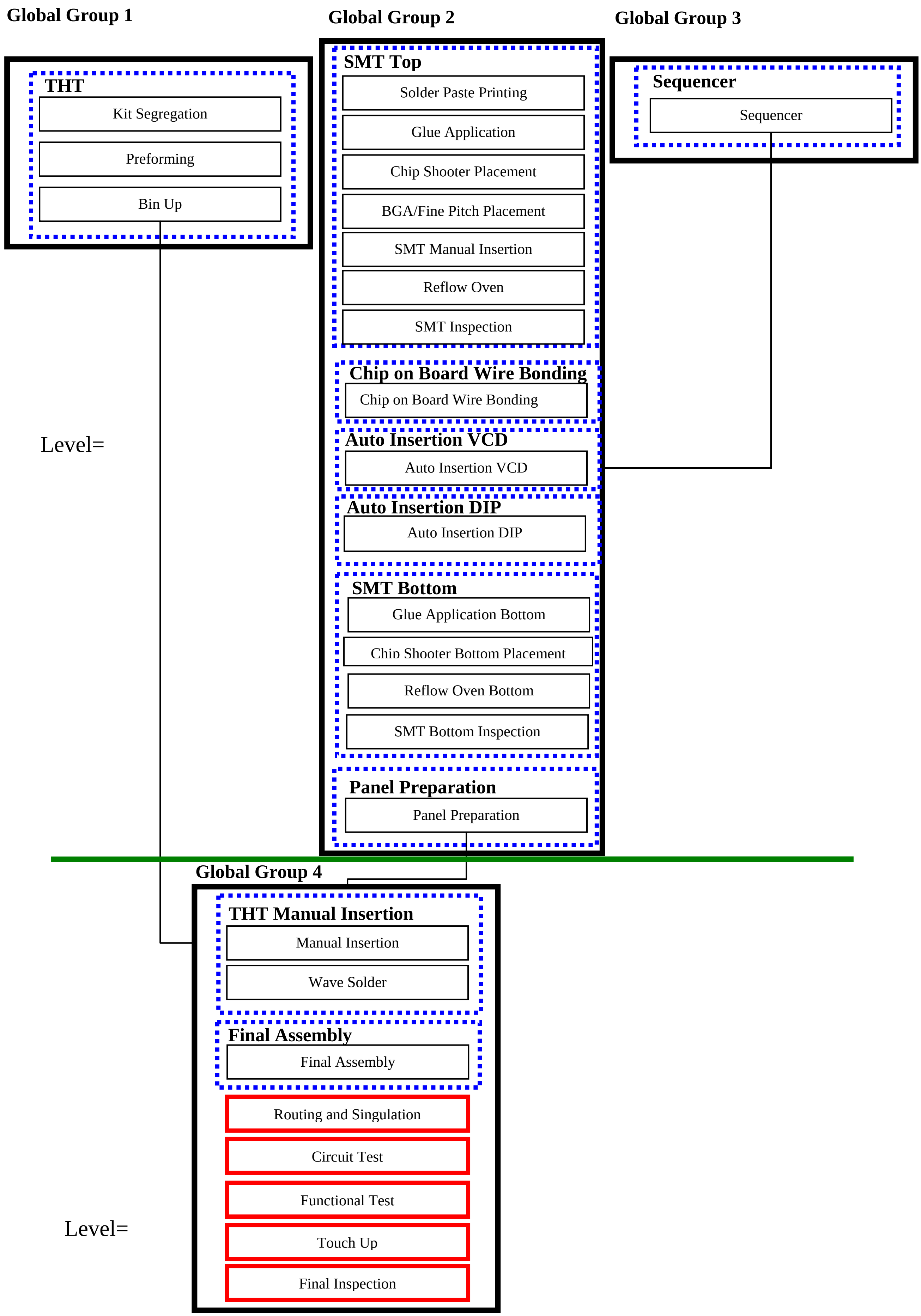
If you choose Process Engineer you can:

- Create, edit or delete a facility.
- Create, edit or delete processes from a facility.
- Calculate products cost in the facility created.
- It will also have all the capabilities presented previously to the product designer Product Developer/Designer.

Once you know how to create a new account, let's explain in detail the capabilities of each account.

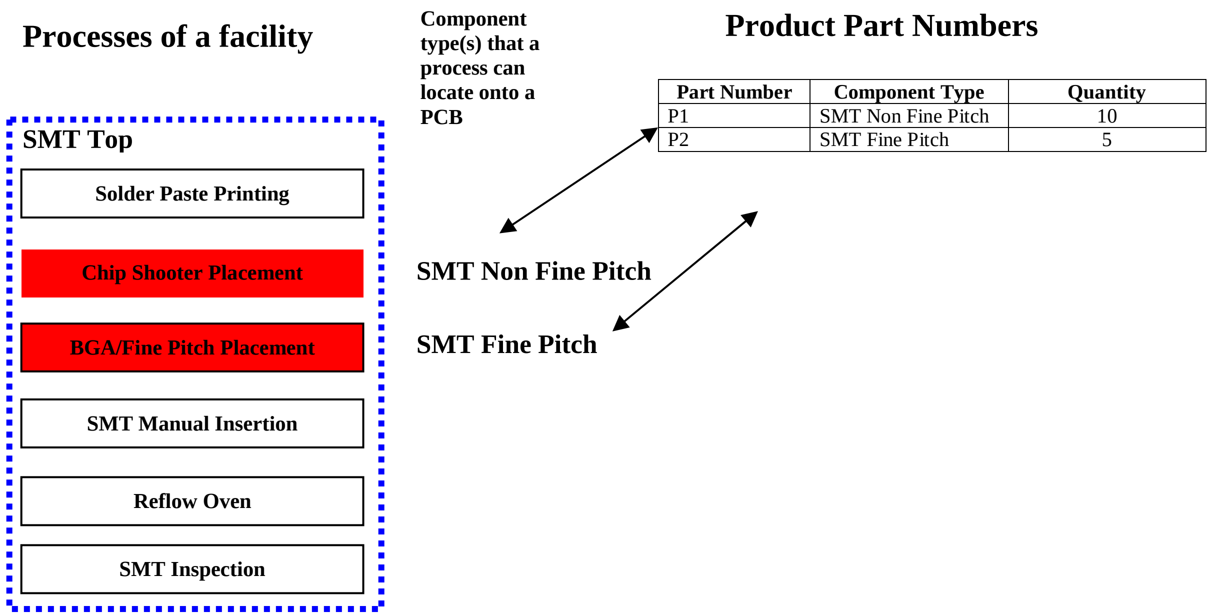
Product Developer/Designer account capabilities

If you log in as a Product Developer/Designer, there are some things you need to know prior to the generation of products and cost calculations. The PCB Cost Model application has a default facility included to make the cost calculations of your products. This default facility includes the typical processes found on an electronic manufacturing environment that were specified in *Mendez* research. The processes considered and the layout of the processes is shown on the following figure.



Global Group 1
THT
Kit Segregation
Preforming
Bin Up
Global Group 2
SMT Top
Solder Paste Printing
Glue Application
Chip Shooter Placement
BGA/Fine Pitch Placement
SMT Manual Insertion
Reflow Oven
SMT Inspection
Chip on Board Wire Bonding
Chip on Board Wire Bonding
Auto Insertion VCD
Auto Insertion VCD
Auto Insertion DIP
Auto Insertion DIP
SMT Bottom
Glue Application Bottom
Chip Shooter Bottom Placement
Reflow Oven Bottom
SMT Bottom Inspection
Panel Preparation
Panel Preparation
Global Group 3
Sequencer
Sequencer
Level=
Global Group 4
THT Manual Insertion
Manual Insertion
Wave Solder
Final Assembly
Final Assembly
Routing and Singulation
Circuit Test
Functional Test
Touch Up
Final Inspection
Level=

Once you know the processes that are included on the default facility, let's proceed to show you how the PCB Cost Model application works. Let's explain you how the PCB Cost Model works with a sample situation. Let's suppose that your facility contain the processes shown on the figure below. These processes are basically the typical processes found on the electronics industry to make the placement and soldering of Surface Mount Technology (SMT) components. The boxes in red represent the processes on a SMT line that place components onto a PCB. The idea behind the PCB Cost Model is to associate the processes that place components onto a PCB with the part numbers of a product. How this is done? Well, basically the application has a method called "Component Type" that allows you to associate part numbers of a product with processes. In the figure shown below, the process Chip Shooter Placement is associated with the component type SMT non fine pitch and the part number P1 is also associated with the Component Type SMT Non Fine Pitch. What the application does is that it search the component types associated with each part number of a product and then search the processes that locates those component types. Once the processes that locate components are identified, another method is used to retrieve the required complementary processes needed to complete the SMT process. This method is called "Group Name". This method basically associates processes in a facility. Consider the processes shown in the figure below. The white boxes represent the complementary processes in SMT that need to be made if an SMT component is assembled onto a PCB. What the Group method does is retrieve the complementary processes needed when a particular process that locates components is needed.



Part Number	Component Type	Quantity
P1	SMT Non Fine Pitch	10
P2	SMT Fine Pitch	5

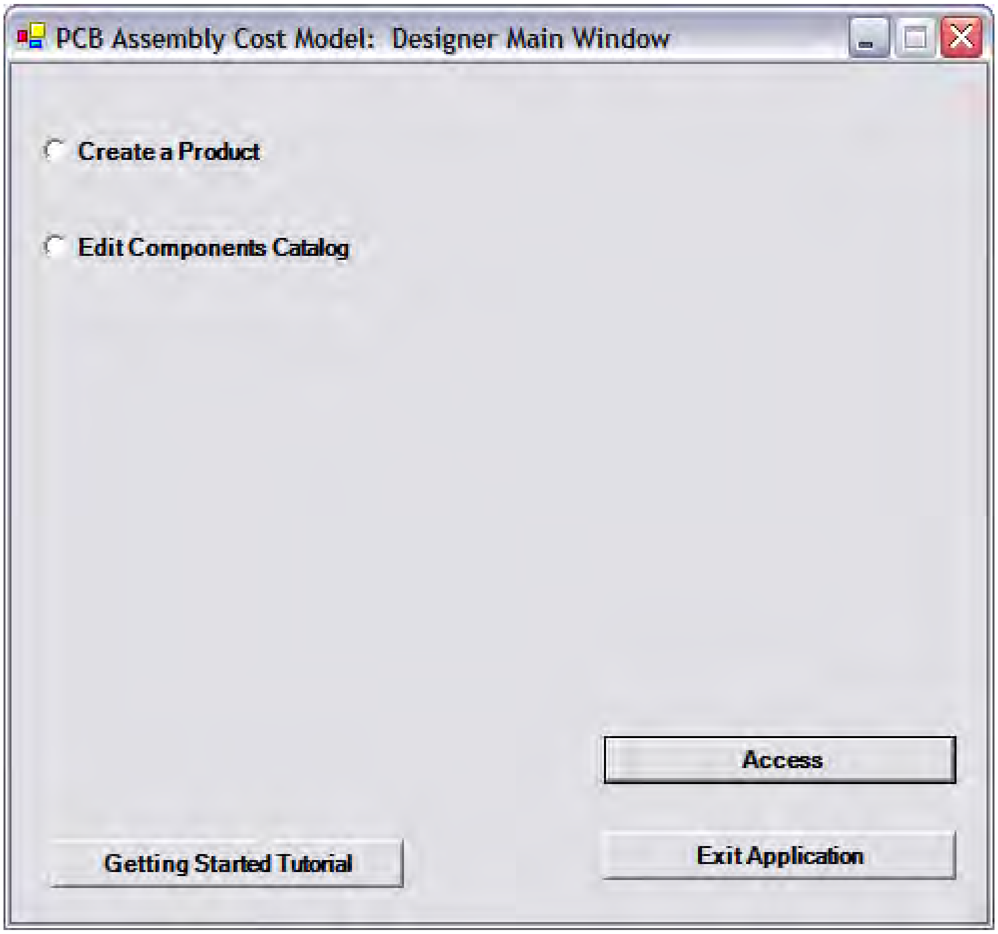
The PCB Cost Model has created some Component Types to associate processes with part numbers of a product. The part numbers included are:

Component Types	
Component Type	**Description**
BRACKETS OR SOCKETS	Usually assembled in the process Final Assembly
DIP	Usually assembled in the process Auto Insertion DIP
GOLD PLATED PARTS	Usually assembled in the process Panel Preparation
SMTCHIP_BOTTOM	Usually assembled in the process Chip Shooter Bottom
SMTFINEPITCH	Usually assembled in the process BGA/Fine Pitch Placement
SMTMANUAL	Usually assembled in the process SMT Manual Insertion
SMTNFP_TOP	Usually assembled in the process Chip Shooter Top
THT	Usually assembled in the process THT Manual Insertion
VCD	Usually assembled in the process Auto Insertion VCD
WIRE	Usually assembled in the process Chip on Board Wire Bonding

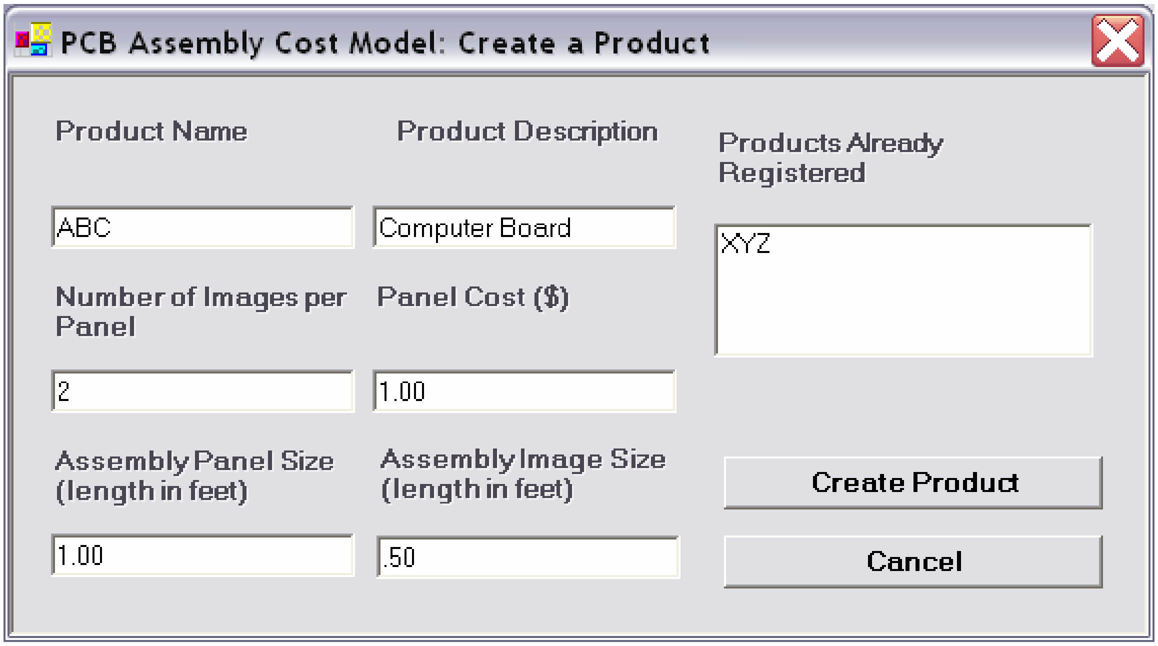
Although these are the only Component Types available so far, you can create your own component types to complement the existing ones. We will show you later how to it.

Our Task: Estimate the cost of a new design as a Product Developer/Designer

In this section we will present you how to create a new product design and estimate the cost of your product. To begin with the creation process, you must log in the PCB Cost Model Application and be registered as a Product Developer/Designer user. Once you have made the log in, the form called Designer Main Window is shown.



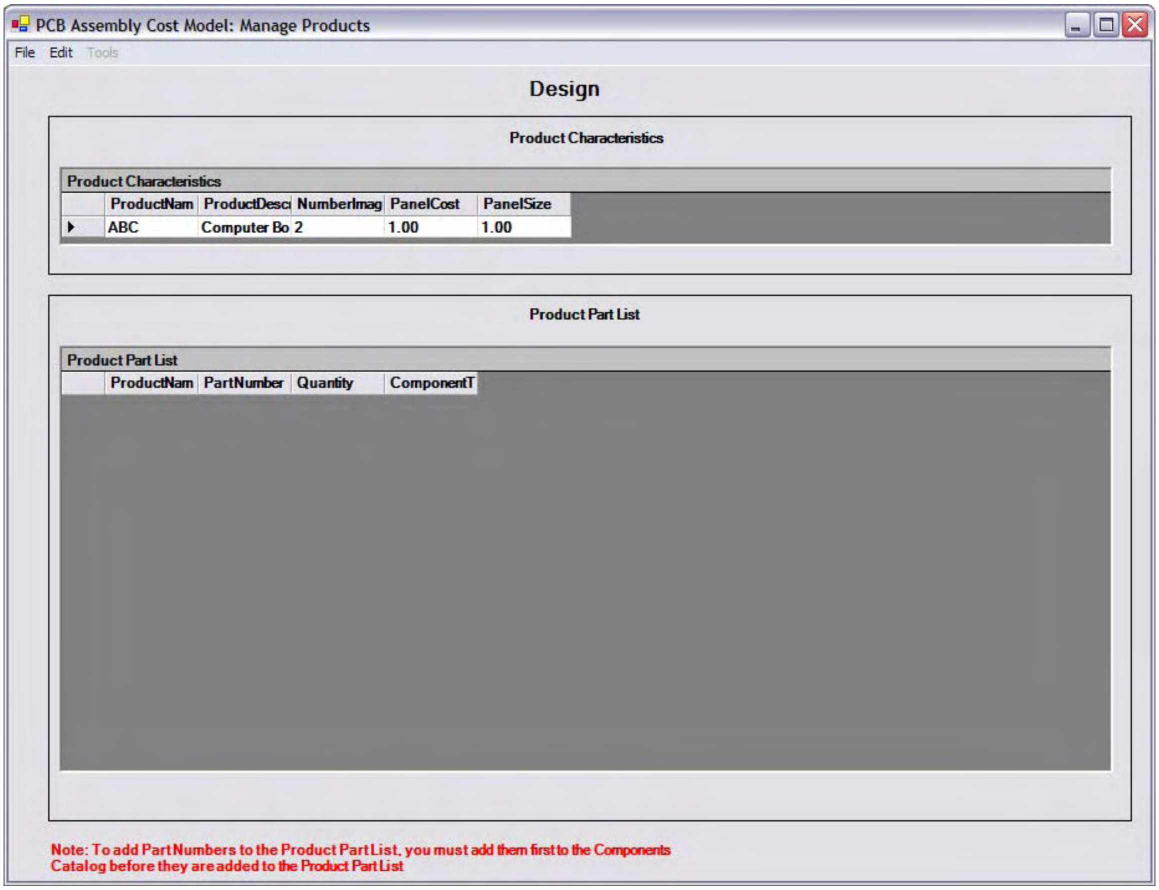
To create a new product, we will choose the option “Create a Product” and click the button “Access”. Once you click the “Access” button, the “Product Creation” form is presented as shown below.



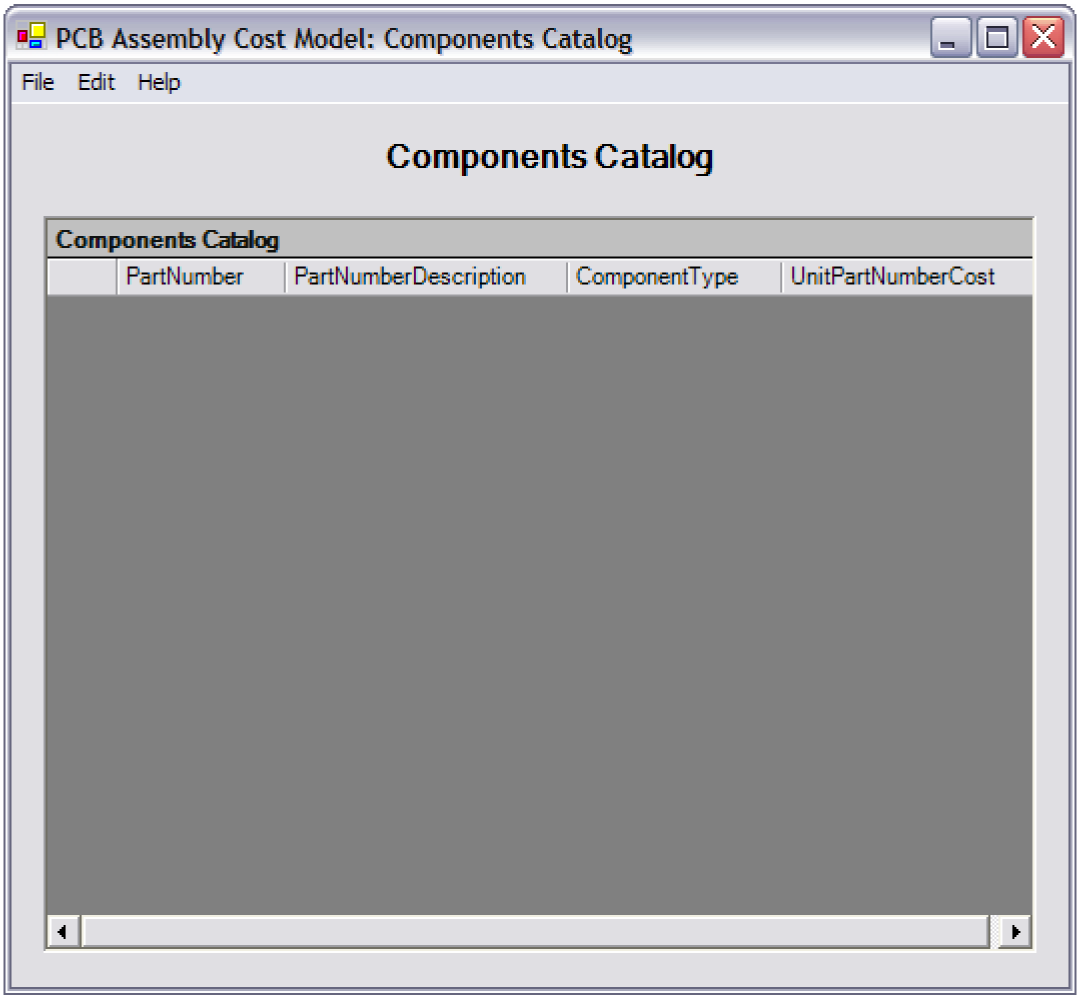
The necessary prompts and valid entries to create a product are on the following table:

Prompt	Valid Entry	Example
Product Name	String	ABC
Product Description	String	Computer Board
Number of Images per Panel	Number (integer)	2
Panel Cost ($)	Number (double)	1.00
Assembly Panel Size (length in feet)	Number (double)	1.00
Assembly Image Size (length in feet)	Number (double)	.50

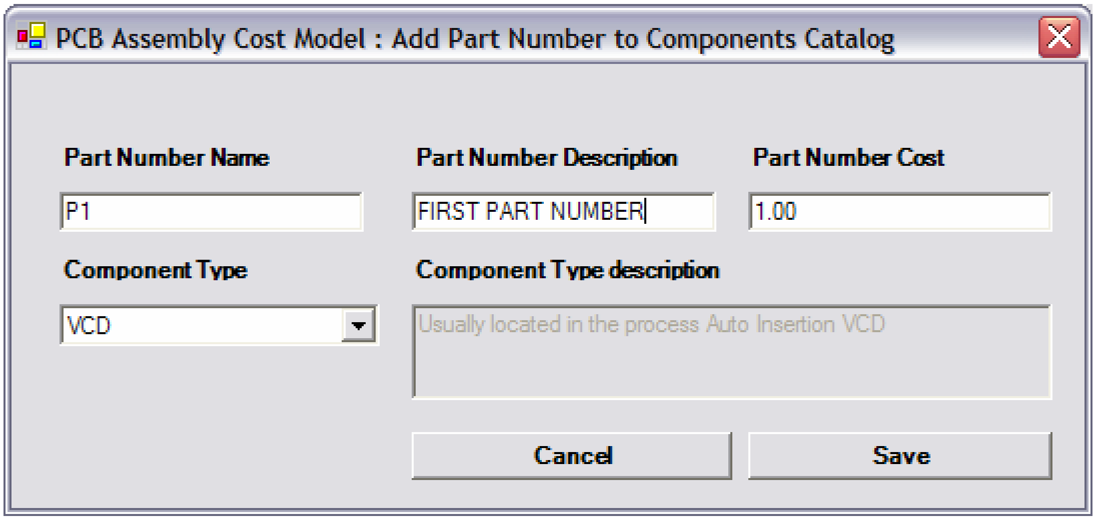
Once all the necessary information for the creation of a product is made, click the "Create Product" button. When you click this button a message box appears that says "Product was created". Following this message box appears another message box that asks you the following: **Do you want to add part numbers to your new product? If you click No, you will returned to the main window.** If you click no you will be returned to the main window. If you click yes, as we will do now, you will be referred to the form "Manage Products" which is shown below. In this form you can practically perform almost all the things required to obtain the cost of your new design. This form contains the general characteristics of a product and the part numbers registered.



At this point, no part number has been added to our product ABC. We will now proceed to add some part numbers to the product ABC. Because at this point it is assumed that you are using the PCB Cost Model for the first time, we will guide you to register part numbers to the catalog of the application prior to add them to a product design. The reason to have a components catalog is because you would need to register a part number only one time and they reuse it in other product designs. To access the components catalog from the "Manage Products" form go to Edit/Components Catalog and the figure shown below will appear.



To add a new part number to the "Components Catalog" form go to File/New/Part Number and the form shown below appears:

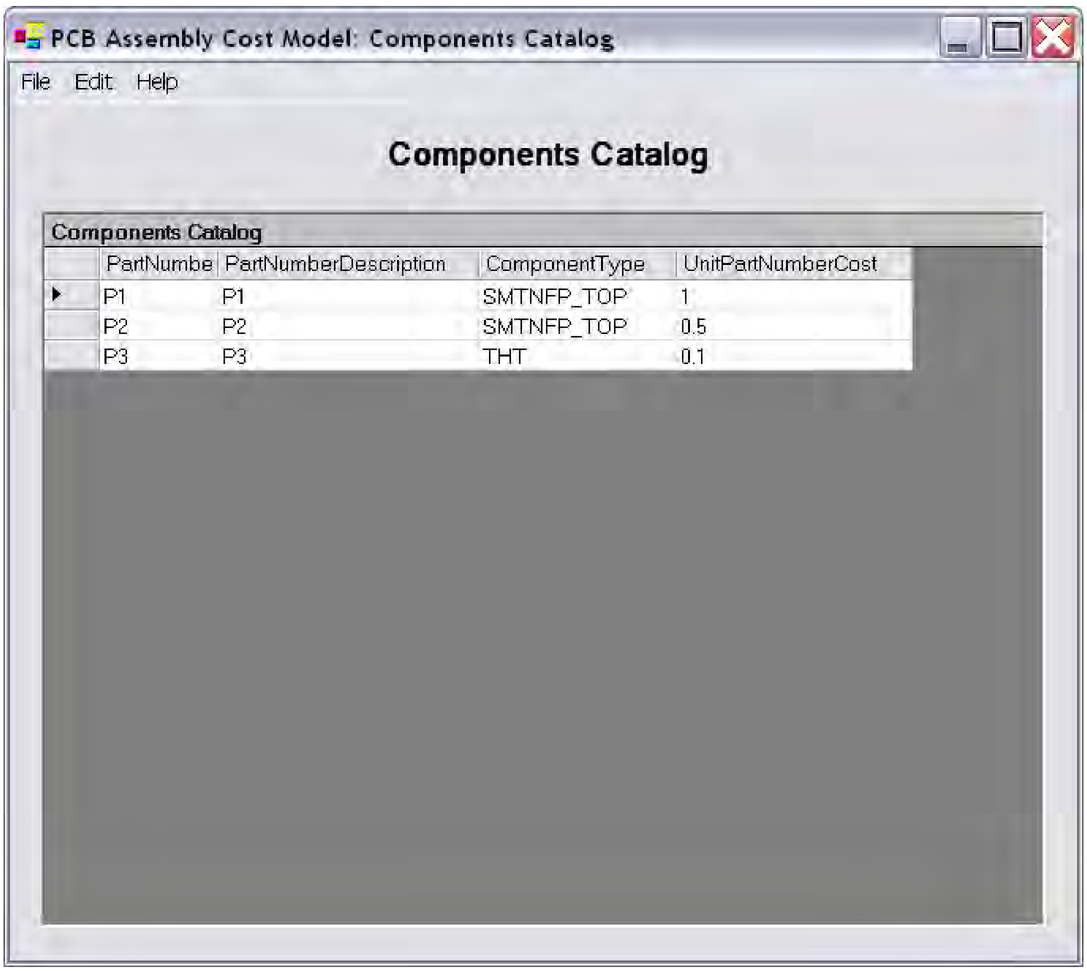


The necessary prompts and valid entries to register a part number to the application are on the following table:

Prompt	Valid Entry	Example
Part Number Name	String	P1
Part Number Description	String	Radial Component
Unit Part Number Cost	Double Number	1.00
Component Type	Choose from existing options	VCD
Component Type Description	String	Usually assembled in the process Auto Insertion VCD

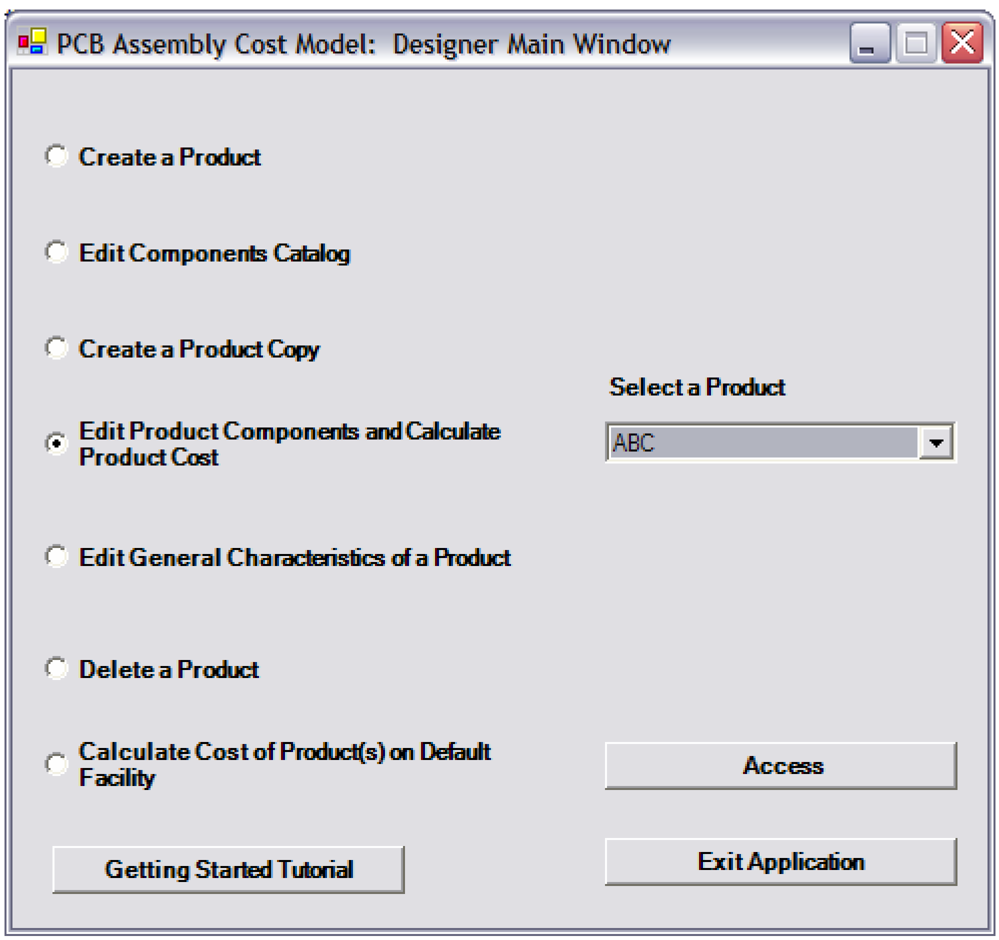
Note: The "Component Type" field is a method to relate the part numbers being added in the Components Catalog with the machine or manual operation that place or insert part numbers in a product. The PCB Cost Model application already has few component types added by default. The "Component Types" added to the application were those most used in the industry. An example of this is the Component Type called VCD. This component belongs to the class of Through Hole Technology (THT) components which are inserted through an image and then soldered on a wave solder machine. The peculiarity of this "Component Type" is that it belongs to the type of components that are inserted through a PCB on an Auto Insertion VCD machine. There are different types of THT components and the most common used in the industry are registered on the application.

Once you have made the registration process of your part numbers, the "Components Catalog" form should look like this:

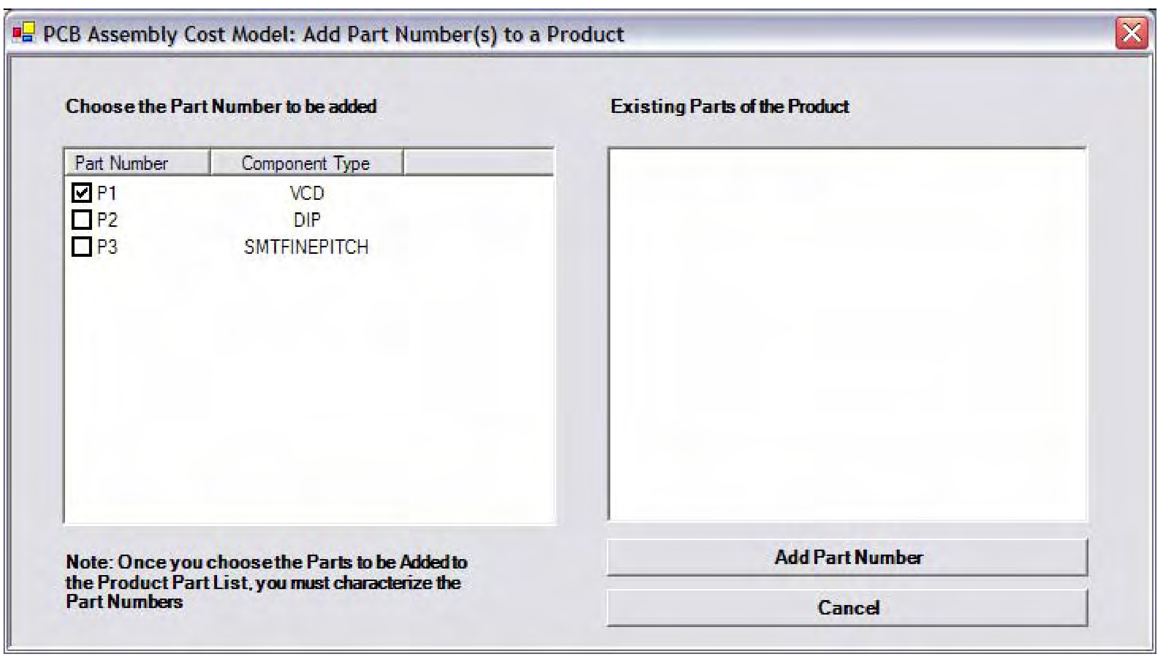


At this point, we have added three components to the catalog. The first component is a VCD component which was presented previously. The second component is a THT component that is placed on an Auto Insertion DIP machine. The third component is a Surface Mount Technology component. Surface Mount Technology

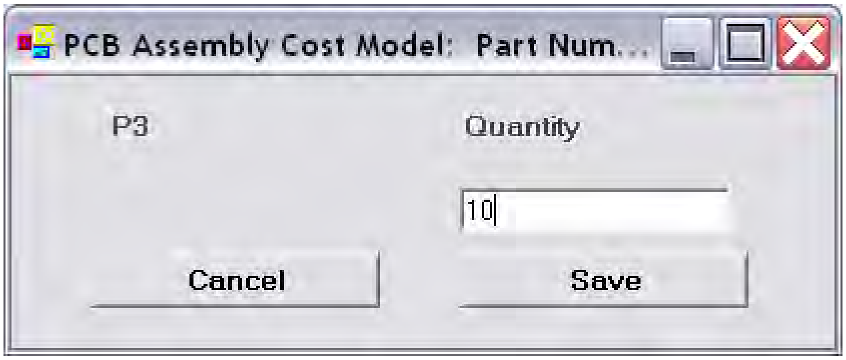
(SMT) refers to the placement of components in a PCB and the soldering of the components onto the PCB with a Reflow Oven machine. Unlike THT, SMT components are only placed on the board and not passed through the board. These two technologies are the two leading strategies to manufacture PCB's nowadays. Once the registration of our new part numbers have been made, we will proceed to add these part numbers to our product assuming these are the only part numbers required for our design. This is only for illustration on how to use the application because it is well known that a typical PCB uses many components. To add part numbers to the product, go to File/Return to Main Window and the following form appears:



As you can notice, the previous form is the Designer Main Window form presented to you earlier but with more options now. The reason why these options are now available is because when you started to use the application there were no products registered or created in the application. To proceed with the product we were creating, choose the option called "Edit Product Components and Calculate Product Cost" and choose the product ABC on the combo box provided and click "Access". When you do that, the form "Manage Products" appear. Then go to File/New/Part Numbers from the Components Catalog and the following form appears:



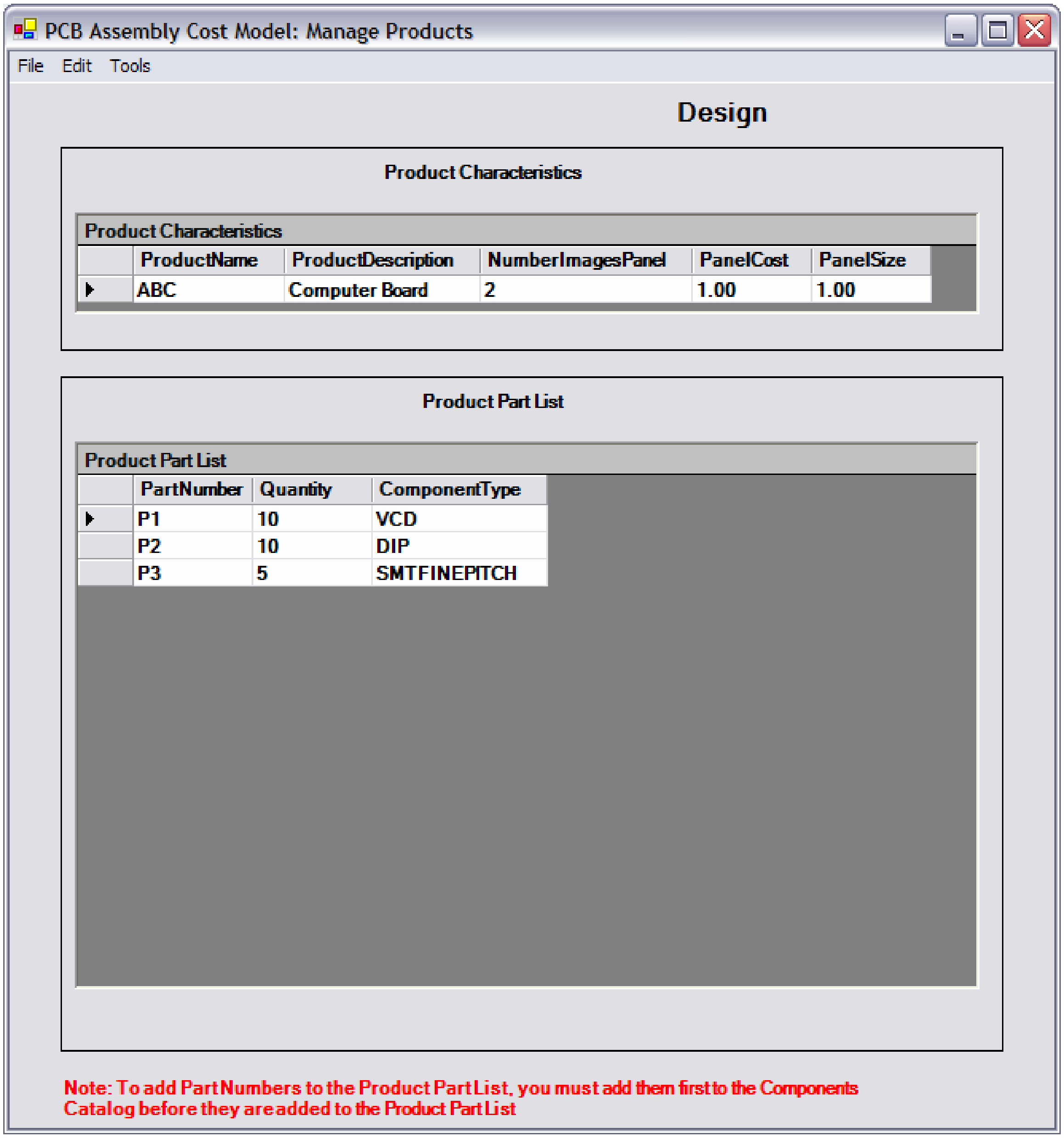
To add a part number to the ABC product simply check the part number that you want to add to ABC and click "Add Part Number". When you do this, the following form appears requesting the quantity needed of that part number and the Unit Cost of the part number to be added.



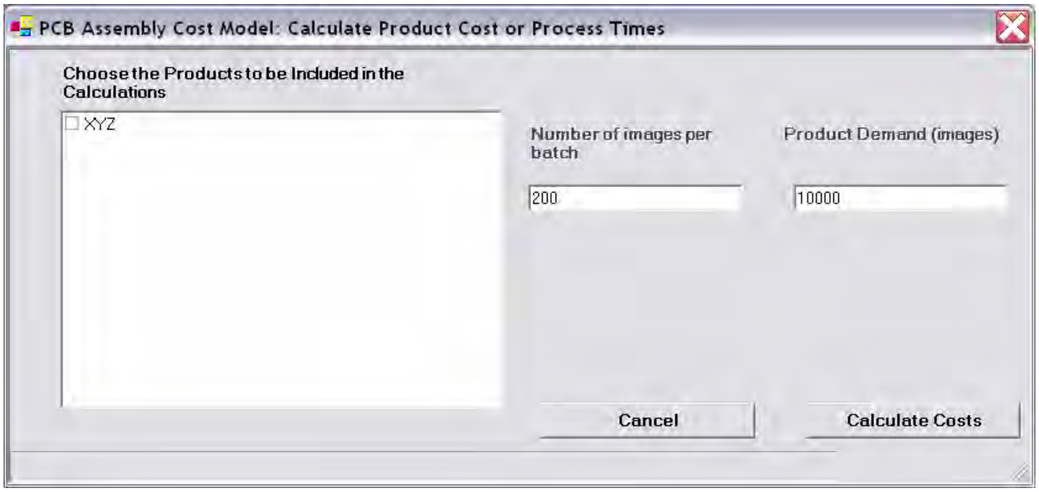
The necessary prompt and valid entry to register a part number to a product are on the following table:

Prompt	**Valid Entry**	**Example**
Quantity	Number (Integer)	10

Once you add the required part numbers to the product, the "Manage Products" form should look like the one below.



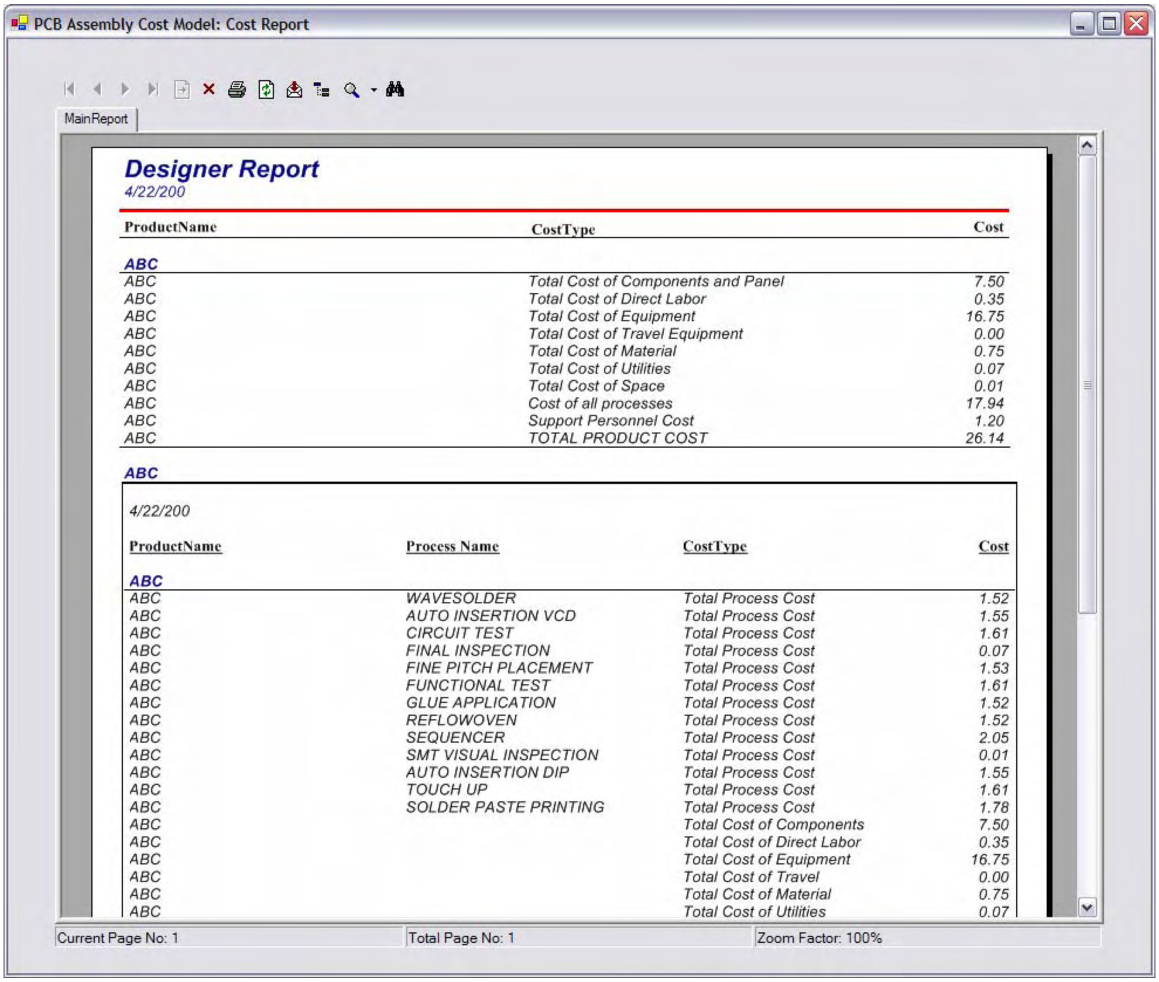
Once all the part numbers has been added to the product you are designing, you are ready to estimate the cost of your new design. All you have to do at this point is go to Tools/Calculate Product Cost. The form Calculate Product Cost is shown appears and is shown below.



The last steps you need to do to perform your cost estimate are to specify the following parameters:

Prompt	Valid Entry	Example
Number of Panels per Batch	Number (Integer)	200
Product Demand	Number (Integer)	10000

Choose the facility that you want to be included in the cost calculations. In this case we will use the Default Facility. After you choose the default facility click on the button "Calculate Product Cost" and wait a message box appears that tells that calculations have been made and the following report appears:


PCB Assembly Cost Model: Cost Report

MainReport

Designer Report

4/22/200

ProductName	CostType	Cost
ABC		
ABC	Total Cost of Components and Panel	7.50
ABC	Total Cost of Direct Labor	0.35
ABC	Total Cost of Equipment	16.75
ABC	Total Cost of Travel Equipment	0.00
ABC	Total Cost of Material	0.75
ABC	Total Cost of Utilities	0.07
ABC	Total Cost of Space	0.01
ABC	Cost of all processes	17.94
ABC	Support Personnel Cost	1.20
ABC	TOTAL PRODUCT COST	26.14

ABC

4/22/200

ProductName	Process Name	CostType	Cost
ABC			
ABC	WAVESOLDER	Total Process Cost	1.52
ABC	AUTO INSERTION VCD	Total Process Cost	1.55
ABC	CIRCUIT TEST	Total Process Cost	1.61
ABC	FINAL INSPECTION	Total Process Cost	0.07
ABC	FINE PITCH PLACEMENT	Total Process Cost	1.53
ABC	FUNCTIONAL TEST	Total Process Cost	1.61
ABC	GLUE APPLICATION	Total Process Cost	1.52
ABC	REFLOWOVEN	Total Process Cost	1.52
ABC	SEQUENCER	Total Process Cost	2.05
ABC	SMT VISUAL INSPECTION	Total Process Cost	0.01
ABC	AUTO INSERTION DIP	Total Process Cost	1.55
ABC	TOUCH UP	Total Process Cost	1.61
ABC	SOLDER PASTE PRINTING	Total Process Cost	1.78
ABC		Total Cost of Components	7.50
ABC		Total Cost of Direct Labor	0.35
ABC		Total Cost of Equipment	16.75
ABC		Total Cost of Travel	0.00
ABC		Total Cost of Material	0.75
ABC		Total Cost of Utilities	0.07

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APPENDIX D. USER MANUAL FOR THE PROCESS ENGINEER OF A FACILITY

Getting Started for Process Engineer

Introduction

- The PCB Cost Model is an application that complements the research done by ***Mendez*** to develop cost models that can be used to estimate the cost of new power electronics systems and products that are being developed.

- The project was sponsored by the Center for Power Electronics Systems (CPES).

- This research addressed a need for cost models to be used as a decision making tool from the early stages of the conception of the device to guide the research and development process.

- An examination of power electronics products revealed that they share the basic characteristics of any modern electronic product, this is, a printed circuit board (PCB) with electronic components that are soldered to it. Given that assumption, a cost model was developed for the board level assembly of electronics products assuming a typical and generic assembly sequence and processes. These sequences include all typical processes for the assembly of a PCB-based electronic product. The processes identified are the ones used in the assembly of through hole technology (THT) components, surface mount technology (SMT) components, chip on board wire-bonded components, or any combination of them.

- The cost model was developed with the power electronics product developer as the main user. Nevertheless, the user needs in this area are very similar to those of the developer of any other type of electronic product. Basically, this person will develop a series of product specifications. Given those specifications, the cost model can be used as a tool to estimate the cost of the product considering how it is manufactured. The basic product specifications to provide include: a bill of materials (BOM), the printed circuit board (PCB) characteristics, the expected market demand, and the expected product life. The resulting cost estimates can be used to compare one design alternative versus another without having to build a unit of the product.
- The cost model assumes that an electronic product consists essentially of a PCB with electronic components soldered to it. It is assumed that this kind of assembly will follow a series of generally sequential steps. In each step of the assembly sequence, resources will be consumed and hence cost will be incurred.
- The resources and costs included in the model are direct labor, materials and components, equipment, support personnel, utilities, and space. Each assembly manufacturing process step is analyzed to understand how the resources are consumed and costs allocated to every board produced.
- Once the cost model was developed, CPES was interested in the development of an application that could implement the model developed by *Mendez* to

estimate the cost of an electronic product and to evaluate the feasibility of design alternatives in terms of cost.

- The PCB Cost Model application implements a revised version of the cost model developed by *Mendez* and extends its capabilities. Primarily, the cost model was developed thinking on the designer of an electronic product as the only user but its implementation has been improved allowing the creation of custom facilities. This capability allows that a process engineer or planner of a facility can define its own facility to determine the cost of its existing products.

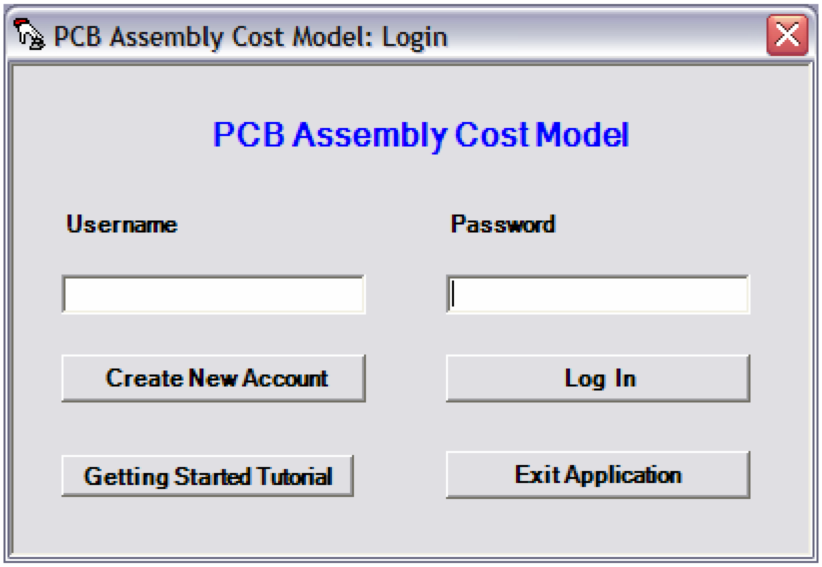
Now that you have an idea of the motivation for the creation of the PCB Cost Model application, we will proceed to explain the capabilities of the PCB Cost Model.

With the PCB Cost Model you can:

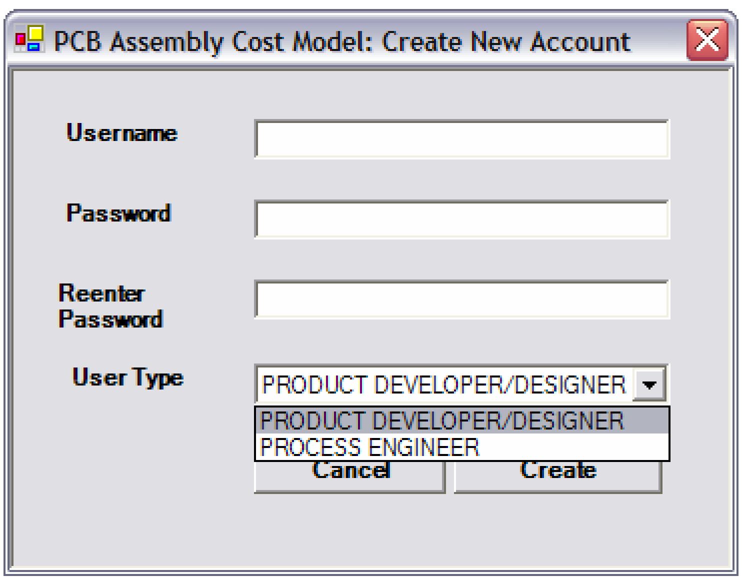
- Estimate the cost of a new electronic design and study the feasibility of alternative designs in terms of cost.
- Estimate the cost of an improved or current electronic design and evaluate the improvements of the designs in terms of cost.
- Estimate the time it will take to manufacture a batch of boards or images in your facility to see if you can meet product demand.
- Visualize the efficiency of your processes and manufacturing lines.

The PCB Cost Model environment

If PCB Cost Model is not already running, start it from the Windows Start menu and navigate to Programs/PCB Cost Model. The PCB Cost Model modeling environment will open with a login window, as shown below.



If you are a new user, you must create a new account to use the PCB Cost Model. When you click in the button "Create New Account", you will be redirected to the form "Create New Account" as shown below.



In this form you provide a username and password to create your new account. Once you provide your username and password, you must identify yourself as the type of user you are in this application. There are two choices in the user type": Product Developer/Designer or Process Engineer.

If you choose Process Engineer as we will do you can:

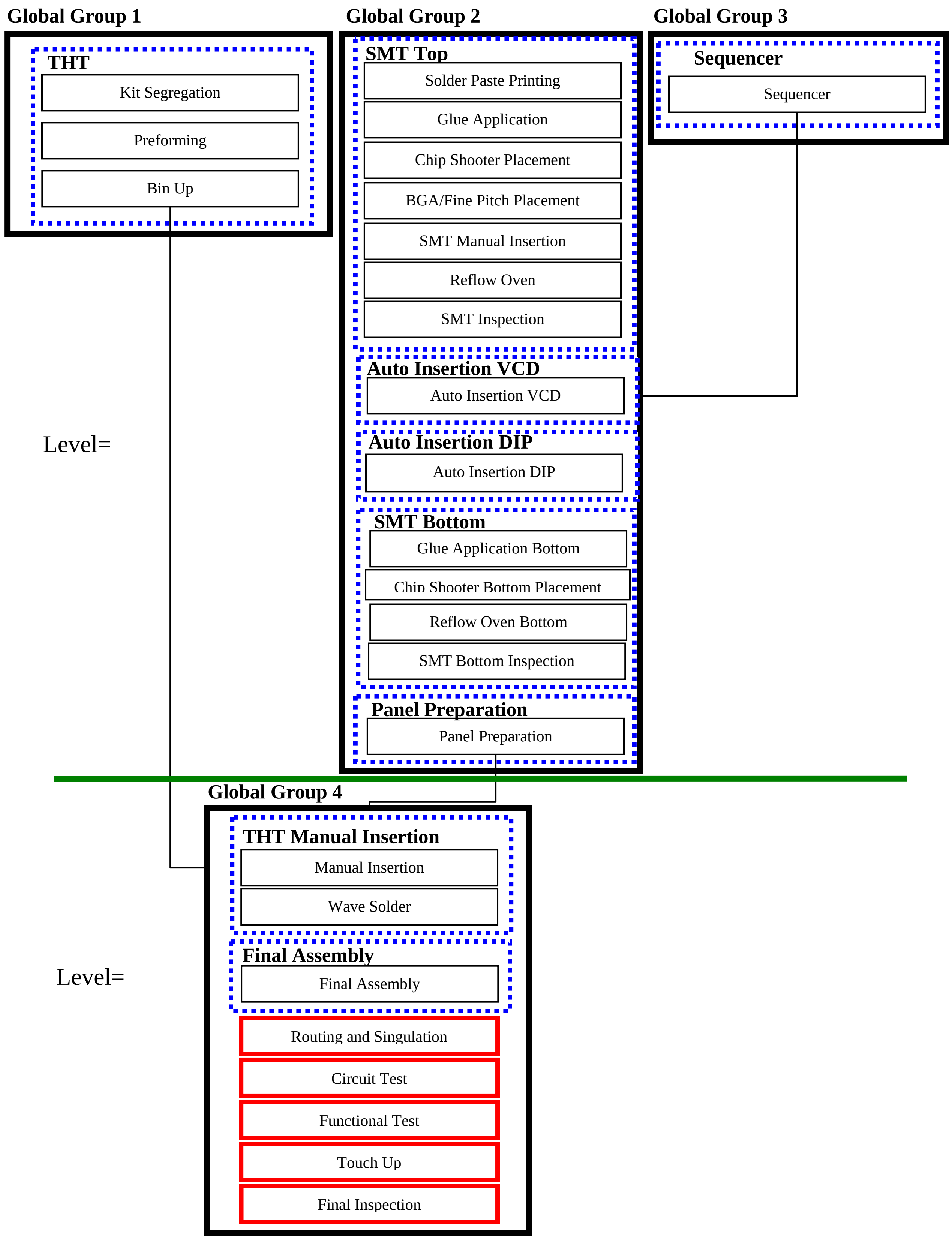
- Create, edit or delete products.
- Add, edit or delete part numbers from your products.
- Add component types.
- Calculate the cost of your products in all the registered facilities in the application evaluate the feasibility of a design in different facilities.
- Edit the Components Catalog of the application.
- Create a product copy.
- Calculate Cost of Product(s) on Default Facility of the application.
- Create, edit or delete a facility.
- Create, edit or delete processes from a facility.
- Calculate products cost in the facility created.

Once you know how to create a new account, let's explain in detail how to create a facility and calculate costs of your products in your facility or in the default facility of the application.

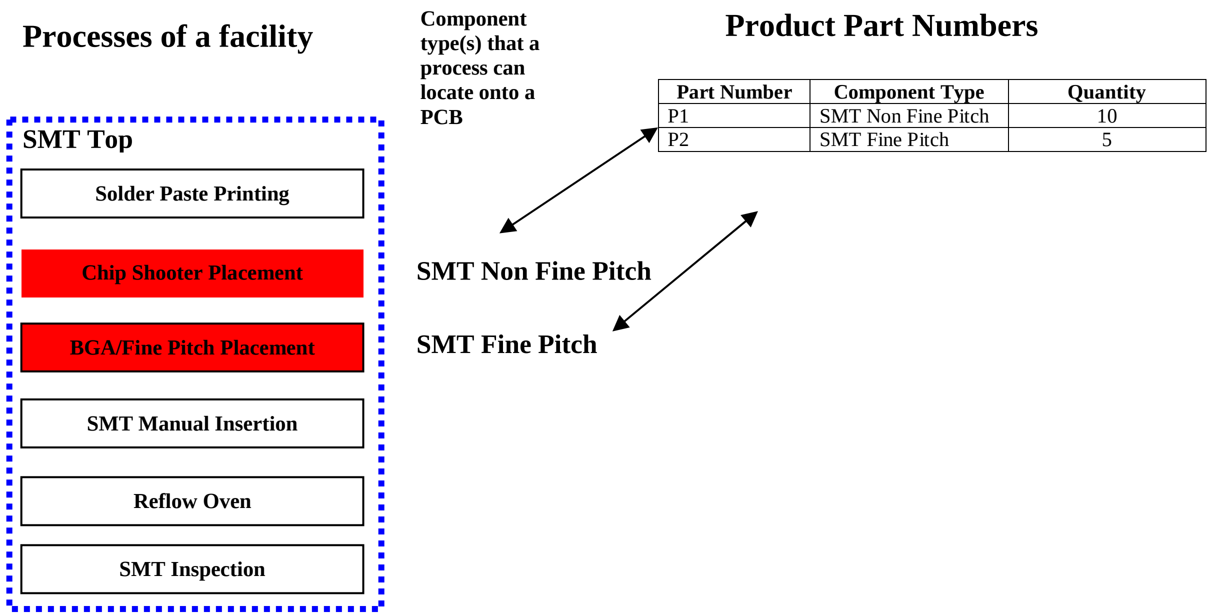
Process Engineer account capabilities

If you log in as a Process Engineer, there are some things you need to know prior to the generation of facilities and products to make cost calculations. The PCB Cost Model application has a default facility included to make cost calculations of products.

This default facility includes the typical processes found on an electronic manufacturing environment that were specified in *Mendez* research and it contains times and details from a research made in a company. The processes considered and the layout of the processes is shown on the following figure. Due to the fact that you are a process engineer in a facility, you should create your own facility to make the cost calculation of your products because it will contain the processes and times you have on the facility you belong. You can either choose to calculate the costs of your products with the default facility or you can make your own facility to calculate the cost of your products.


Global Group 1
THT
Kit Segregation
Preforming
Bin Up
Global Group 2
SMT Top
Solder Paste Printing
Glue Application
Chip Shooter Placement
BGA/Fine Pitch Placement
SMT Manual Insertion
Reflow Oven
SMT Inspection
Auto Insertion VCD
Auto Insertion VCD
Auto Insertion DIP
Auto Insertion DIP
SMT Bottom
Glue Application Bottom
Chip Shooter Bottom Placement
Reflow Oven Bottom
SMT Bottom Inspection
Panel Preparation
Panel Preparation
Global Group 3
Sequencer
Sequencer
Level=
Global Group 4
THT Manual Insertion
Manual Insertion
Wave Solder
Final Assembly
Final Assembly
Routing and Singulation
Circuit Test
Functional Test
Touch Up
Final Inspection
Level=

Once you know the processes that are included on the default facility, let's proceed to show you how the PCB Cost Model application works. Let's explain you how the PCB Cost Model works with a sample situation. Let's suppose that your facility contain the processes shown on the figure below. These processes are basically the typical processes found on the electronics industry to make the placement and soldering of Surface Mount Technology (SMT) components. The boxes in red represent the processes on a SMT line that place components onto a PCB. The idea behind the PCB Cost Model is to associate the processes that place components onto a PCB with the part numbers of a product. How this is done? Well, basically the application has a method called "Component Type" that allows you to associate part numbers of a product with processes. In the figure shown below, the process Chip Shooter Placement is associated with the component type SMT non fine pitch and the part number P1 is also associated with the Component Type SMT Non Fine Pitch. What the application does is that it search the component types associated with each part number of a product and then search the processes that locates those component types. Once the processes that locate components are identified, another method is used to retrieve the required complementary processes needed to complete the SMT process. This method is called "Group Name". This method basically associates processes in a facility. Consider the processes shown in the figure below. The white boxes represent the complementary processes in SMT that need to be made if an SMT component is assembled onto a PCB. What the Group method does is retrieve the complementary processes needed when a particular process that locates components is needed.



The PCB Cost Model has created some Component Types to associate processes with part numbers of a product. The part numbers included are:

Component Types	
Component Type	**Description**
BRACKETS OR SOCKETS	Usually assembled in the process Final Assembly
DIP	Usually assembled in the process Auto Insertion DIP
GOLD PLATED PARTS	Usually assembled in the process Panel Preparation
SMTCHIP_BOTTOM	Usually assembled in the process Chip Shooter Bottom
SMTFINEPITCH	Usually assembled in the process BGA/Fine Pitch Placement
SMTMANUAL	Usually assembled in the process SMT Manual Insertion
SMTNFP_TOP	Usually assembled in the process Chip Shooter Top
THT	Usually assembled in the process THT Manual Insertion
VCD	Usually assembled in the process Auto Insertion VCD
WIRE	Usually assembled in the process Chip on Board Wire Bonding

Although these are the only Component Types available so far, you can create your own component types to complement the existing ones. We will show you later how to it.

The application also has some Group Names which are the most common found in the electronic industry. These groups are shown on the following table

Group Name
Group Name
AUTO INSERTION DIP
AUTO INSERTION VCD
FINAL ASSEMBLY
MANUAL INSERTION
REQUIRED OPERATIONS
SEQUENCER
SMT BOTTOM
SMT TOP
THT
WIRE BONDING

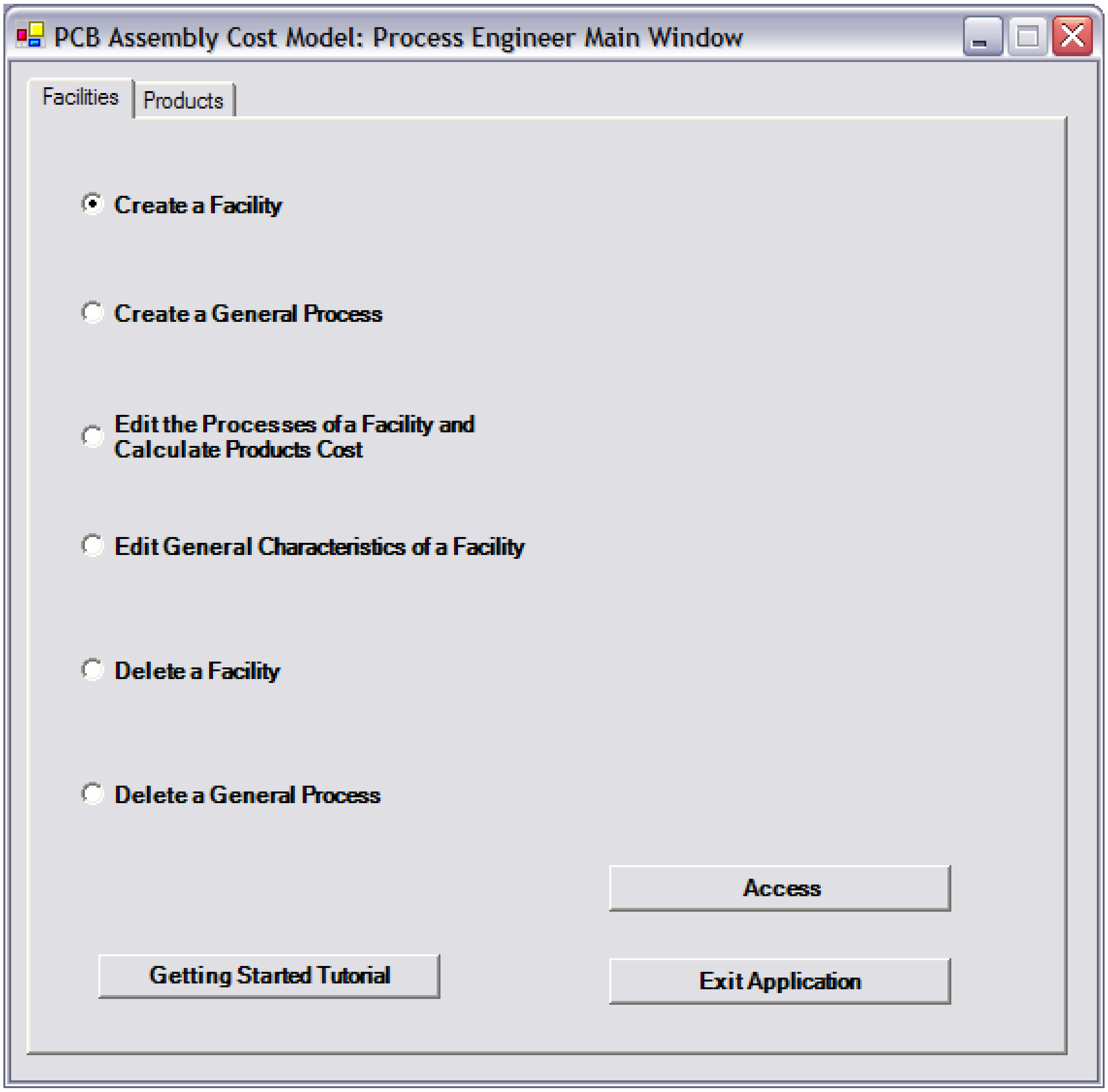
Although these are the only Groups available so far, you can create your own Groups types to complement the existing ones.

Now that you know how the PCB Cost Model work's and understand that you can make calculation of your products with the default facility, let's create a new facility , add processes to it and design a product and calculate its cost to illustrate the uses of the PCB Cost Model application.

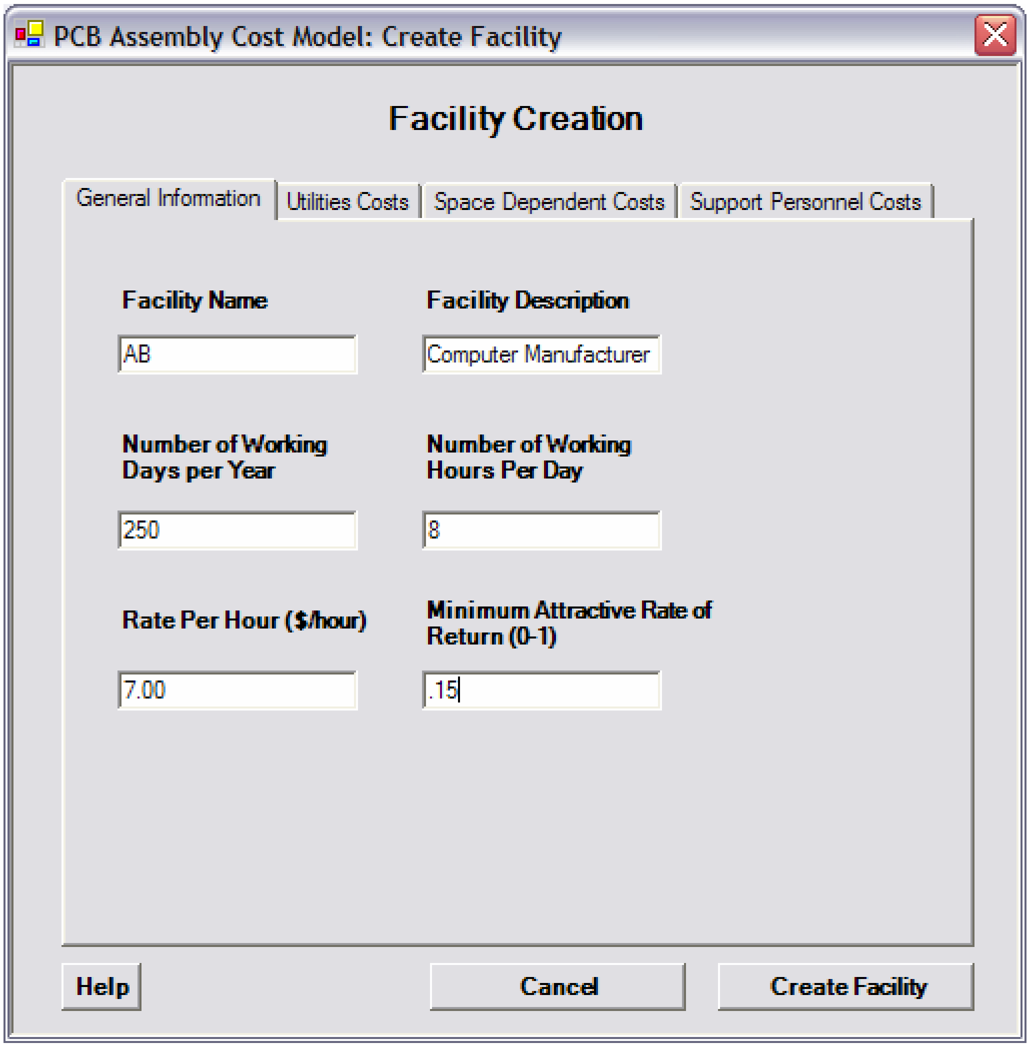
Our Task: Create a New Facility as a Process Engineer

In this section we will present you how to create a facility, add processes to your facility and calculate the cost of a product with the new facility created. To begin with the creation process, you must log in the PCB Cost Model Application and be registered as a

Process Engineer user. Once you have made the log in, the form called Designer Main Window is shown.



To create a new facility, we will choose the option “Create a Facility” and click the button “Access”. Once you click the “Access” button, the “Facility Creation” form is presented as shown below.



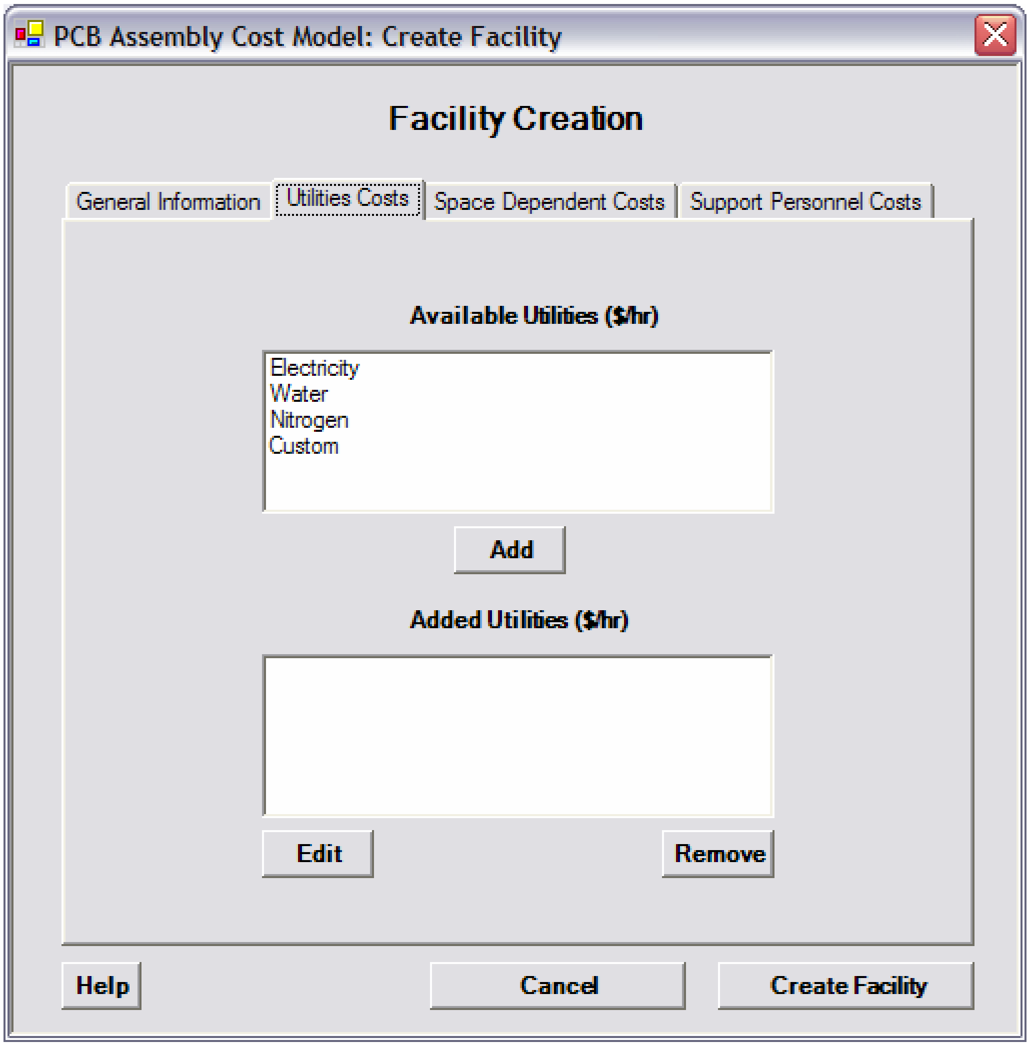
The necessary prompts and valid entries of the first tab in the "Facility Creation" form are on the following table:

Prompt	Valid Entry	Example
Facility Name	String	AB
Facility Description	String	Computer Manufacturer
Number of Working Days per Year	Number (integer)	250
Number of working hours	Number (double)	8

Prompt	Valid Entry	Example
per day		
Rate per Hour ($/hour)	Number (double)	7.00
Minimum Attractive Rate of Return(MARR)	Number (double) 0 < MARR <= 1	.15

Once you have provided the fields of the first tab, proceed to the second tab as shown below. In this tab, you must specify all the utilities that are used on your facility. The most common utilities found in the electronics industry are already available to be added. These ones are: Electricity, Water and Nitrogen. If you want to include any other utility you can make it selecting the option Custom. After you click the button "Add" you will be requested to specify the cost per hour of each utility in your facility. In you choose to add a "Custom" utility you must provide the name of the utility.

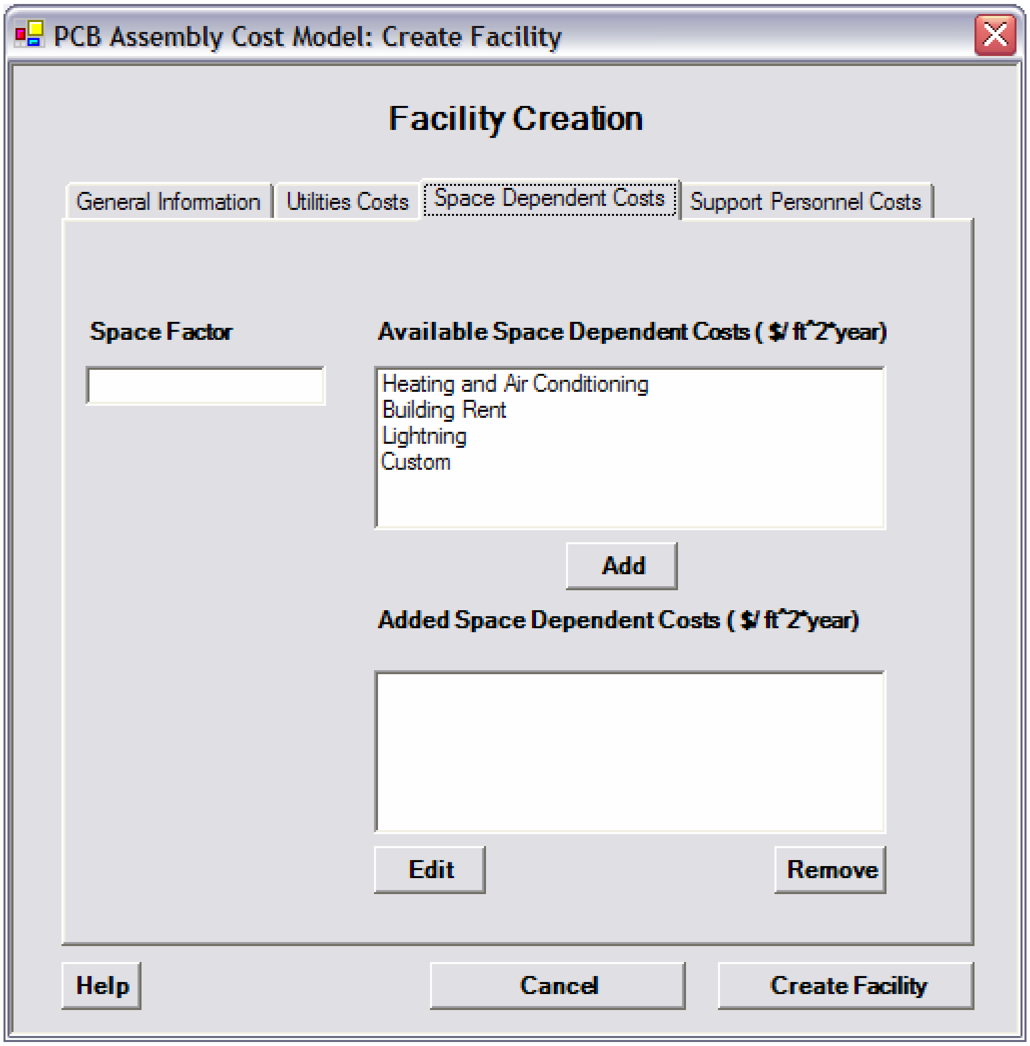
Note: You must be careful to maintain integrity in the units you are using. If you use kilowatts as the unit to specify electricity consumption, you must remember to specify all the electricity consumption of the processes of your facility in kilowatts. This point will be discussed later in the creation of a process.



If you are creating the sample facility with us, provide the following utilities and costs:

Utility	Cost per Hour
Electricity	.10
Water	.10
Nitrogen	.10

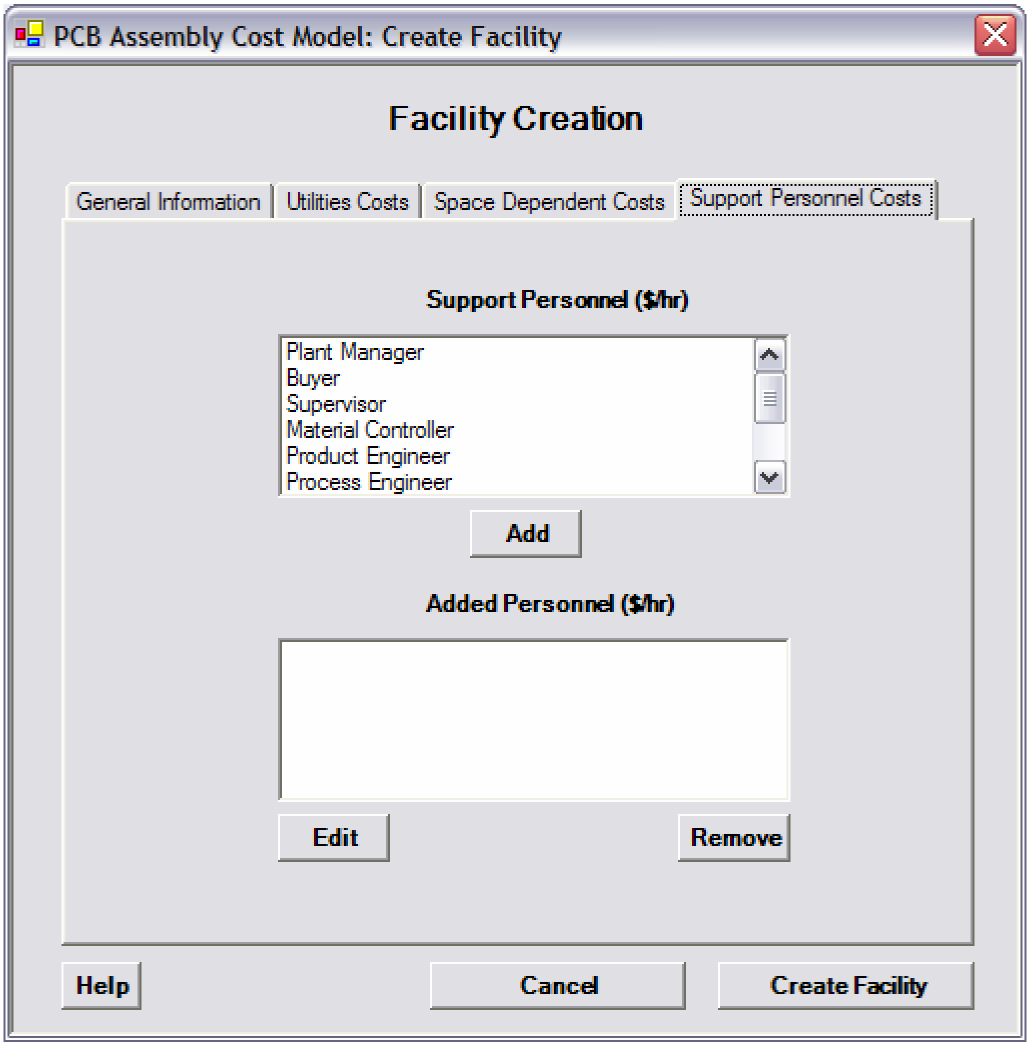
Once you have chosen the Utilities to add, proceed to the third tab as shown below. In this tab, you must specify all the costs that depend on the space used in the facility. The most common space dependent costs found in the electronics industry are already available to be added. These ones are: Heating and Air Conditioning, Building and Rent and Lightning. If you want to include any other space dependent cost you can make it selecting the option Custom. After you click the button "Add" you will be requested to specify the cost per square feet per year of each space dependent cost in your facility. In you choose to add a "Custom" space dependent cost; you must provide the name of the cost. A space factor is also required. A space factor is an allowance that you give to each operation in the facility



If you are creating the sample facility with us, provide the following space dependent costs:

Space Dependent Cost	Cost per Square Feet per Year
Heating and Air Conditioning	.10
Building and Rent	.10
Lightning	.10
Space Factor	
.5	

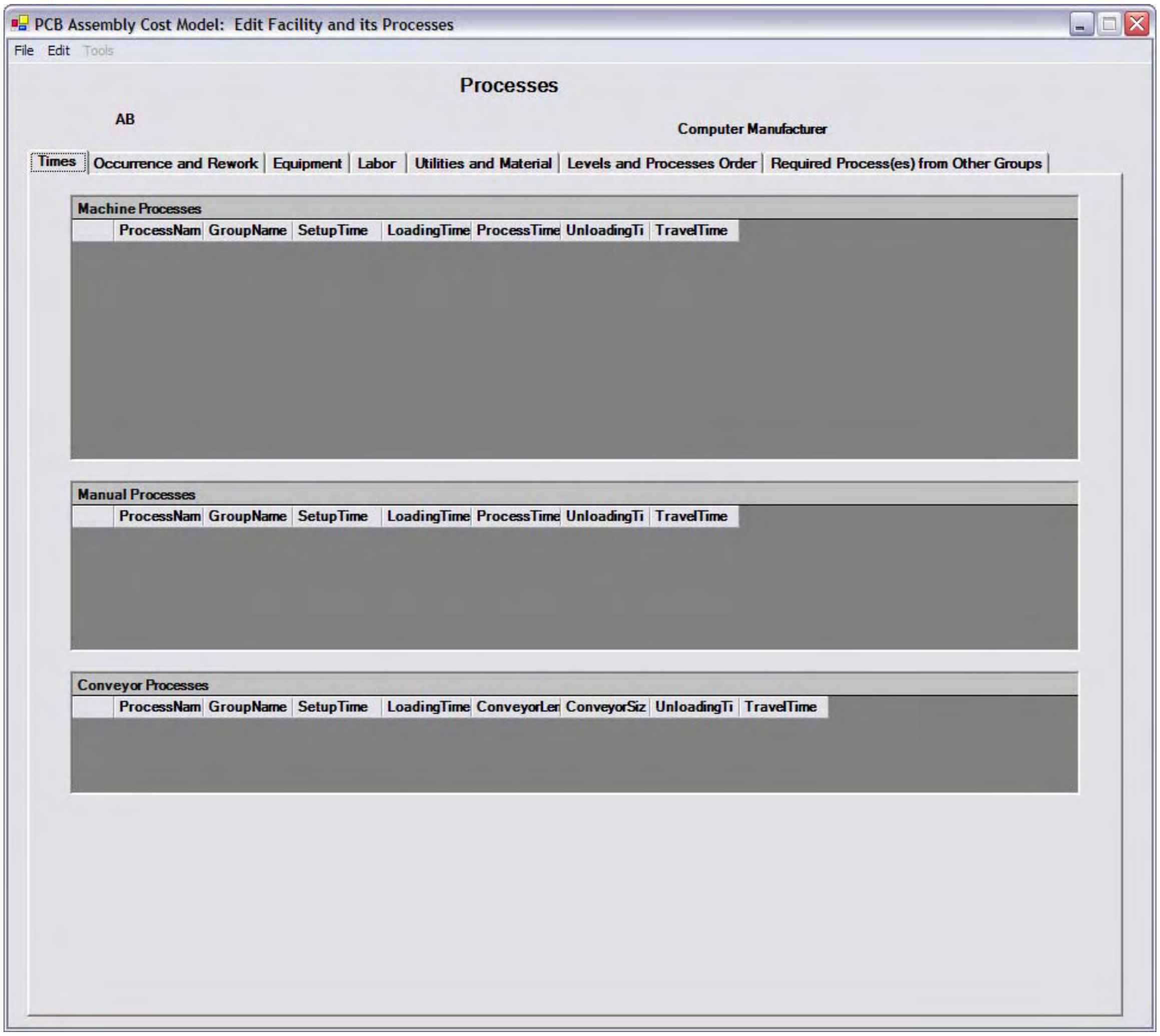
Once you have chosen the Space Dependent Cost to add, proceed to the fourth tab as shown below. In this tab, you must specify all the personnel that support the production of products in the facility. The most common support personnel found in the electronics industry are already available to be added. These ones are: Plant Manager, Buyer, Supervisor, Material Controller, Product Engineer, Process Engineer, Process Technician, Test Support Technician and Maintenance Technician. If you want to include any other support personnel you can make it selecting the option Custom. After you click the button "Add" you will be requested to specify the salary per year of each support person in your facility. In you choose to add a "Custom" support person; you must provide the position of the person. The "Average Number of Hours per Year that Support Personnel dedicate to product processing" is also required.



If you are creating the sample facility with us, provide the following support personnel information:

Utility	Salary per Year
Plant Manager	100000
Process Engineer	60000
Product Engineer	70000

At this point you are ready to register your new facility in the PCB Cost Model application. Click on the button "Create Facility" and a message box appears indicating that your new facility has been created. Once you click “Ok” in the previous message box, another message box appears asking you the following: “Do you want to add Processes to your facility?”. At this point we will click “Yes” to add processes to our new facility and calculate products cost. Once you click “Yes” in the previous message box, the form called “Edit Facility and its Processes” appears and is shown below. In this form you can register all the processes of your facility and control the logic and order of the processes in your facility. Once you have created all the processes and logic of your facility you can create the products currently being produced in your facility and calculate its cost.



Our Task: Register a General Process to the application

Prior to the registration of processes in your facility, let's create a General Process in the PCB Cost Model application. A General Process in the PCB Cost Model application is a method used to establish a general characteristic of a process and reuse these processes in the creation of facilities. A General Process has the following characteristic: Process Type. The available Process Types and its description are the following:

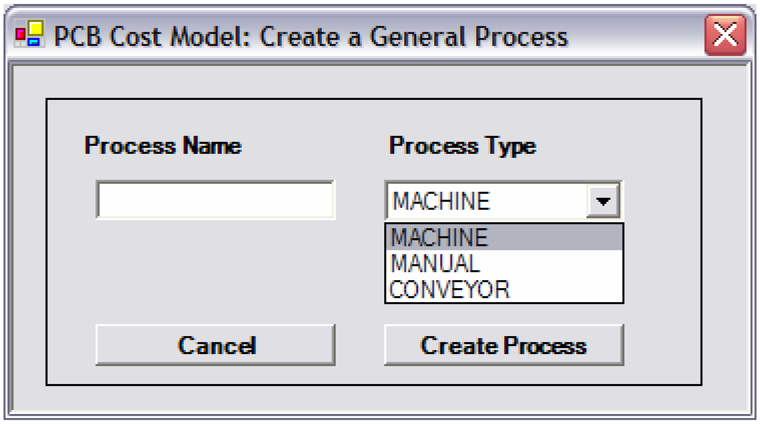
- MACHINE – it refers to processes where mostly all the work is made by a machine and minor or no operator intervention is required.
- CONVEYOR- it refers to processes where an electronic product is processed through a conveyor with a specified length and velocity.
- MANUAL – it refers to processes that are made by operators.

The idea of a General Process is used because the PCB Cost Model Application has several processes already defined and ready to use. The general processes defined in the PCB Cost Model are those most used in the electronics industry and its type has been previously specified. The processes previously defined in the PCB Cost Model are the following:

Process Name	Process Type
AUTO INSERTION DIP	MACHINE
AUTO INSERTION VCD	MACHINE
BIN UP	MANUAL
CHIP ON BOARD WIRE BONDING	MACHINE
CHIP SHOOTER	MACHINE
CHIP SHOOTER BOTTOM	MACHINE
CIRCUIT TEST	MACHINE
FINAL ASSEMBLY	MANUAL
FINAL INSPECTION	MANUAL
FINE PITCH PLACEMENT	MACHINE
FUNCTIONAL TEST	MACHINE
GLUE APPLICATION	MACHINE
GLUE APPLICATION BOTTOM	MACHINE
KIT SEGREGATION	MANUAL
MANUAL ASSEMBLY OF SMT	MANUAL
MANUAL INSERTION OF THT	MANUAL
PANEL PREPARATION	MANUAL
PREFORMING	MACHINE
REFLOW OVEN BOTTOM	CONVEYOR

Process Name	Process Type
REFLOWOVEN	CONVEYOR
ROUTING AND SINGULATION	MACHINE
SEQUENCER	MACHINE
SMT VISUAL INSPECTION	MANUAL
SMT VISUAL INSPECTION (BOTTOM)	MACHINE
SOLDER PASTE PRINTING	MACHINE
TOUCH UP	MACHINE
WAVESOLDER	CONVEYOR

Although these are predefined processes ready to use in the application, you can create your own general processes. Let's create a general process now. Let's go to the general form "Process Engineer Main Window". If you are following us from the previous section called "Create a New Facility as a Process Engineer" go to File/Return to Main Window and the form "Process Engineer Main Window" take the focus. Simply choose from the option "Create a General Process" and click "Access" and the following form appears:

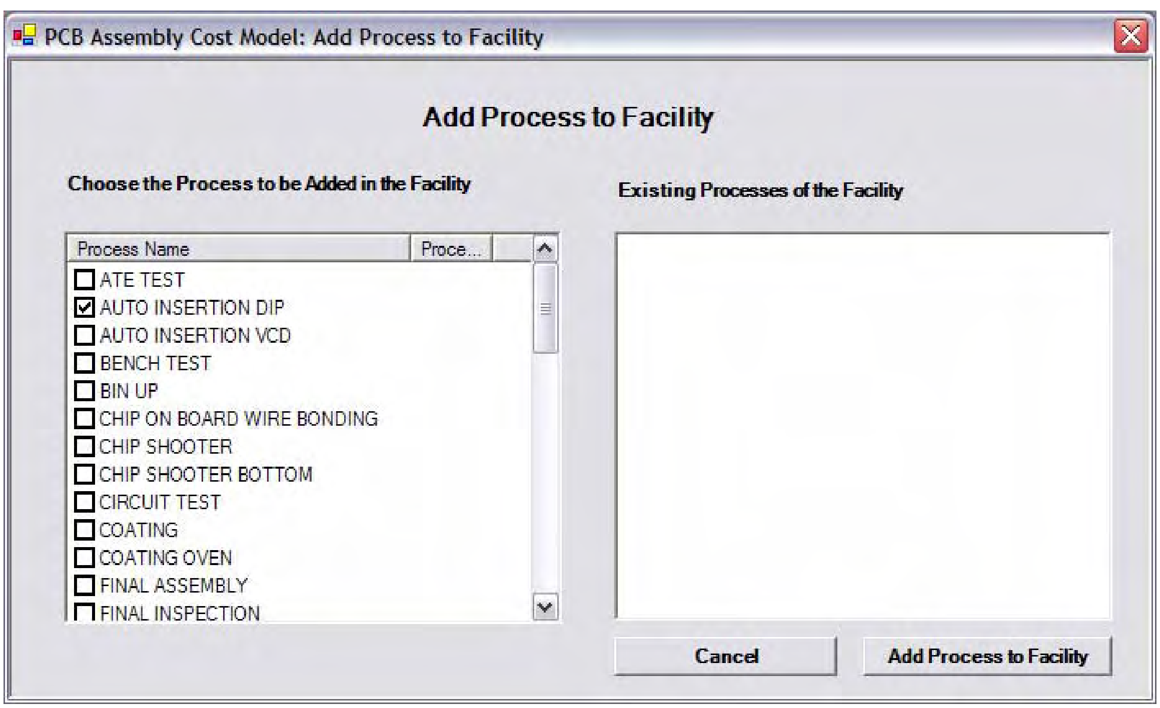


The necessary prompts and valid entries of the "Create a General Process" form are on the following table and when your are finished locating prompts click the bottom "Create

Process" and a message box appears indicating that a new general process has been created.

Prompt	Valid Entry	Example
Process Name	String	PCB Coating
Process Type	MACHINE MANUAL CONVEYOR	CONVEYOR

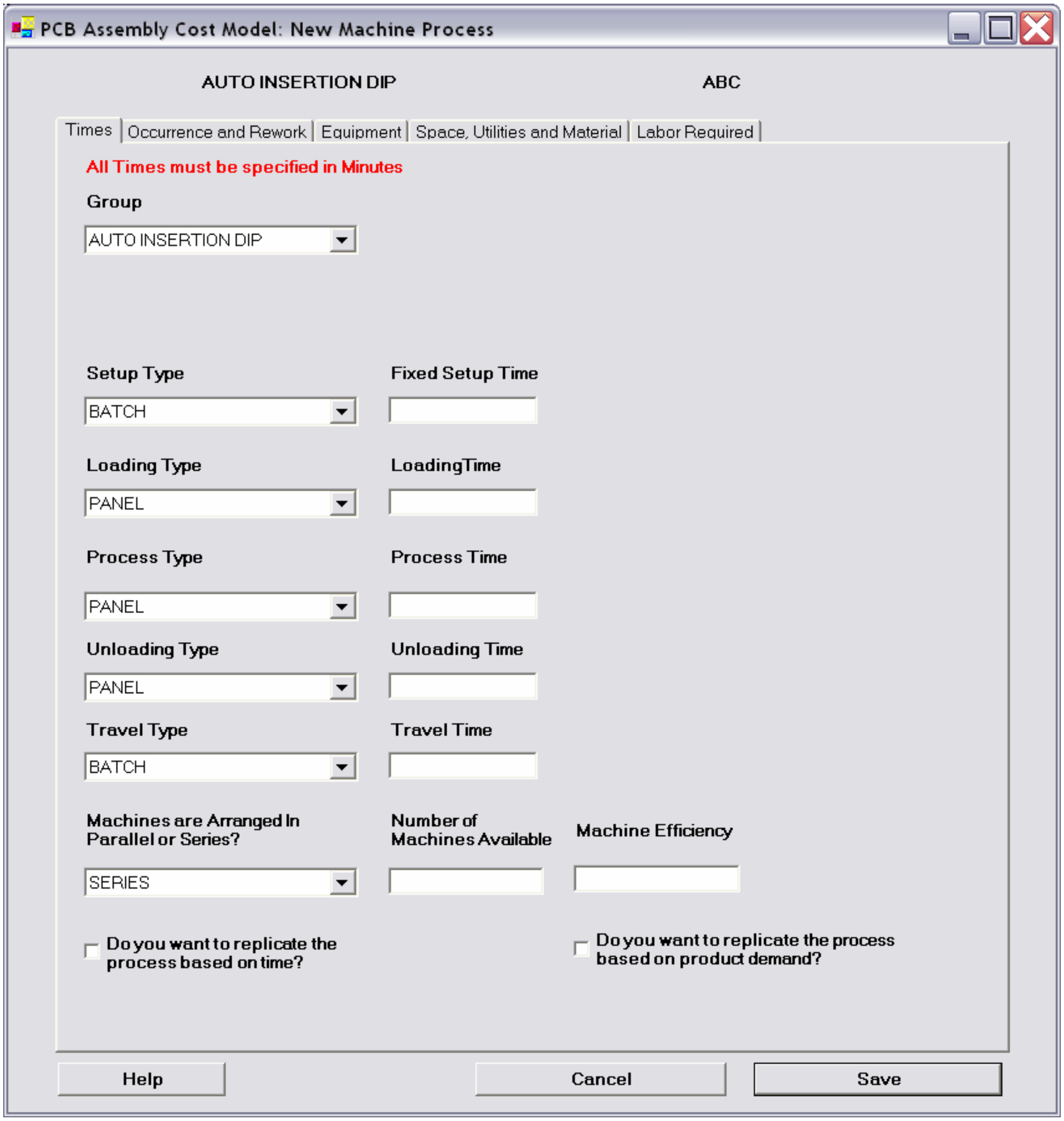
Once you have created your new facility and you how to add general processes to the application, let's add a process to your new facility. The section of this document will show you how to register a process to your facility. Choose "Edit the Processes of a Facility and Calculate Products Cost" from the main menu options and select the facility "ABC" and click "Access" and it will take you to the form "Edit Facility and its Processes" and go to File/New/Process(es) and the following form shown below will be presented to you.



As you can see, the PCB Cost Model application has several processes already defined. These processes are the most common used in the electronic industry and its more general characteristics has been previously defined.

Our Task: Register a machine process to a facility

Let’s register a new process to the facility ABC. From the previous form, choose the process AUTO INSERTION DIP and click the button “Add Process to Facility”. When you click the button the following form appears:



This form has five tabs. In the first tab you must specify the following parameters:

Times Tab (All times must be specified in minutes)

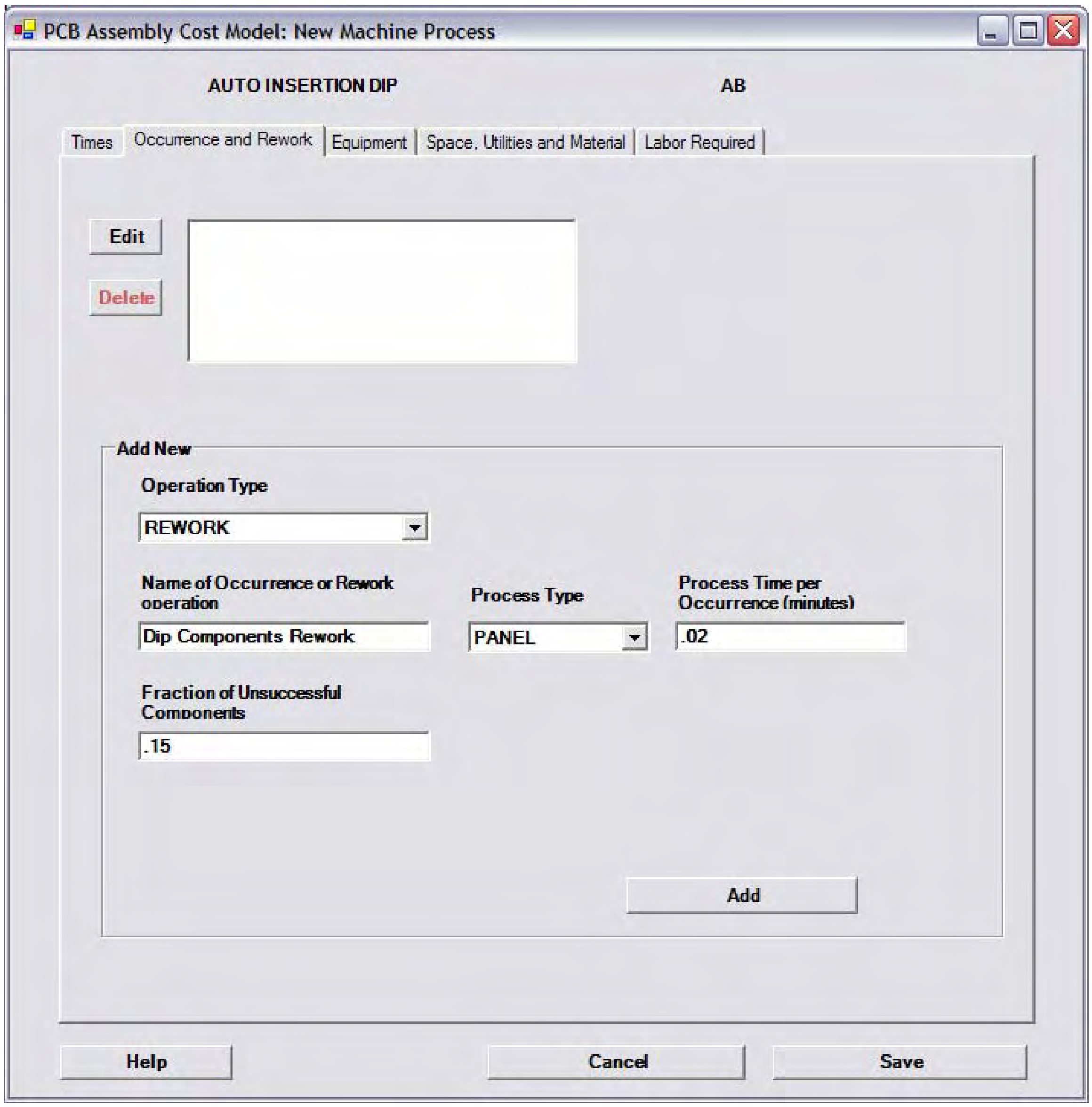
Prompt	Valid Entry	Example
Group – Method to retrieve the processes that are required when a component type is required. A typical example found in the electronics industry is the placement	Any Group registered in the application	AUTO INSERTION DIP

Prompt	Valid Entry	Example
of Surface Mount Technology (SMT) components in an image. This group typically includes a Placement Machine, Solder Paste Printer and a Reflow Oven. In this case, the application will retrieve the Placement process when a product has SMT components but it will not retrieve the Reflow Oven process because no components are assembled on the Reflow Oven or on the Solder Paste Printer. The group method allows the retrieval or inclusion of the processes Reflow Oven and Solder Paste Printer where no components are assembled but is needed when SMT components are assembled on a placement machine.		
Component Type- It is a method to specify the type of components that are inserted or placed in a process. Note: This option is visible only if Setup Type = BATCH(DESIGN) or Process Type= DESIGN	Any Component Type registered in the application	DIP
Setup Type – It refers to the type of setup that is made in this process.	*BATCH, PANEL, IMAGE, PANEL(# PANELS PROCESSED) IMAGE(# IMAGES PROCESSED) BATCH(DESIGN)* NOTAPPLY	BATCH(DESIGN)
Fixed Setup Time- the amount of fixed time spent preparing the machine or manual operation to process an image, panel, batch, etc.	Double	10
Variable Setup Time- it refers to the time is spent locating the rolls of the part numbers required. Note: This option is visible only if Setup Type = BATCH(DESIGN)		.0333
Loading Type- It refers to the type of loading that is made in this process.	*PANEL, IMAGE PANEL(# PANELS PROCESSED) IMAGE(# IMAGES PROCESSED)* NOTAPPLY	PANEL
Loading Time- time spent locating a panel, image, etc. in the machine	Double	.0333

Prompt	Valid Entry	Example
of manual operation where it will be processed.		
Process Type – It refers to the type of process time that is applied in this process.	*BATCH, PANEL, IMAGE, PANEL(# PANELS PROCESSED) IMAGE(# IMAGES PROCESSED) DESIGN* NOTAPPLY	DESIGN
Process Time- time spent processing the machine or manual operation to process an image, panel, batch, etc.	Double	.05
Unloading Type- It refers to the type of unloading that is made in this process.	PANEL, IMAGE PANEL(# PANELS PROCESSED) IMAGE(# IMAGES PROCESSED) NOTAPPLY	PANEL
Unloading Time- time spent removing a panel, image, etc. from the machine of manual operation where was processed.	Double	.0333
Travel Type- It refers to the type of travel that is used or made to move a panel, image, etc to the next process. Note: If CONVEYOR option is chosen you must specify Conveyor Length, Conveyor Speed, and Separations Distance Between Panels.	*BATCH, PANEL, IMAGE, PANEL (# PANELS PROCESSED) IMAGE (# IMAGES PROCESSED) CONVEYOR*, NOTAPPLY.	BATCH
Travel Time- time spent transporting a panel, image, etc. in the machine of manual operation where it was processed to the next process.	Double	1
Machines are Arranged in Series or Parallel? - Is a method to specify if the identical machines of your facility are arranged in parallel or in series. It only applies when the number of machines is greater than 1.	SERIES,PARALLEL	PARALLEL
Number of Machines Available- It refers to the number of identical machines that you have in your facility and that are either in series or parallel. Note: In the Default Facility, this option is	Integer	2

Prompt	Valid Entry	Example
not available because the number of machines required is calculated.		
Machine Efficiency (0-1). It refers to the capacity of the machine to process panels, images, etc.	Double number greater than 0 and less than 1	1
Do you want to Replicate the Process as needed? Note: If this option is checked, the textbox provided to specify the number of machines or operators available is disabled. This option allows you to let the application determine the number of required machines or manual operators that are needed to manufacture a specific product based on its annual demand.	Checked=Yes Unchecked=NO	Unchecked
Do you want to Replicate the Process based on time? Note: If this option is checked, the textbox provided to specify the number of machines or operators available is disabled. This option allows you to let the application determine the number of required machines or manual operators that are needed to manufacture a specific product based on it's the number of required images per hour in the process. You must provide the number of required images per minute in this process.	Checked=Yes Unchecked=NO	Unchecked

Once the necessary prompts and valid entries in the first tab are specified proceed to the second tab. The second tab is shown below. In this tab you specify all the Rework or Occurrence operations of the process. This tab is optional because it will depend on each process requirements. As an example of the electronics industry, a Solder Paste Printer machine, which is used to locate solder flux in an image or panel, needs to be cleaned after a specified number of panels have been processed. This type of operation is considered an Occurrence operation because its frequency is not on each image or panel processed. Its time is attributed to each image depending on the number of panels processed before an occurrence operation takes place. Another example is when a component needs to be reworked prior to be inserted in the panel or image been processed.



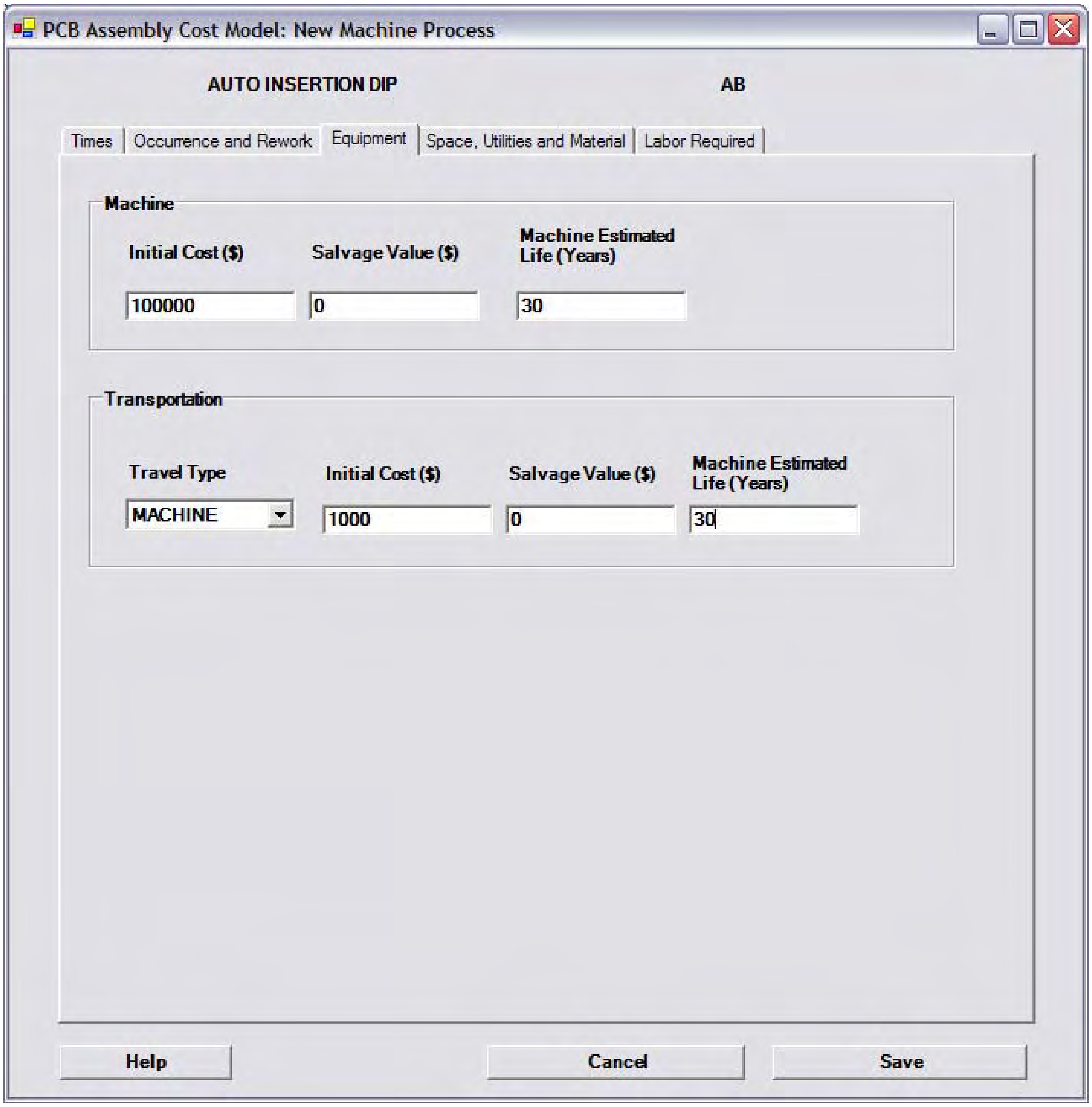
We will add a rework operation to the process AUTO INSERTION DIP and its required parameters are shown below

Occurrence and Rework Operations Tab

Prompt	Valid Entry	Example
Operation Type- method to choose	*OCCURRENCE*	REWORK

Prompt	Valid Entry	Example
between occurrences or rework operations. An occurrence operation is defined as an operation that will be done after a specified number of panels or images are processed. A rework operation consists in the rework of a panel, image, etc. that will be reworked again due to failure.	*OPERATION* *REWORK*	
Name of Occurrence or Rework- it refers to the name of the rework or occurrence operation	String	DIP Components Rework
Process Type- It refers to the type of rework or occurrence operation Note: DESIGN option is only visible if Process Type = "DESIGN" or Setup Type is "BATCH(DESIGN)"	PANEL,IMAGE,DESIGN	DESIGN
Process Time per Occurrence- it refers to the time spent making an occurrence or rework operation		.02
Fraction of Unsuccessful Components- It refers to the faulty rate of panels, images, etc. Note: It only applies when Operation Type is rework	Double number greater than 0 and less than 1	.15
Number of (Panels/Images) per Occurrence- It refers to the number of panels that must be processed prior to an occurrence operation. Note: this option is visible only is Operation Type is OCCURRENCE	Integer	
Component Type- it refers to the type of components that are affected by the rework operation. Note: this option is visible only is Operation Type is OCCURRENCE and Process Type= DESIGN	Choose from existing Component Types	DIP

Once the necessary prompts and valid entries in the second tab are specified proceed to the third tab. In this tab you will specify the costs of the machine used in this process and specify the type of equipment of resources you are using to transport the images to the next station or process.



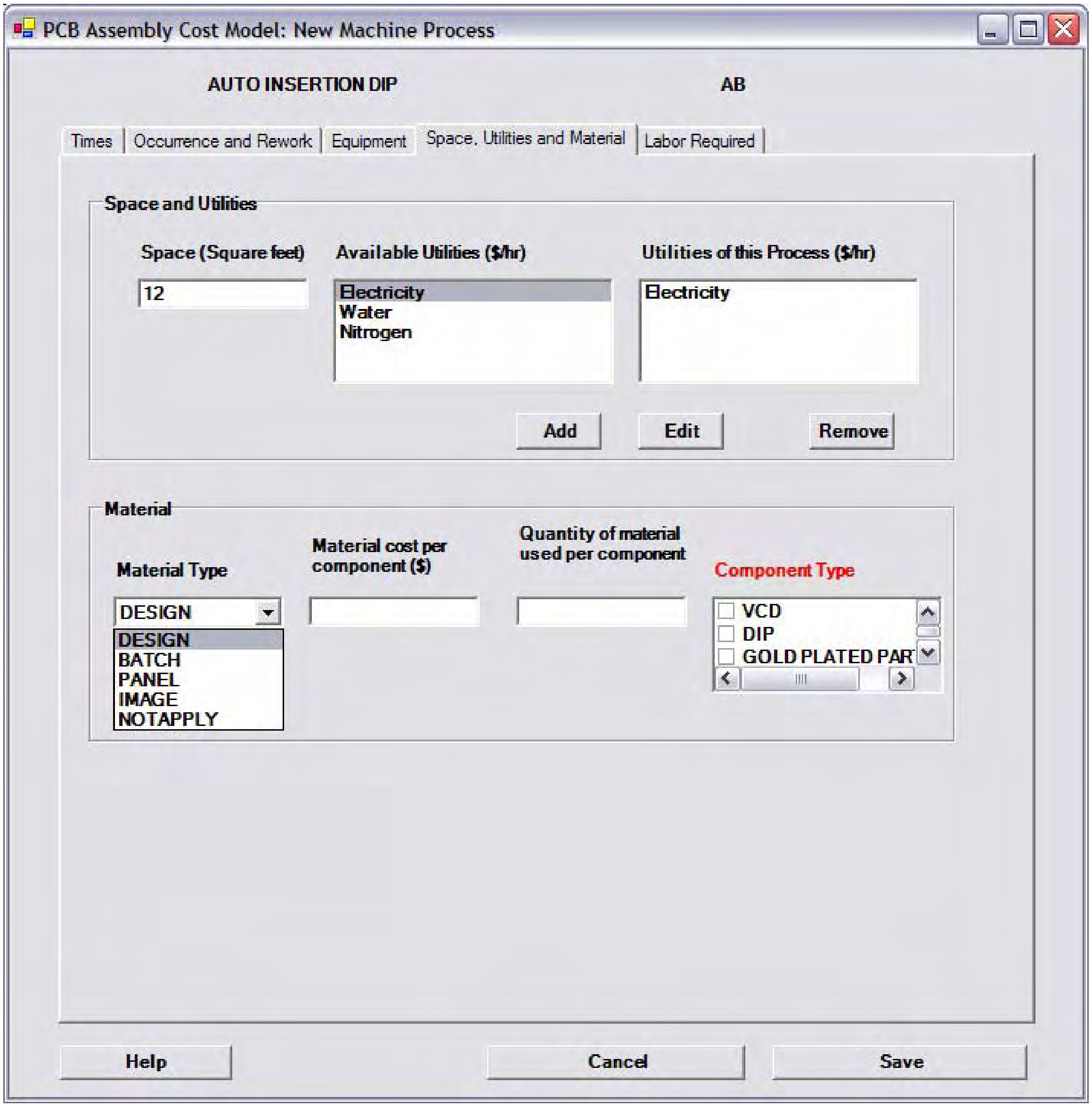
The prompts and valid entries for the AUTO INSERTION DIP process are shown below

Equipment Tab

Prompt	Valid Entry	Example
Machine Equipment		
Initial Cost ($)- is the initial cost of the machine	Double	100000
Salvage Value ($)- is the salvage value of the machine	Double	0

Prompt	Valid Entry	Example
Machine Estimated Life (years)- is the machine estimated life or years of usage	Double	30
Machine Efficiency (0-1). It refers to the capacity of the machine to process panels, images, etc.	A number greater than 0 and less than 1	.95
Transportation Equipment		
Travel Type- it refers to the use of persons of machines to transport panels, images, etc to another process.	MACHINE, MANUAL	MACHINE
Initial Cost ($)- is the initial cost of the machine	Double	1000
Salvage Value ($)- is the salvage value of the machine	Double	0
Machine Estimated Life (years)- is the machine estimated life or years of usage	Double	30

Once the necessary prompts and valid entries in the third tab are specified proceed to the fourth tab. In this tab you will specify the space in feet it occupies this process and the utilities used by this process. The material used in this process if any will also be specified.



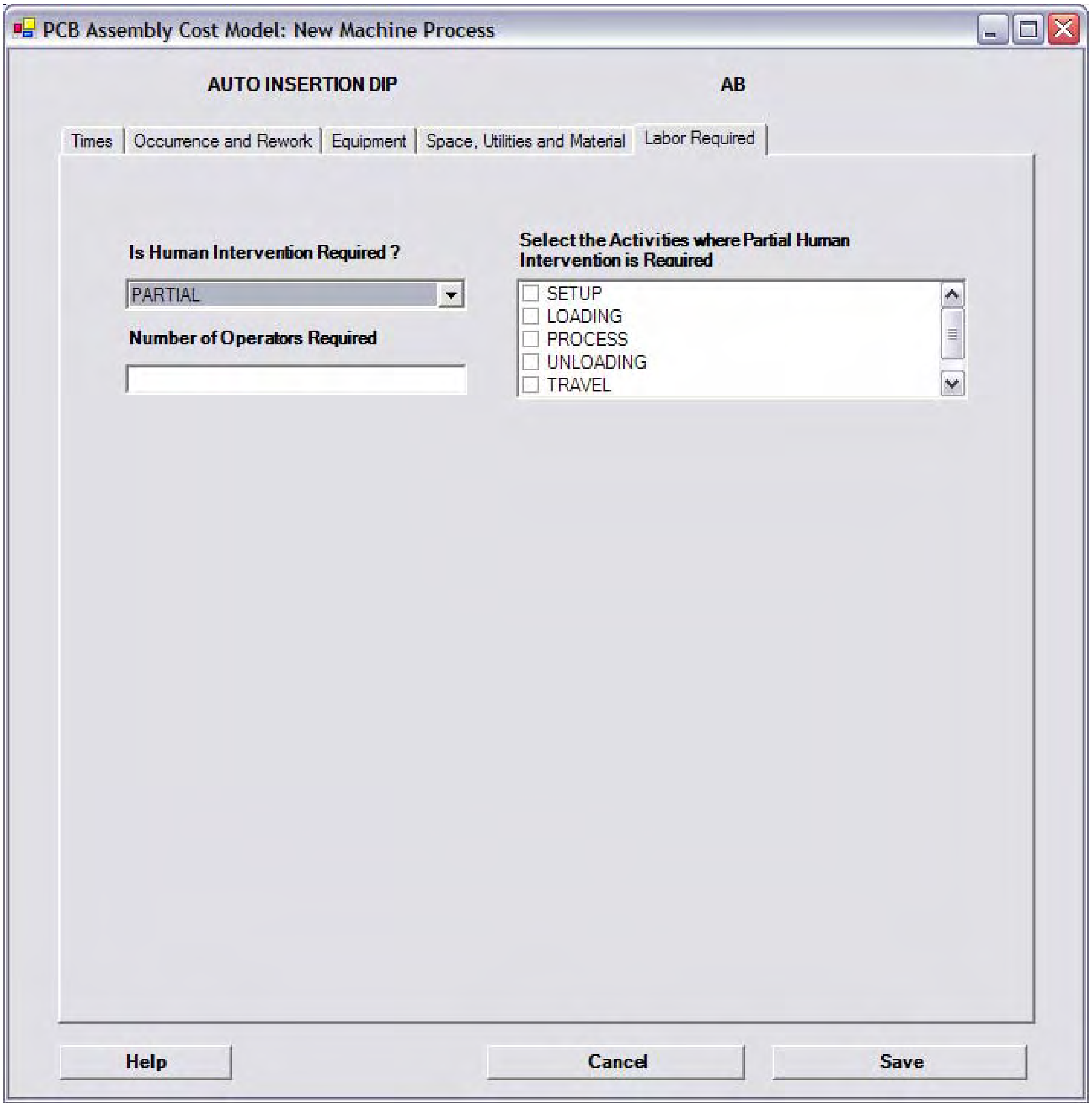
The prompts and valid entries for the AUTO INSERTION DIP process are shown below

Space, Utilities and Material Tab

Prompt	Valid Entry	Example
Space (ft^2)-It refers to the space in square feet that is occupied by a machine or manual operation.	Double	12
Material Type- It refers to the type of material that is used in this process. DESIGN- is when the quantity of material used depend on the components	DESIGN BATCH PANEL IMAGE	NOTAPPLY

Prompt	Valid Entry	Example
processed in this process.	NOTAPPLY	
Material Cost ($) - it is the cost of material used in this process. Note: When Material Type is NOTAPPLY, this textbox is not available		
Quantity of Material Used- It refers to the quantity of material used in this process. Note: You must be careful when specifying this quantity because it must have the same units of the material cost. Note: When Material Type is NOTAPPLY, this textbox is not available	Number	
Component Type- it refers to the type of components that are affected by the rework operation. Note: this option is visible only is Material Type is DESIGN	Choose from existing Component Types	

Once the necessary prompts and valid entries in the fourth tab are specified proceed to the fourth tab. In this tab you will specify the type of labor you will be using and specify if any human intervention is required in the process.



Direct Labor Tab

Prompt	Valid Entry	Example
Human Intervention is Required?-It refers to the type of human labor that is required on the machines. YES = it means that an operator is required in all the operations. NO= it means that no operator is required in this operation PARTIAL = it refers to the requirement of an operator mon a specified operation of the	*YES, NO, PARTIAL INDIRECT,PARTIAL AND INDIRECT*	YES

Prompt	Valid Entry	Example
process. • Example: Operator is required only to setup the machine. INDIRECT- is a method to distribute persons that are required on several processes of a same group. • Example: On a Surface Mount Technology (SMT), two operators are required to setup, supply the components required to the machines and maintain the processes of that group or manufacturing line running. PARTIAL AND INDIRECT – it refers to the last two options combined. • Example. You could have a group or manufacturing line that requires operators to maintain machines up and running and have special or other operators to setup the machines.		
Select the Activities where Partial Human Intervention is Required Note: This option is visible only is Human Intervention is Required?= "PARTIAL" or when Human Intervention is Required?= PARTIAL AND INDIRECT	SETUP LOADING PROCESS UNLOADING TRAVEL OCCURRENCE	
Number of operators required in this operation	Integer Number	

Once you know how to register processes to your facility, the two variations of Process Type are Conveyor processes and Manual processes. The only difference between a Conveyor process and the Machine process previously registered is that the process time in the Conveyor process is based on the length and speed of the conveyor and the separation distance between panels in the conveyor. The difference between a machine process and a manual process is that the tab for the Direct Labor is not included because it is assumed that direct labor is required due to the fact that it is a manual operation.

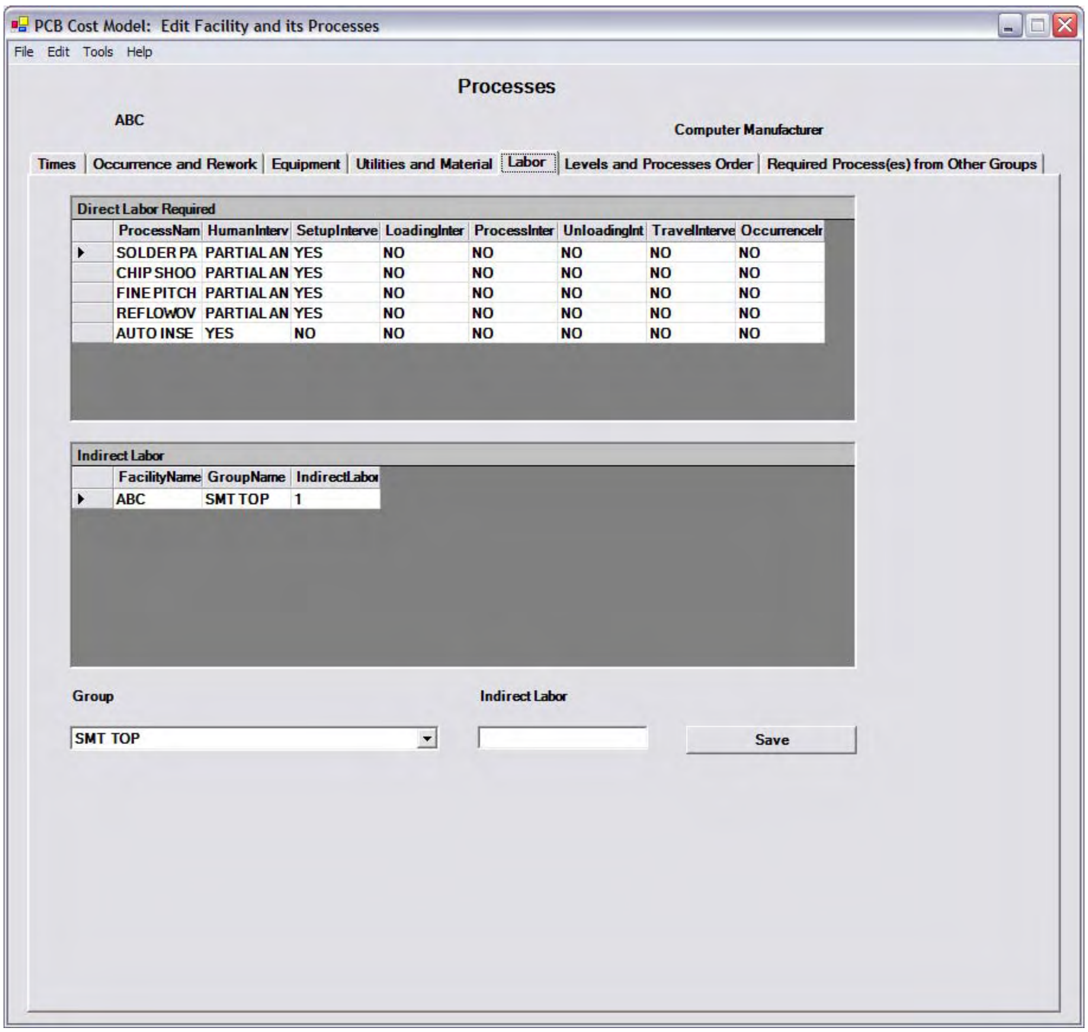
Assuming that you have registered all the needed processes in your facility and have provided all the needed information of the processes, there are three more sections that would help you to finish the integration of your facility to make cost calculations. The first of them is related to the number of operators that are required on a particular group of processes. This type of labor is what was called in the previous section Indirect Labor. Indirect Labor refers to the number of operators that are required on a group of processes but that are not dedicated to a particular process. An example of this is found on operators in a Surface Mount Technology line that need to setup and maintain running the placement and solder paste printer machines.

Our Task: Indirect Labor

To explain this part, you must register the following processes:

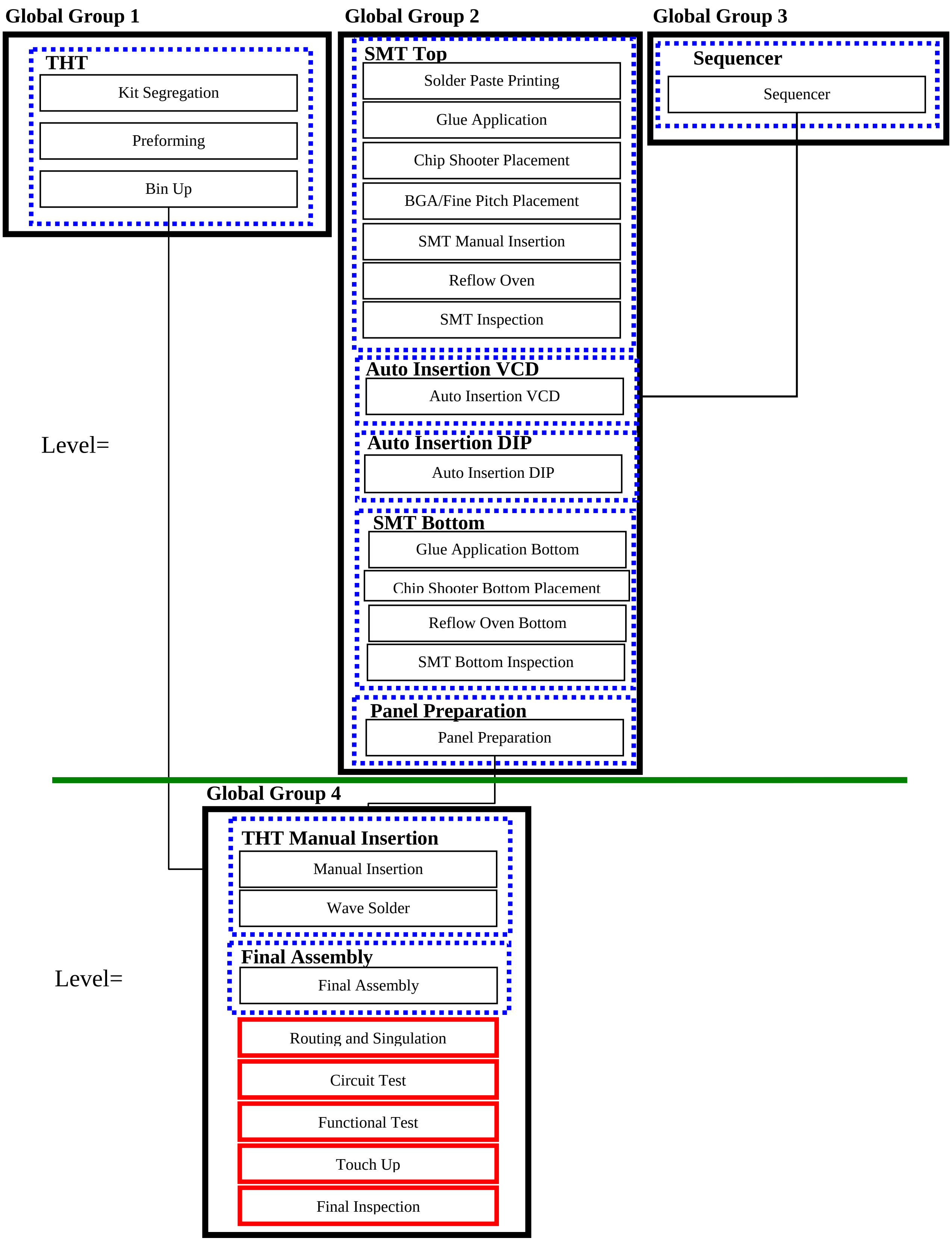
1) Solder Paste Printing
2) Chip Shooter Placement
3) BGA/Fine Pitch Placement
4) Reflow Oven

Because at this point you would need to repeat all the process of registering a process to the facility four times, we have a facility called ABC that has these four processes with its details to ease the explanation of this section. This group of processes belongs to the group called SMT TOP, and in the Labor tab of the process registration form, Indirect Labor was the method chosen to characterize these processes. What you have to do is to specify the number of operators required as indirect labor in these processes is the following: Go to the form "Edit Facility and its processes" choosing the facility ABC as the facility to be edited and go to the Labor tab as shown below. Proceed to the lower part of the tab and choose the group SMT TOP and provide a 1 in the Indirect Labor textbox indicating that 1 person is required to setup and maintain this group of processes running and up.



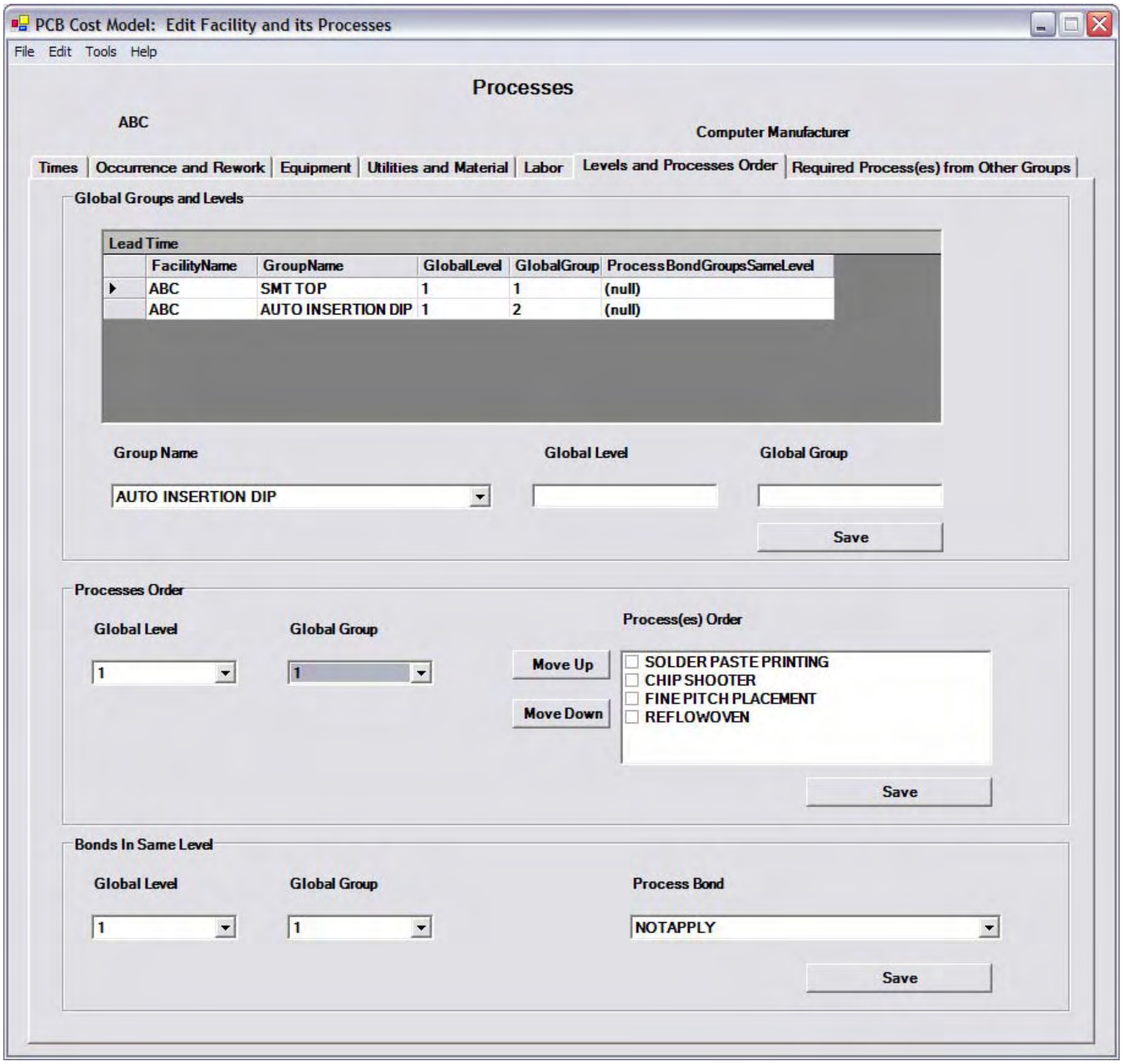
Our Task: Levels, Global Groups and order of your processes

This section will explain you why you need to create levels, global groups and the need to order the processes of your facility. The explanation refers to the figure shown below.


Global Group 1
THT
Kit Segregation
Preforming
Bin Up
Global Group 2
SMT Top
Solder Paste Printing
Glue Application
Chip Shooter Placement
BGA/Fine Pitch Placement
SMT Manual Insertion
Reflow Oven
SMT Inspection
Auto Insertion VCD
Auto Insertion VCD
Auto Insertion DIP
Auto Insertion DIP
SMT Bottom
Glue Application Bottom
Chip Shooter Bottom Placement
Reflow Oven Bottom
SMT Bottom Inspection
Panel Preparation
Panel Preparation
Global Group 3
Sequencer
Sequencer
Level=
Global Group 4
THT Manual Insertion
Manual Insertion
Wave Solder
Final Assembly
Final Assembly
Routing and Singulation
Circuit Test
Functional Test
Touch Up
Final Inspection
Level=

Imagine that the layout of your facility is the one shown below which is the one used by default in the PCB Cost Model. In this layout the processes follow a logical order. In order to manufacture a PCB who uses all the processes in the layout you must order your processes like this. But this order has three characteristics that helps you to define this layout.

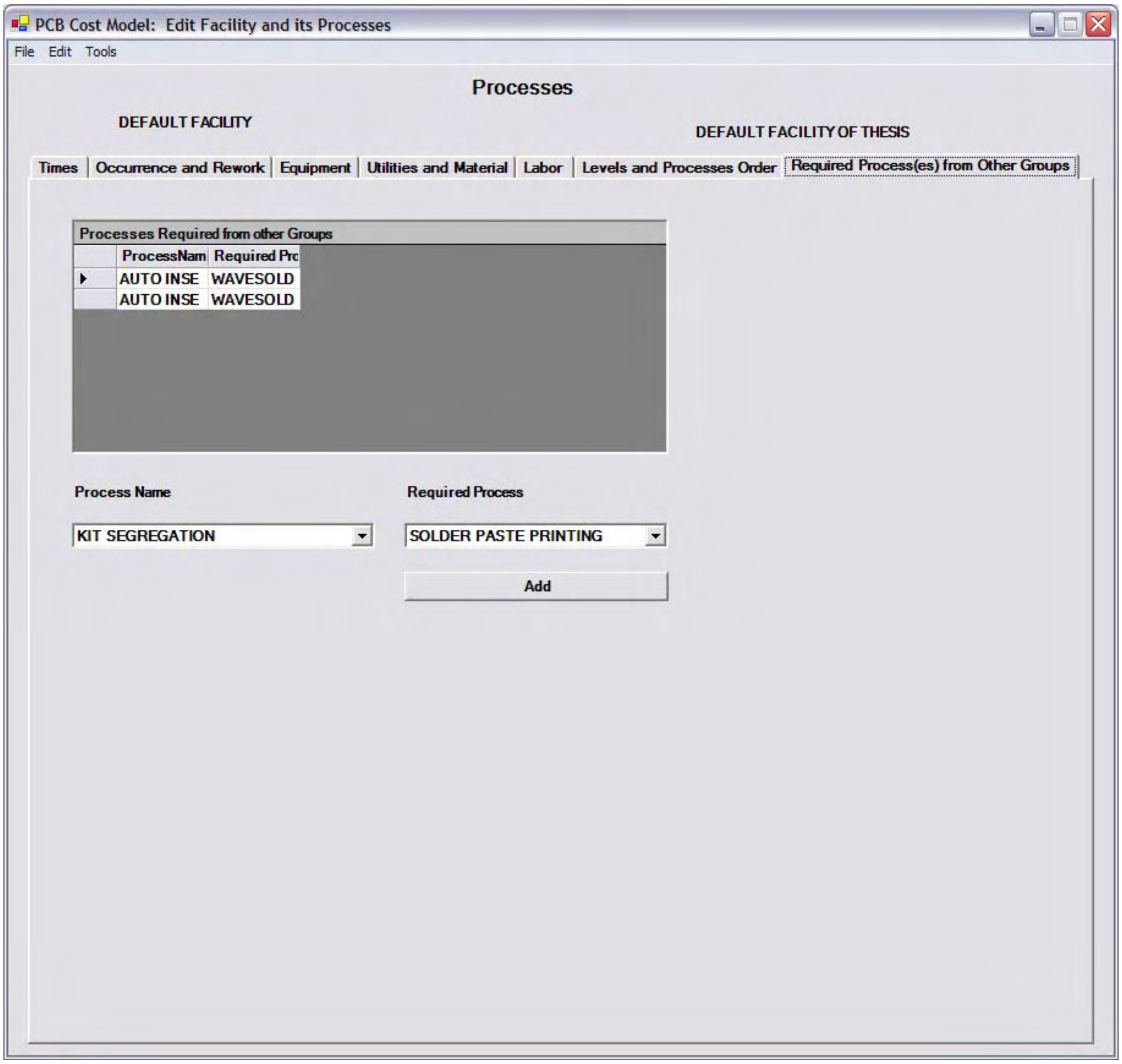
1) The green line represents the levels of your facility. In this case there are two levels. Levels are used to join all the processes or groups that can be manufactured in parallel and that the maximum time of the processes or groups in that level is the time to be considered to calculate lead times.
2) The black boxes represent the global groups of the facility. The global groups is a method to relate groups of processes in a same level
3) The blue boxes represent the groups of the facility. These groups are the ones specified in each processes registration form.


PCB Cost Model: Edit Facility and its Processes
File Edit Tools Help
Processes
ABC
Computer Manufacturer
Times
Occurrence and Rework
Equipment
Utilities and Material
Labor
Levels and Processes Order
Required Process(es) from Other Groups
Global Groups and Levels
Lead Time
FacilityName GroupName GlobalLevel GlobalGroup ProcessBondGroupsSameLevel
ABC SMT TOP 1 1 (null)
ABC AUTO INSERTION DIP 1 2 (null)
Group Name
Global Level
Global Group
AUTO INSERTION DIP
Save
Processes Order
Global Level
Global Group
Process(es) Order
1
1
Move Up
Move Down
SOLDER PASTE PRINTING
CHIP SHOOTER
FINE PITCH PLACEMENT
REFLOWOVEN
Save
Bonds In Same Level
Global Level
Global Group
Process Bond
1
1
NOTAPPLY
Save

Our Task: Required processes from other Groups

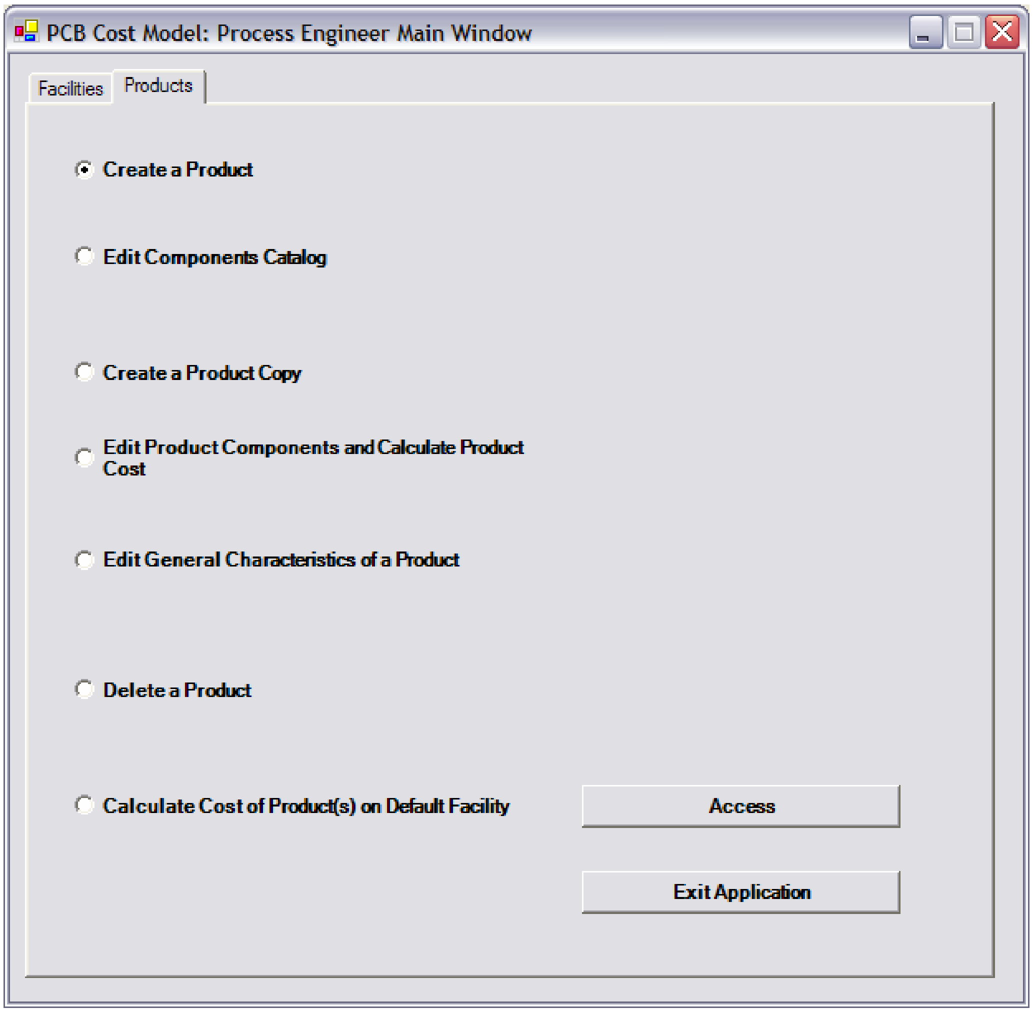
Let's explain you the last process to need to make to complete the requirements of a facility to make cost calculations in the PCB Cost Model. This step is optional but you need to make sure you don't need it. Let's start by looking a particular situation so that we can make you understand the point. In the default facility of the PCB Cost Model, the process Wave Solder is used if there are components to be placed in the following processes: Manual Insertion of THT, Auto Insertion DIP and Auto Insertion VCD. But as you can see in the previous figure, the processes Auto Insertion DIP and Auto Insertion VCD belongs to a different group. The way that the PCB Cost Model is programmed only retrieve those processes that belongs to a particular group but that do not place components. Let's imagine now that you have a product that has components to be placed on a Auto Insertion Dip machine or in an Auto Insertion VCD machine but no Manual Insertion of THT components is required. If you run the application at this point, the calculations will be made but the Wave Solder process will not be included in the calculations because the process that locates components in the group is not required. To alleviate that problem and provide the inclusion of the Wave Solder process in the calculations you must relate the process in the "Required processes from other groups" section. In this section you relate a process where components are placed with processes from another group in case these processes are not included in the calculations because its primary process or the process (es) where components are placed in this group are not needed.

To illustrate the use of this section go to the tab Required Processes from Other groups in the form “Edit Facility and its processes” and choose the process that you want to relate to another from other group.

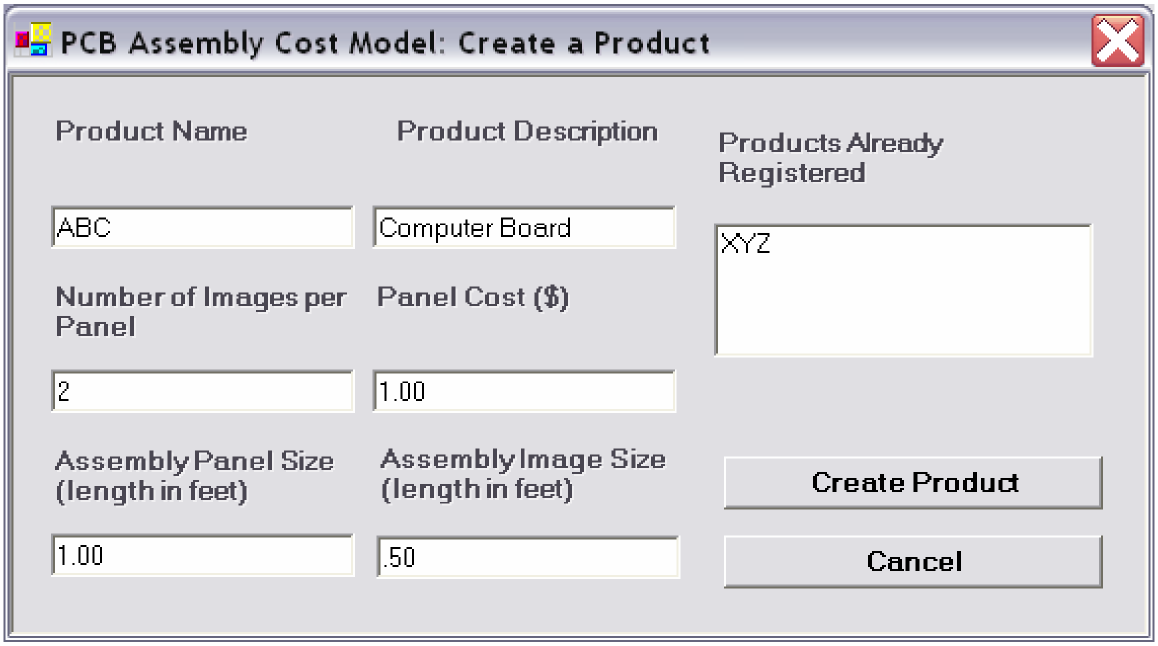


Our Task: Estimate the cost of a new design

In this section we will present you how to create a new product design and estimate the cost of your product. To begin with the creation process, you must log in the PCB Cost Model Application and be registered as a Process Engineer user. Once you have made the log in, the form called Process Engineer Main Window is shown.



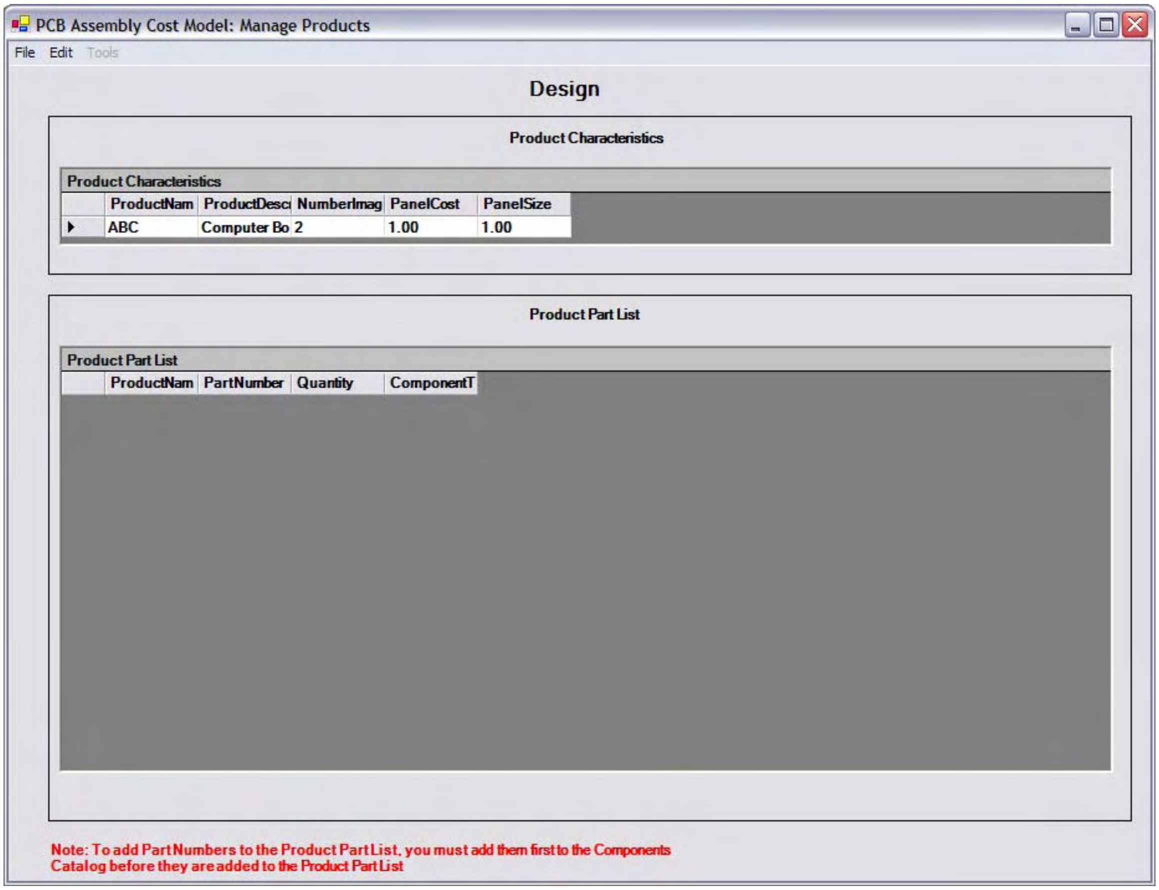
To create a new product, we will choose the option "Create a Product" and click the button "Access". Once you click the "Access" button, the "Product Creation" form is presented as shown below.



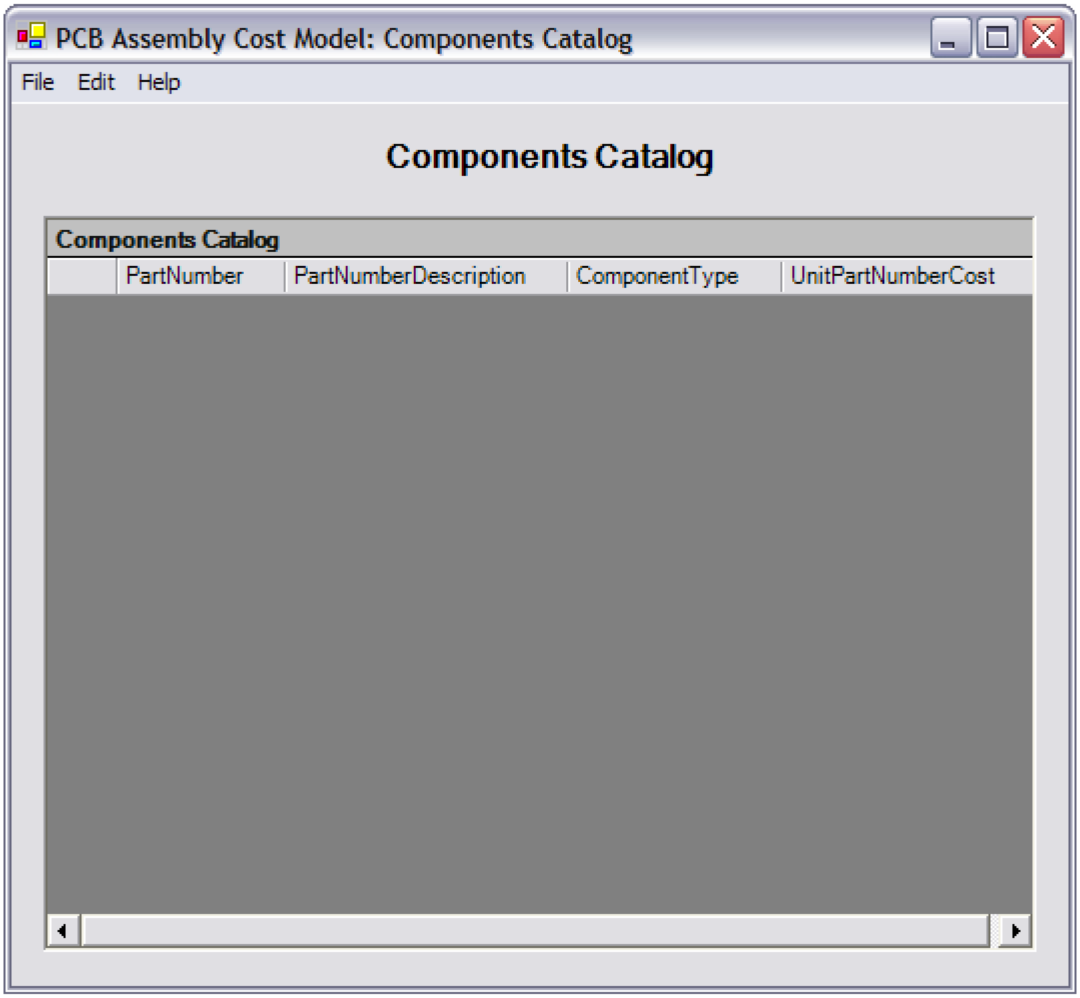
The necessary prompts and valid entries to create a product are on the following table:

Prompt	Valid Entry	Example
Product Name	String	ABC
Product Description	String	Computer Board
Number of Images per Panel	Number (integer)	2
Panel Cost ($)	Number (double)	1.00
Assembly Panel Size (length in feet)	Number (double)	1.00
Assembly Image Size (length in feet)	Number (double)	1.00

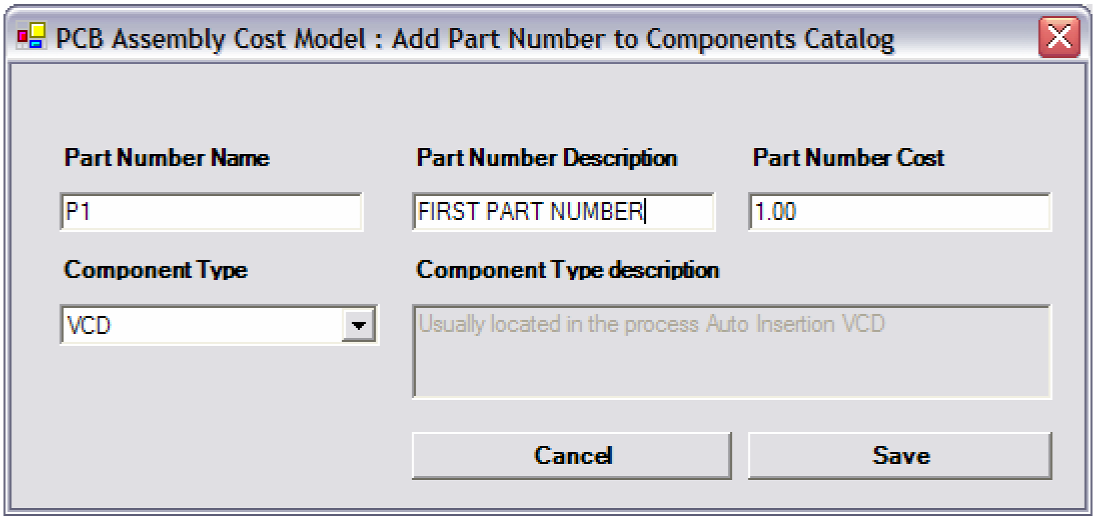
Once all the necessary information for the creation of a product is made, click the “Create Product” button. When you click this button a message box appears that says “Product was created”. Following this message box appears another message box that asks you the following: **Do you want to add part numbers to your new product? If you click No, you will returned to the main window.** If you click no you will be returned to the main window. If you click yes, as we will do now, you will be referred to the form “Manage Products” which is shown below. In this form you can practically perform almost all the things required to obtain the cost of your new design. This form contains the general characteristics of a product and the part numbers registered.



At this point, no part number has been added to our product ABC. We will now proceed to add some part numbers to the product ABC. Because at this point it is assumed that you are using the PCB Cost Model for the first time, we will guide you to register part numbers to the catalog of the application prior to add them to a product design. The reason to have a components catalog is because you would need to register a part number only one time and they reuse it in other product designs. To access the components catalog from the “Manage Products” form, go to Edit/Components Catalog and the figure shown below will appear.



To add a new part number to the “Components Catalog” form, go to File/New/Part Number and the form shown below appears:

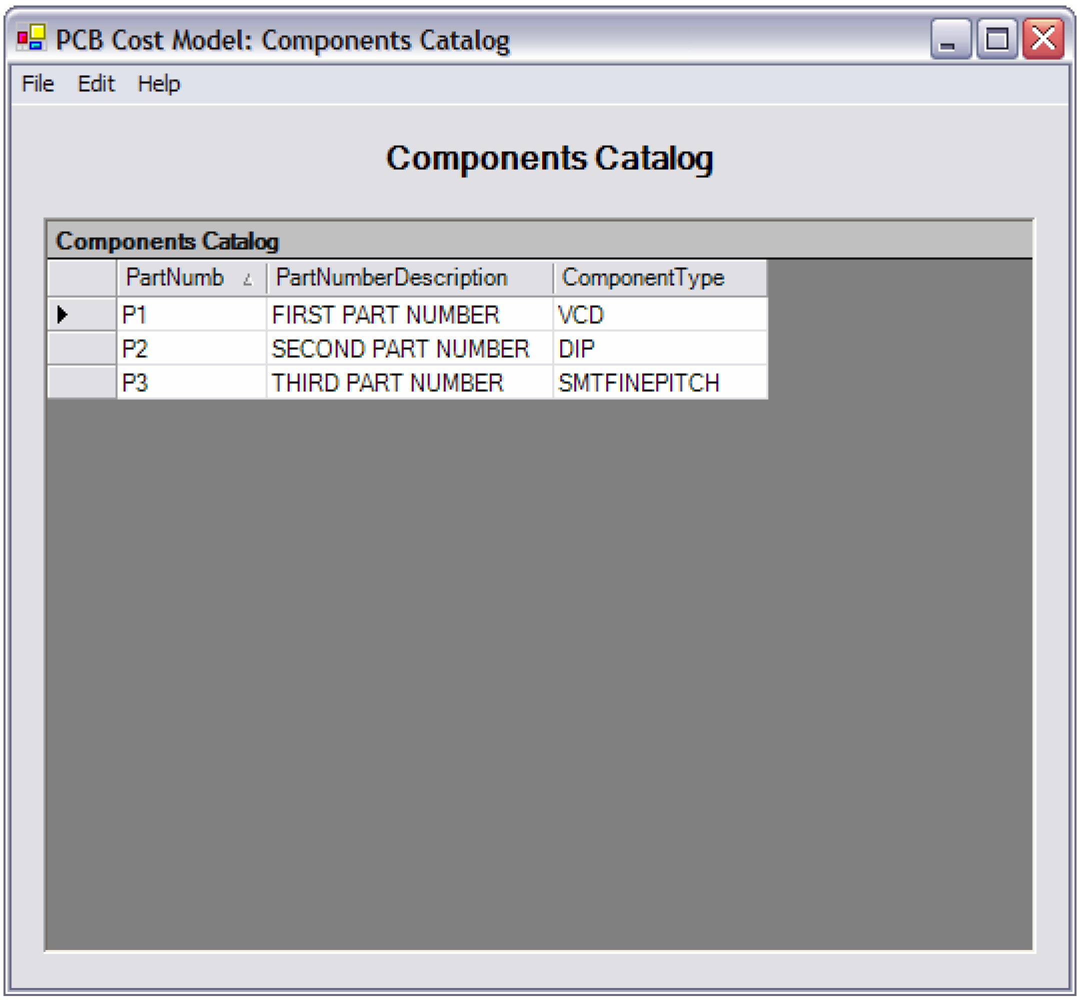


The necessary prompts and valid entries to register a part number to the application are on the following table:

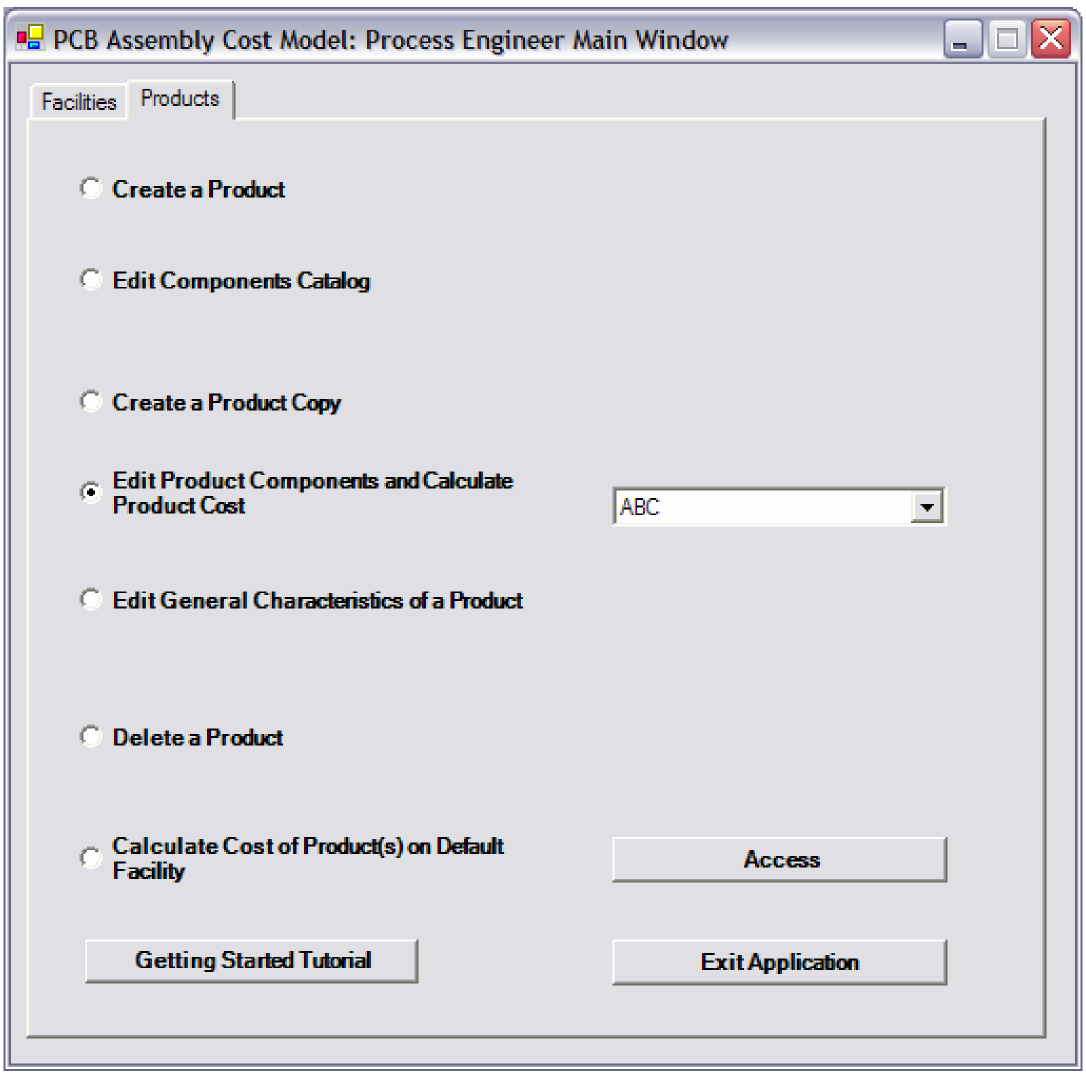
Prompt	**Valid Entry**	**Example**
Part Number Name	String	P1
Part Number Description	String	Radial Component
Component Type	Choose from existing options	VCD
Component Type Description	String	Usually assembled in the process Auto Insertion VCD

Note: The "Component Type" field is a method to relate the part numbers being added in the Components Catalog with the machine or manual operation that place or insert part numbers in a product. The PCB Cost Model application already has few component types added by default. The "Component Types" added to the application were those most used in the industry. An example of this is the Component Type called VCD. This component belongs to the class of Through Hole Technology (THT) components which are inserted through an image and then soldered on a wave solder machine. The peculiarity of this "Component Type" is that it belongs to the type of components that are inserted through a PCB on an Auto Insertion VCD machine. There are different types of THT components and the most common used in the industry are registered on the application.

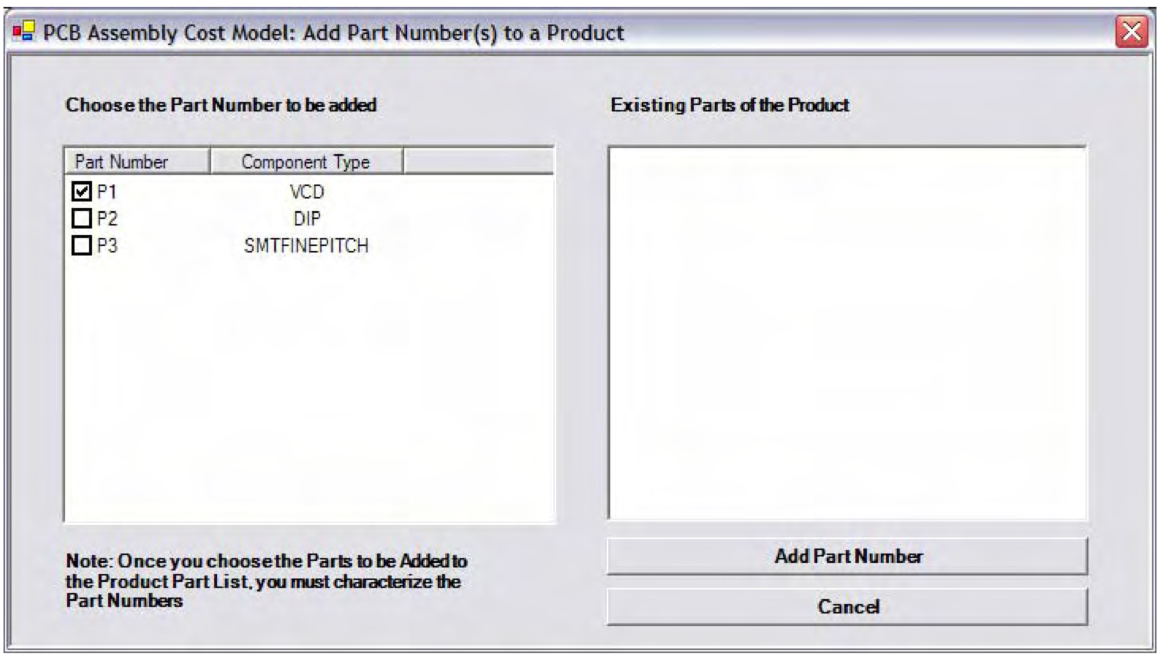
Once you have made the registration process of your processes, the "Components Catalog" form should look like this:



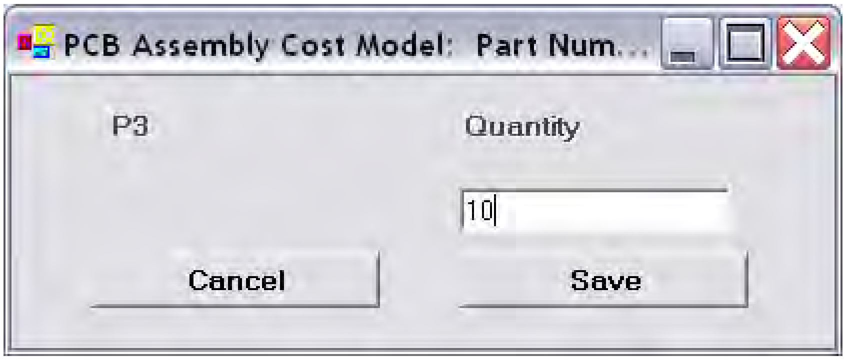
At this point, we have added three components to the catalog. The first component is a VCD component which was presented previously. The second component is a THT component that is placed on an Auto Insertion DIP machine. The third component is a Surface Mount Technology component. Surface Mount Technology (SMT) refers to the placement of components in a PCB and the soldering of the components onto the PCB with a Reflow Oven machine. Unlike THT, SMT components are only placed on the board and not passed through the board. These two technologies are the two leading strategies to manufacture PCB's nowadays. Once the registration of our new part numbers have been made, we will proceed to add these part numbers to our product assuming these are the only part numbers required for our design. This is only for illustration on how to use the application because it is well known that a typical PCB uses many components. To add part numbers to the product, go to File/Return to Main Window and the following form appears:



As you can notice, the previous form is the Designer Main Window form presented to you earlier but with more options now. The reason why these options are now available is because when you started to use the application there were no products registered or created in the application. To proceed with the product we were creating, choose the option called “Edit Product Components and Calculate Product Cost” and choose the product ABC on the combo box provided and click “Access”. When you do that, the form “Manage Products” appear. Then go to File/New/Part Numbers from the Components Catalog and the following form appears:



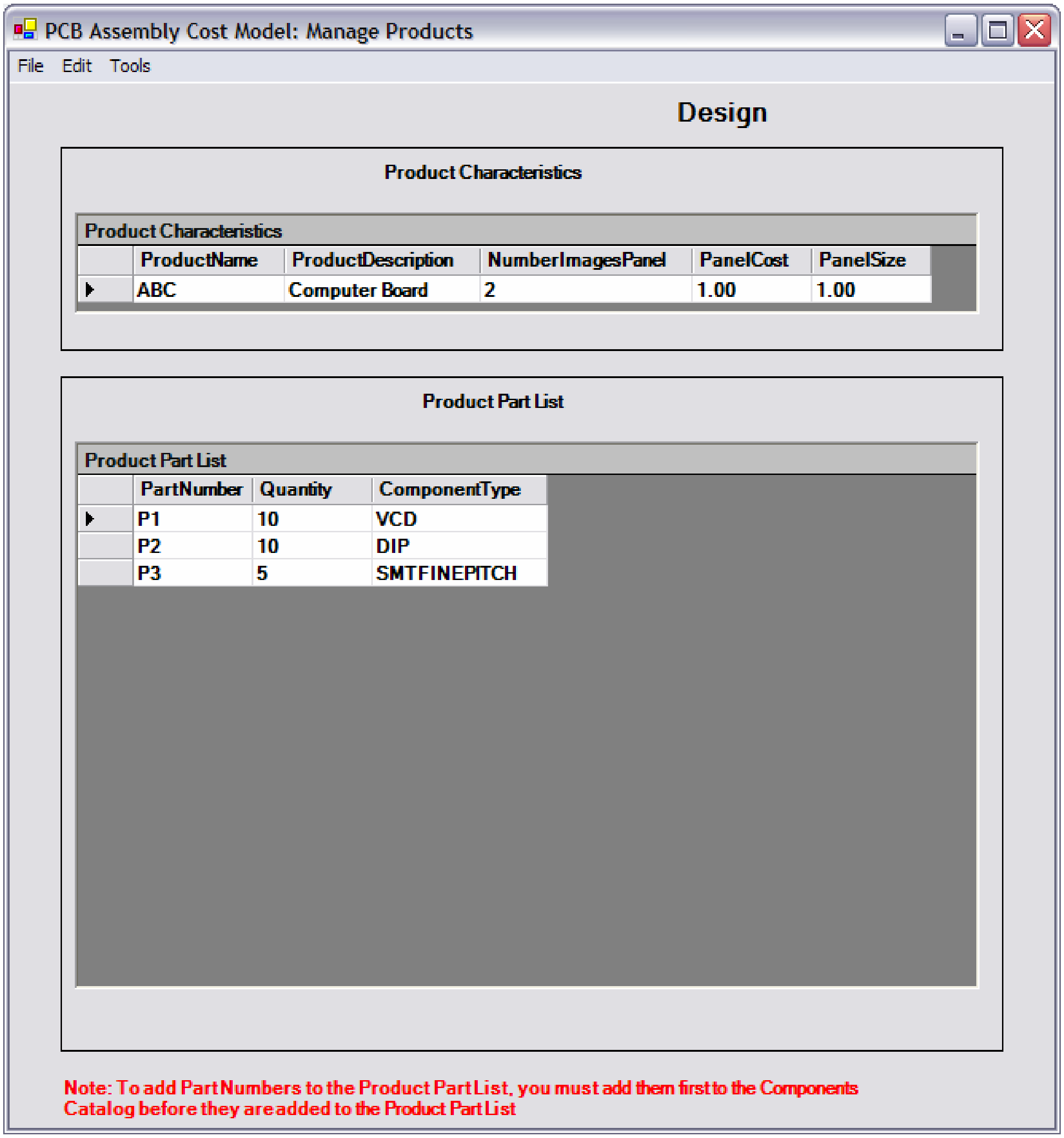
To add a part number to the ABC product simply check the part number that you want to add to ABC and click “Add Part Number”. When you do this, the following form appears requesting the quantity needed of that part number and the Unit Cost of the part number to be added.



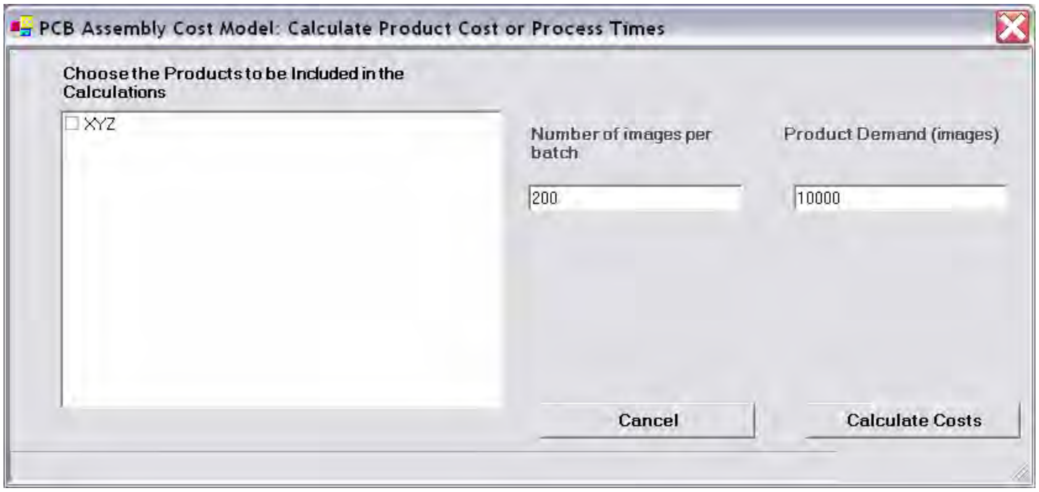
The necessary prompts and valid entries to register a part number to a product are on the following table:

Prompt	Valid Entry	Example
Quantity	Number (Integer)	10

Once you add the required part numbers to the product, the "Manage Products" form should look like the one below.



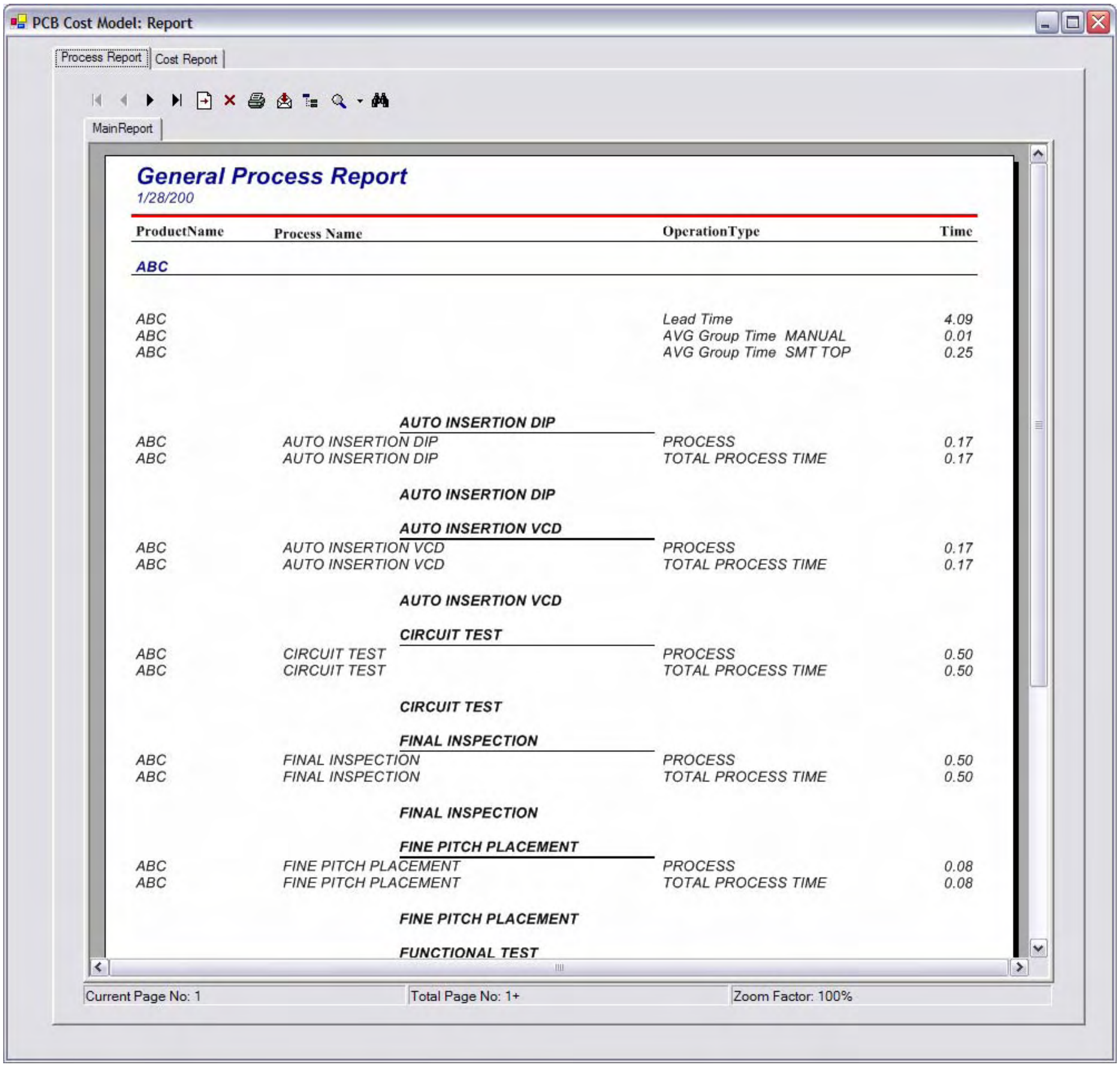
Once all the part numbers has been added to the product you are designing, you are ready to estimate the cost of your new design. All you have to do at this point is go to return to the main window go to the facilities tab and choose Edit the processes of a Facility and Calculate Product Cost, choose DEFAULT FACILITY and click Access. Go to Tools/Calculate Product Costs or Times and. The form Calculate Product Costs appears and is shown below.



The last steps you need to do to perform your cost estimate are to specify the following parameters:

Prompt	Valid Entry	Example
Number of Panels per Batch	Number (Integer)	200
Product Demand	Number (Integer)	10000

Choose the facility that you want to be included in the cost calculations. In this case we will use the Default Facility. After you choose the default facility click on the button "Calculate Product Cost" and wait a message box appears that tells that calculations have been made and the following report appears:



Glossary

BATCH – refers to a typical production run or lot that needs to be processed

Example: 200 panels of the product ABC need to be produced today.

IMAGE- A substrate of epoxy glass, clad metal or other material upon which a pattern of conductive traces is formed to interconnect components.

PANEL – several images joined to be manufactured together.

PANEL(# PANELS PROCESSED) = it refers to the number or panels processed

IMAGE(# IMAGES PROCESSED)= it refers to the number of images processed

BATCH(DESIGN)- is a method to specify the part numbers that will be used in a setup operation

Example: The part number P1 is assembled on a Chip Shooter machine to locate three parts of this part number in an image. BATCH(DESIGN) is a method to describe the rolls that are typically inserted or placed on a Chip Shooter machine to put parts to an image. When you specify BATCH(DESIGN) as your Setup Type in a machine operation you need to provide a variable setup time. This variable time is typically the time it will take you to locate a roll of a particular part number and put it on the machine.

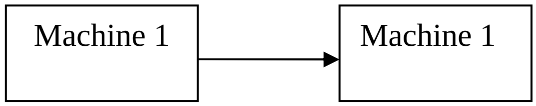
DESIGN**-** is a method to specify the part numbers processed on a machine

Example: The machine Chip Shooter locates the part numbers P1, P2, P3 of the product ABC. DESIGN is a method to describe the part numbers that are processed by a machine. When you specify DESIGN as your Process Type in a machine operation you need to provide a process time. This time is variable and it will depend on the number of parts assembled on the machine. Let's say that the process time is specified as .5 minutes and the number of parts to be processed is 5, then the process time will be .5*5 = 2.5 minutes. You only need to specify the time per part processed. The quantity of parts processed will depend on each product design.

CONVEYOR- is a method to specify that a conveyor is used to transport panels to the next station.

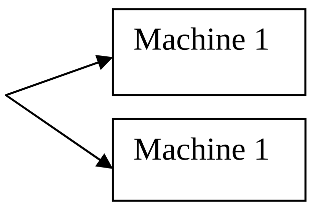
Example: In a typically SMT line, the processes are connected through conveyors.

SERIES- it refers to machines that are one next to the other as on the following diagram. In this case you need to be processed by the first Machine 1 in order to be processed by the second Machine 1.



In this example, you must pass through the machine 1 to pass to the machine 2

PARALLEL- it refers to the following diagram. In this case the incoming product can be processed by either one of the Machines 1



YES = it means that an operator is required in all the operations.

NO= it means that no operator is required in this operation

PARTIAL = it refers to the requirement of an operator on specified operations of the process.

Example: Operator is required only to setup the machine.

INDIRECT- is a method to distribute persons that are required on several processes of a same group.

Example: On a Surface Mount Technology (SMT), two operators are required to setup, supply the components required to the machines and maintain the processes of that group or manufacturing line running.

PARTIAL AND INDIRECT- it refers to the last two options combined.

Example. You could have a group or manufacturing line that requires operators to maintain machines up and running and have special or other operators to setup the machines.

APPENDIX E. EXPLANATION OF THE MOST RELEVANT ROUTINES OF THE APPLICATION

The most relevant routines of the application are explained.

1) Setup Time- This routine calculates the setup time per image of a product in a particular process and sends it to a temporary table.
2) Loading Time- This routine calculates the loading time per image of a product in a process and sends it to a temporary table.
3) Process Time- This routine calculates the process time per image in a process and sends it to a temporary table.
4) Unloading Time- This routine calculates the unloading time per image in a process and sends it to a temporary table.
5) Travel Time - This routine calculates the travel time per image in a process and sends it to a temporary table.
6) Occurrence time- This routine calculates the time per image of all the special operations of a process. This includes the predetermined and the random special events.
7) Total process time- This routine calculates the total process time per image in a process and sends it to a temporary table.
8) Calculate Number of Machines Required Designer To Replicate Processes- this routine calculates the number of required machines needed to manufacture a batch of images.
9) LeadTime2- This routine calculates the lead time of the product and send it to a temporary table

10) Cost Components Cost- this routine calculates the total cost of the components of a product.

11) Costs Direct Labor Cost- this routine calculates the direct labor cost of a product in a process.

12) Costs Direct Labor Cost Indirect- This routine calculates the cost of indirect labor which is defined as the labor cost that is distributed in a group of processes where an operator or operators are needed to operate a group of processes instead of one as made in the direct labor cost routine.

13) Costs Equipment Cost- this routine calculates the equipment cost of a product in a process a product in a process.

14) Costs Equipment Cost Travel Equipment- this routine calculates the cost of the equipment that is used to transfer a product image to the next station.

15) Costs Material Cost- This routine calculates the cost of the material used by a product in a particular process.

16) Costs Utilities Costs- This routine calculates the cost of all the utilities that are used while a product is being processed in a manual or machine operation.

17) Costs Space Cost- This routine search all the space related costs of a facility and calculates the cost of a process for a product.

18) Costs Total Process Cost- This routine calculates the total cost that is allocated to a product in a process. It is the sum of all the previous process costs.

19) Costs Support Personnel Cost- This routine calculates the support personnel cost that is allocated to a product based on the hours that support personnel dedicates to product processing.

20) Costs Total Product Cost- This routine sum all the costs necessary to calculate the total product cost.

21) Retrieve All Required Processes Time Calculations- This routine makes the search of all the processes needed to assembly an image. The following steps are made in the routine.

    a. It searches the distinct component types of a product.

    b. For each distinct component type, the process or processes needed to assemble this component are identified.

    c. Once the process or processes needed to assemble this component on the image are identified, the complementary processes that accompany this process are identified.

    d. Once all the necessary processes to assemble an image of a product are identified, all the processes that are required for all images are identified.