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An Effective And Optimal Quality Control Approach For Green Energy Manufacturing Using Design Of Experiments Framework And Evolutionary Algorithm

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AN EFFECTIVE AND OPTIMAL QUALITY CONTROL APPROACH FOR GREEN ENERGY MANUFACTURING USING DESIGN OF EXPERIMENTS FRAMEWORK AND EVOLUTIONARY ALGORITHM

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Dedication

To my beloved wife and daughter.

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by

JUAN ALEJANDRO SAAVEDRA

DISSERTATION

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Abstract

Quality Control (QC) and Quality Assurance (QA) strategies vary significantly across industries in the manufacturing sector depending on the product being built. Such strategies range from simple statistical analysis and process controls, decision-making process of reworking, repairing, or scraping defective product. This study proposes an optimal QC methodology in order to include rework stations during the manufacturing process by identifying the amount and location of these workstations. The factors that are considered to optimize these stations are cost, cycle time, reworkability and rework benefit. The goal is to minimize the cost and cycle time of the process, but increase the reworkability and rework benefit.

The specific objectives of this study are: (1) to propose a cost estimation model that includes energy consumption, and (2) to propose an optimal QC methodology to identify quantity and location of rework workstations. The cost estimation model includes energy consumption as part of the product direct cost. The cost estimation model developed allows the user to calculate product direct cost as the quality sigma level of the process changes. This provides a benefit because a complete cost estimation calculation does not need to be performed every time the processes yield changes. This cost estimation model is then used for the QC strategy optimization process.

In order to propose a methodology that provides an optimal QC strategy, the possible factors that affect QC were evaluated. A screening Design of Experiments (DOE) was performed on seven initial factors and identified 3 significant factors. It reflected that one response variable was not required for the optimization process. A full factorial DOE was estimated in order to verify the significant factors obtained previously.

The QC strategy optimization is performed through a Genetic Algorithm (GA) which allows the evaluation of several solutions in order to obtain feasible optimal solutions. The GA evaluates possible solutions based on cost, cycle time, reworkability and rework benefit. Finally it provides several possible solutions because this is a multi-objective optimization problem. The

solutions are presented as chromosomes that clearly state the amount and location of the rework stations. The user analyzes these solutions in order to select one by deciding which of the four factors considered is most important depending on the product being manufactured or the company's objective. The major contribution of this study is to provide the user with a methodology used to identify an effective and optimal QC strategy that incorporates the number and location of rework substations in order to minimize direct product cost, and cycle time, and maximize reworkability, and rework benefit.

Keywords: cost estimation, design of experiments, genetic algorithm, green energy manufacturing, process simulation, quality control, quality strategy, and recursive rework.

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Chapter 1: Introduction

1.1 Background and Research Motivation

Establishing an effective and optimal Quality Control (QC) strategy is critical for any manufacturing corporation to survive in the current market environment. QC strategies can vary significantly from product to product, industry to industry, and even company to company. Strategies, such as thoroughgoing inspection, reworking and finalizing a product, scraping a product completely if it is damaged or random sampling, are some examples of these strategies. Companies often lack a clear understanding of which QC strategy is the best fit for their product as well as the reasons for such strategies. This void is one this study intends to close. In order to evaluate different strategies this study relies on two main parameters as decision variables: (1) cost and (2) rework benefit.

Cost reduction is a central concern for companies; thus, it is proposed as one of the main decision factors for the optimization process. In manufacturing industry, product cost estimation has been approached in many different ways. This study will be including energy consumption during the process. Focusing on rework processes and including the fact that rework can be recursive. Rework benefit refers to the advantage gained by the company when reworking a product. Every time a product is reworked during the optimization process allows the production to flow better after the rework. Reworking a product at the end of the manufacturing process provides confidence to the manufacturer that the client will not receive defective products.

This study develops simulation models for the manufacturing process of products such as solar cells and wind turbines in order to test several scenarios of different QC strategies. The cost per product and the rework benefit of each of these scenarios will be analyzed in order to understand what quality strategy works best. Equations that include energy consumption will be proposed in order to estimate cost. With a cost estimation per product and the rework benefit estimated, several optimal solutions can be generated. The end user makes the final decision of a quality strategy depending on their needs.

The objectives of this study are to 1) develop cost estimation models which include energy consumption of the manufacturing process and 2) determine the optimal QC strategy for a manufacturing line in order to minimize the cost and cycle time and maximize the reworkability and rework benefit. The QC strategy refers to the quantity and location of the rework substations. The long-term goal of this study is to establish a method to evaluate different QC strategies, and understand the factors that make them work under specific conditions.

This study focuses mainly on the decision making process of one QC station versus several throughout the manufacturing process. It is assumed that for every QC station a rework process can be implemented to "fix" the problem and continue on. In order to achieve this comparison, a mathematical model for cost estimation will be developed. This model is generated through the use of process simulation tools and regression analysis. This model is different from existing ones because it includes energy consumption and rework processes as inputs.

This study develops a general mathematical model for cost estimation that includes energy consumption, and then evaluates if QC substations foster a cost benefit for manufacturing lines. With this, the evaluation of amount of rework substations is possible in order to propose an optimal QC strategy. Manufacturing lines in series will be included in the simulations with off-line rework stations for defects. The mathematical model can be developed using a simulated environment and performing a regression analysis for the main parameter, which is cost per product. This study focuses on avoiding a specific processes or characteristics, because most of the study already being published focuses on a specific product or process [Kalowekamo, 2009]. The estimation is required as a broad tool for decision making in order to establish and understand if there is a clear QC strategy that will be beneficial to manufacturing companies. This Quality strategy depends on the type and usage of the product being manufactured. Zero defects are expected for critical or expensive products (Ex. Airplane, car, television, etc.) but this criterion does not apply to consumable products (Ex. Pens, lunch box, shirt, etc.) and it is in non-zero defect situations where the threshold can be identified.

The scope of the study will include only the industry sector of production processes for both the manufacture of parts and assembly of products. Service, health care, construction and supply chain management sectors are not included because off-line rework cannot be performed in service industry. The decision making process will be focused on creating profitable products and will not include process planning or scheduling of different products. The study requires estimation of cost at various quality sigma levels. The study will include sigma levels from 2-sigma up to 6-sigma, which is considered a manufacturing standard for excellent product quality [Castanheira, 2011].

The main motivation behind this study is to address the lack of research on solving optimal problems for rework stations. Overall, identifying optimal QC Strategies can develop an advantage for manufacturing companies; but this topic has not been explored extensively. This is due to the fact that most manufacturing company are focusing on Lean and Six sigma methodologies to improve the QC strategies and overall performance. This approach focuses the objective of achieving zero defects in the manufacturing line. Zero defects are impossible to achieve due to normal variation in any process. The motivation comes in order to study different QC strategies in order to provide the optimal manufacturing process for any company. This optimal process is considered as the one that provides the best cost-benefit for a company.

The most important aspect to evaluate for companies when deciding any changes to their manufacturing line is cost. Direct cost is critical and many times considered as the only bottom line. Nonetheless, aspects that affect direct cost are often overlooked. Energy consumption is one of these aspects; it must be considered a direct cost to develop a sustainable manufacturing process. Once companies understand that energy consumption is as important as materials used; the process will become more efficient and greener.

1.2 Problem Statement and Rationale for the Study

Manufacturing companies scrutinize the effects of selecting a non-optimal QC strategy on product direct cost [Schiffauerova, 2006] and rework benefit. Existing QC strategies are

assumed to be correct because they have always been used the same way or because the specific industry does it the same way. Mass production manufacturing tends to include only rework stations at the end of the process with the objective of creating a continuous flow for the manufacturing line [Kenny, 1993]. Alternatively, lean production has the philosophy of stopping the production line to solve problems at each workstation as they arise [Womak, 1990]. This study focuses on creating a balance between both strategies and understanding how this balance impacts product cost and rework benefit of the product being manufactured.

QC strategies are commonly changed based on empirical knowledge of manufacturing processes; however, there is a great need to consider the effect of change on cost [Gunasekaran, 1994]. These strategies normally change depending on the amount and type of customer complaints being received by the manufacturer. The line of reasoning is that as customer complaints increase (or more defects are found at the end of the manufacturing line) more QC and rework stations are required to increase quality. As these QC stations increase, the cost of the product also increases, and in many cases also the energy consumption.

Despite the direct use of energy in order to manufacture a product, energy is not commonly considered in the estimation of the direct cost of that product. Due to this, decisions that affect directly the cost of the product can be made without receiving the expected benefits [Timmer, 2003]. A simple example of this issue is when a process is automated, direct cost savings are considered because operator(s) are no longer required; but energy used by the equipment is not usually taken into consideration.

Even though cost is considered the bottom line of most manufacturing companies, when creating a QC strategy other factors also come into play. Two factors that are being considered are the reworkability [Kuczynski, 2007] and the rework benefit. These factors refer to the ability of the manufacturing company and the QC strategy to identify defective products and turn them into good products again. When a rework station is placed at the end of the line, its product reworkability is very low because the entire product has been manufactured; but the rework benefit is high because the company is assuring that all defective products are being reworked

before shipping to the customer. A tradeoff between these reworkability and rework benefit must be acknowledged and understood before deciding on an optimal QC strategy.

1.3 Objectives and Significance of the Study

The main objective of this study is to propose an effective and optimal methodology in order to define an optimal QC strategy for manufacturing lines. This strategy refers to the ability of identifying the optimal amount and location of QC and rework substations. In order to propose a solution, the factors of cost, cycle time, reworkability and rework benefit are considered. A unique optimal solution is not feasible due to the nature of the multi objective problem. The user decides the final solution depending on the priorities required for the product being manufactured.

This study is divided into two main objectives. The first one refers to the aspects of cost estimation while including energy consumption as a direct cost. The second objective focuses on identifying the optimal QC strategy or strategies for any manufacturing line. To achieve the first objective the goal is to develop a cost estimation mathematical model, which includes energy consumption as a direct cost of the product. This model can be used in cost estimation through the process simulation and for multi-objective optimization. To achieve the second objective, the methodology used evaluates the main factors impacting direct product cost: cycle time and average resource utilization of different QC strategies that include rework. With the results, a multi-objective optimization algorithm is used to minimize cost and cycle time, and maximize reworkability and rework benefit.

Several research opportunities were identified after performing the literature review on the topics of cost estimation and the topic of manufacturing QC strategy. Cost estimation is commonly performed for a specific product or process due to the complexity of generalizing cost estimation. However, there has been very little effort on generalizing cost estimation models other the ones proposed for construction projects [Garcia, 2014]. Including energy consumption in product cost calculation has not been explored because energy consumption research has been

expanded mostly for estimation total building consumptions, but has not been isolated exclusively for manufacturing processes.

The aim of the study is to propose a methodology that has the ability to determine optimal QC strategy by evaluating several factors for different manufacturing processes. The aim is to have the ability to select one of QC strategy, or a combination of both, to provide an optimal process for the manufacturer.

1. A single QC inspection station at the end of the manufacturing line (illustrated in Figure 1.1). This is a final product QC inspection that is commonly used. After the final inspection, rework is performed in order to manufacture good product. This is commonly the approach for mass production manufacturing.

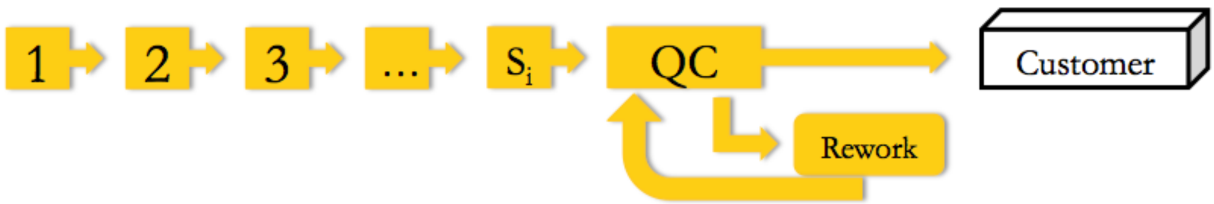


Figure 1.1: Example of single inspection station.

2. Multiple QC sub-workstations throughout the manufacturing line (illustrated in Figure 1.2). Utilizing QC inspections and rework stations through out the manufacturing line, is a Lean manufacturing approach. This prevents defects continuing the process, but initially causes the cycle time and cost of the product to increase.

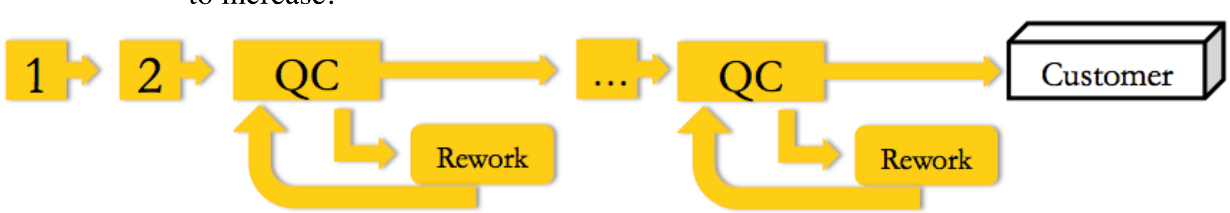


Figure 1.2: Example of multiple inspection station.

Having the ability to clearly identify a QC strategy can significantly benefit manufacturing companies by reducing direct cost. This study is meaningful thanks to the ability to attack this study opportunity. Optimal QC strategy depends on several factors mentioned previously. The process sigma level of the manufacturing line is a factor due to the possibility of eliminating quality checks in the process as it goes up.

This study also identifies the main factors that affect direct cost creating several benefits, such as: cost reduction projects that can be proposed and encouraged, production rates and requirements that can be adjusted to reflect optimal manufacturing capabilities, and automation and equipment upgrades which can be evaluated with a more accurate Return of Investment value.

The mayor contribution of this study is to the body of knowledge in the area of QC and Quality Assurance (QA) through Mathematical Modeling for decision-making by proposing a general model to predict product cost including energy consumption; and using them to compare different quality strategies that use off-line rework process, in order to select an optimal QC strategy.

1.4 Scope and Limitations

This study will focus only on manufacturing lines with a case study in the Green Energy Manufacturing sector. Green Energy Manufacturing processes generate products for Green Energy, but that does not mean they are sustainable and/or efficient processes. This emphasis is due to the nature of using off-line rework stations for the products. On-line rework stations are not considered due to the extent required for both analyses. Comparing on-line rework stations to off-line process can be included as future work. This methodology can be applied to any manufacturing line as long as it includes at least two separate workstations, and rework of the product is possible.

The methodology is based on process simulation; the assumptions used for the simulation are explained in Chapter 3. One key element that is not considered in this study is machine

maintenance and failures. Including this variability could change the results for selecting optimal QC strategies, but it would also present a challenge due to time-dependent and machine-specific processes.

The proposed multi objective optimization algorithm has also limitations when trying to evaluate manufacturing lines that have parallel processes. If these processes are included as a series manufacturing line (which is possible, but different for every specific case) the optimization algorithm does work; but it is not able to propose different QC strategies when dealing with series or parallel production lines.

The scope of the current study is also limited only to a single manufacturing line and a single process. It does not include the analysis of the entire supply chain manufacturing process. Sub-assemblies of a product are considered, but have to be included as in-house manufacturing processes.

1.5 Thesis Organization

This study is divided into 5 chapters. Chapter 1 states the background of the study, the motivation to propose this methodology, its significance and contribution, the objective of the methodology, and its scope and limitations.

Chapter 2 describes the theoretical tools used to develop the proposed methodology. The chapter starts by explaining the methodology and a summary table of the literature review. The chapter continues with QC, its importance and defining QC strategy. It then explains the different types of rework that manufacturing lines can use and their advantages and benefits. Then it goes in depth into product cost estimation processes. In this section of the chapter the inclusion of energy consumption as a direct cost is introduced and justified. The concept of reworkability is also explained because it is used for the optimization algorithm. The final subsections of this chapter briefly cover the tools used for this study such as Design of Experiments (DOE), Process simulation and GA.

Chapter 3 presents the methodology that will be followed to solve this problem and how the solution is obtained. It is important to understand the problem theoretically, which is the intent of this chapter. A simple example of the methodology used is presented in order to clarify and explain clearly all the steps.

Chapter 4 further clarifies the methodology being proposed. Several case studies are presented in this chapter. The first sets of case studies are presented in order to achieve objective 1 of this study. The second sets of case studies are focused on the second objective (optimal QC strategy). Finally a case study for solar panels manufacturing is reviewed in this chapter and the results are compared to field data obtained in order to validate the methodology.

Finally, Chapter 5 presents the major findings of the study including the contributions of this work to the manufacturing field. This chapter further provides the recommendation for future work.

Chapter 2: Literature Review

2.1 Introduction

In order to accomplish the objectives of this study, Figure 2.1 illustrates the overall research approach.

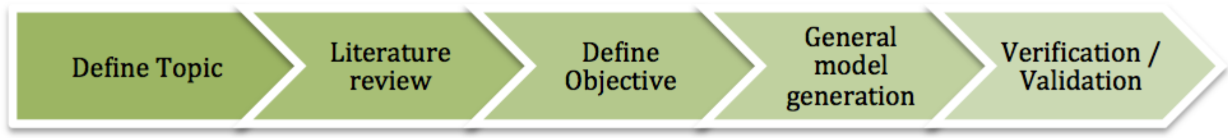


Figure 2.1: Research approach.

The first step is to define the topic for the study. This will guide the entire efforts on the right direction. The topic must be broad enough in order to identify gaps that can be worked on. The defined topic helps to focus the study. The topic of parameter estimation is selected and complies with all the requirements previously stated.

The second step is the literature review. This process is where the gaps on the topic of parameter estimation will be identified. The review must be vast, but never going outside the defined topic. Once a gap has been identified, then the literature review can close into topics related to that gap. This step is where a large amount of time is spent. I identified that simulation is not commonly used in parameter estimation for cost and/or energy estimation. Cost estimation methodologies are used to provide cost estimates mainly for projects in the Project Management scope [Cooper et al., 1985] including construction. Energy estimation study is focused mainly on algorithms and tools to estimate energy consumption [Wu et al., 2000], but not on trends of changes. The main gap identified is the trends changes for both cost and energy depending on the manufacturing line quality levels.

The third step of the methodology is to define the objective. This includes defining and answering the study question proposed from the literature review gap identified. This is the stepping-stone for all the study. Once the objectives have been defined, they must not be changed or the study might not be completed. It is important that it reflects a realistic, achievable

and clear goal. The deliverables of the study must be understandable from the objective. In the step the scope must also be included because this will establish how broad the objective will be. The objective and scope have been previously defined.

The forth step develops the general mathematical model. The general process simulations developed at this step will represent a single machine server, and multiple machine servers in series and parallel. The statistical analysis using the basics of DOE and regression analysis is used to generate trends [Montgomery, 2008]. Finally a GA is programed in order to propose optimal solutions of a QC strategy [Deb, 2002] as the fifth step.

In the sixth and final step of the study, new data from a manufacturing process is gathered in order to validate or verify the models prediction [Laplante, 2013]. The validity of the GA is verified through an evaluation of different scenarios of QC strategies.

2.2 Theoretical Background

The main areas covered in this study are Cost estimation, Energy consumption estimation and the use of Simulation models to estimate cost. Table 2.1 contains information on the literature review performed on these three areas. The first three articles refer to Cost estimation, the second three energy consumption estimation and the final two process simulation.

Table 2.1: Comprehensive article review.

Author and Year	Title	Summary
Jianglin Huanga, Yan-Fu Lib, Min Xie. 2015.	An empirical analysis of data preprocessing for machine learning-based software cost estimation.	This study aims for an empirical assessment of the effectiveness of data preprocessing techniques on ML methods in the context of software cost estimation. The results indicate that data preprocessing techniques may significantly influence the final prediction. In order to reduce prediction errors and improve efficiency, a

		careful selection is necessary according to the characteristics of machine learning methods, as well as the datasets used for software cost estimation.
Narges Sajadfara, Yongsheng Ma. 2015.	A hybrid cost estimation framework based on feature-oriented data mining approach.	A new cost estimation method combining feature-based engineering concept with data mining algorithms is proposed. It leverages empirical linear regression and data-mining algorithms with historical data. With the result comparison between the empirical prediction and five different data mining algorithms, the ANN algorithm shows to be the most accurate for welding operations.
Sérgio Sequeira, Eurico Lopes. 2016.	Simple Method Proposal for Cost Estimation from Work Breakdown Structure.	Regardless the extensive literature in project management, the model for cost estimation remains unclear and unexploited mainly in terms of simple methods. This paper introduces streamlining procedures from project Work Breakdown Structure (WBS) evaluating the duration processes and either the input cost hour or the fixed costs. The measures are made via hypothesis testing over the Responsibility Assignment Matrix (RAM). The cost methodology approach offers a simplified decision tool for assessing the construction cost on the project managers' decision.
Giorgio Graditia, Sergio Ferlitoa, Giovanna Adinolfia,	Energy-yield estimation of thin-film photovoltaic plants by using	Energy yield estimation of a micro-morph silicon modules PV plant is proposed. Physical and AI-based approaches are presented and compared. A new Hybrid Physical Artificial Neural Network model is proposed.

Giuseppe Marco Tinab, Cristina Ventura. 2016.	physical approach and artificial neural networks.	Different approaches to estimate PV plant energy yield are developed. Performances analysis of the proposed models is provided. Results demonstrate that the HPANN approach allows a more precise estimation of the ac energy yield, obtaining, in the worst case, values of Relative Root Mean Square Error less than 10%.
Carutasiu Mihail–Bogdan, Ionesecu Constantin, Necula Horia. 2016.	The Influence of Genetic Algorithm Parameters Over the Efficiency of the Energy Consumption Estimation in a Low–energy Building	Dynamic mathematical models are widely used for estimating the energy consumption in buildings. This paper presents the procedure to follow in order to optimize a simplified gray-box model by using an improved GA. The purpose of this paper is to analyze the influence of the parameters required in the implementation of the GA to estimate the energy consumption in a low–energy building.
Alfonso Capozzolia, Daniele Grassia, Francesco Causone. 2015.	Estimation models of heating energy consumption in schools for local authorities planning.	The annual heating energy consumptions of eighty school buildings are analyzed. Two energy estimation models were developed to support public authorities planning. A multiple regression model was built using nine different influencing variables. CART enables also non-expert users to extract information for decision-making. MAE, RMSE and MAPE were calculated to compare the performance of estimation models.
Brahmadeep, Sébastien Thomassey.	A simulation based comparison: Manual and	This paper aims to explain the production flow and the distribution logic of bobbins for rewinding process. The simulation model is used as a tool for the comparison

2014.	automatic distribution setup in a textile yarn-rewinding unit of a yarn-dyeing factor.	of present manual setup and future automated setup for the production management of bobbin distribution in yarn rewinding process in terms of delays and costs.
M. Bornschlegla, S. Kreitleinb, M. Bregullaa, J. Franke. 2015.	A Method for Forecasting the Running Costs of Manufacturing Technologies in Automotive Production during the Early Planning Phase.	The running costs of production sites are a decisive factor in the overheads of automotive production. They try to reduce both the energy consumption costs of production systems, as well as their maintenance costs. The approach in this paper shows how the decision for a specific manufacturing technology influences the factory costs. This paper shows how cost relevant parameters can be identified and introduces a method to determine the prospective costs for maintenance and energy consumption in advance.

2.3 Existing Quality Control Strategies

When referring to quality in manufacturing settings there are several terms that must be understood and separated. QC refers to the tasks required to assure if a product complies with customer requirements before its delivery. Quality Management helps to implement and control a QC strategy incorporating human behavioral change. Quality strategy is the operations side of creating QC. Examples of QC strategies are: number of QC inspections, sampling plans, definition of defects and their criticality, as well as Rework processes.

In manufacturing environments the term of Quality strategy is defined as the structured plan that the company will follow in order to improve or sustain desired quality levels [Stevenson, 1993]. Defining the QC strategy for each manufacturing company can be very different and very specific depending on the product being manufactured. One thing that all

manufacturing companies do have in common is that there is a quality check of the product at one or several points during the process. Quality strategies focus manly on management techniques while overlooking the operational aspect of it. One aspect that is not commonly evaluated, and that this study aims to evaluate is the cost benefit of using QC substations as opposed to a single final inspection.

Companies in the Green Energy Manufacturing industry develop, follow and innovate on their Quality strategy in order to become more profitable. One example is TrinaSolar, which is considered by Forbes the number one producer of solar panels in the world [Wang, 2014]. Trina Solar explains in their annual report of 2014 the Quality strategy to follow in order to be more competitive. This strategy focuses on creating a stringent QC by including product life cycle analysis, development of suppliers, reliability management, and others. The report also mentions in-house quality testing of 30 aspects of the product [Trina Solar, 2014]. These 30 tests must be performed during the manufacturing of the product, and a strategy of using quality sub-workstations or a final inspection only must be established. The 2014 TrinaSolar report does not mention how or at which steps these tests are performed. This study is focused on providing evidence on, which strategy will provide a cost benefit for TrinaSolar, or any, manufacturing company.

For wind blades manufacturers the story is similar; LM Wind Power claims to be one of the top wind blades manufacturer. Their quality strategy is based on continues non-destructive testing in order to assure quality and performance of the wind turbine blades they manufacturer. While not providing a specific number of checks, they do say there are a number of different checks performed [LM Wind Power, 2016].

Most Quality strategies focus on management skills and how to develop a culture of quality in an organization. There was no study found on how to organize and develop a manufacturing flow (including layout) to minimize cost with different quality strategies of product inspection. There are two main strategies for inspection, which are: A single finished goods inspection, or several sub-workstations throughout the manufacturing line.

Utilizing a single finished good inspection at the end of the production line reduces the Work In Process (WIP), can improve flow, and reduces the amount of Quality personnel required. The disadvantage is that it is not able to stop defective products from continuing on the process, even if the defect occurs in the first station. This strategy would definitely not work for products were rework is not possible, but for products that can be reworked it viable.

The other quality strategy utilizes sub-workstations throughout the manufacturing line for quality inspection or QA purposes. This allows the company to identify defects as they occur and rework the product before it is sent to the next station. It also prevents work being performed on already defective products. The disadvantage of this strategy is that it requires more quality personnel to perform this inspections and that increases the overall product cost.

2.4 Rework Processes

Rework consists of an iterative process where the product passes through the same steps twice, or more, due to a defect or any other cause after it has gone through the normal process. The objective of rework is to bring a product into conformance with its original requirements and/or specifications. Rework is normally the outcome of poor operating policy, poor design or poor process that causes failures or defects in any of the stages of the entire life cycle of a product [Lavasa, 2009]. This life cycle goes from customer need to product design, manufacturing, delivery, usage and disposal of the product.

QC and Manufacturing rework strategies can directly impact a product final production cost, and reduce customer complaints. Hines finds that cost and customer complaints have not been evaluated because till date study is focused mainly on Lean principles [Hines, 2004]. Industries assume that if a product can be reworked, it must be reworked to avoid more economical losses. Common practices in manufacturing are to add QC sub-workstations when quality sigma level decreases.

2.4.1 Rework Strategies

Rework process can be classified in based on the resources used, in-line or off-line [Flapper, 2002]. This classification depends on the process or product that must be reworked or repaired:

- In-line: Is when the same resource, used for regular operations) is used to rework the product (Figure 2.2).

Figure 2.2: In-line process rework.

- Off-line: Is when a different resource is used (Figure 2.3).

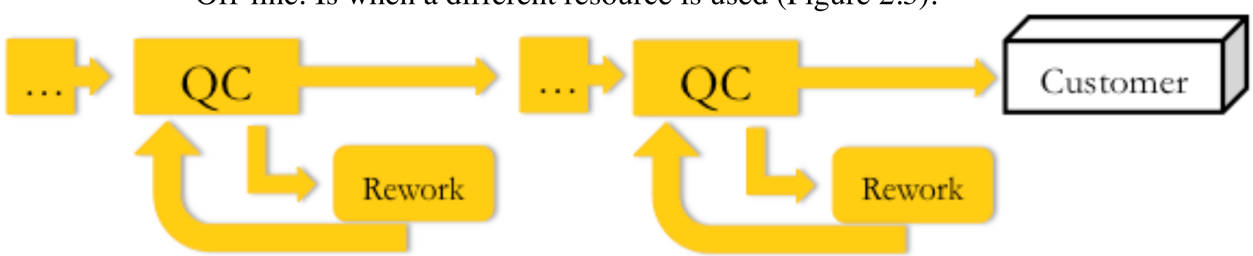


Figure 2.3: Off-line process rework.

Defect classification is a topic that has many approaches depending on the type of industry and the objective to be achieved. One of the most used approaches to identify, classify and reduce defects in a manufacturing process is though the creation of a Failure Mode and Effect Analysis (FMEA). FMEA were developed to evaluate military systems. Quantitative analysis evaluates each component of the system and its possible defects. There are three main aspects to FMEA: the probability of the defect, the detection rate of the defect and the severity. Severity can be used to classify defects. It refers to the worst-case scenario that the defect can have over the system. The typical classification of defects with respect to severity is shown in Table 2.2.

Table 2.2: FMEA severity rating.

Rating	Meaning
I	No relevant effect on reliability or safety.
II	Very minor, no damage, no injuries, only results in maintenance action (only noticed by discriminating customers).
III	Minor, low damage, light injuries (affects very little of the system, noticed by average customer).
IV	Moderate, moderate damage, injuries possible (most customers are annoyed, mostly financial damage).
V	Critical (causes a loss of primary function; Loss of all safety Margins, 1 failure away from a catastrophe, severe, damage, severe injuries, max 1 possible death).
VI	Catastrophic (product becomes inoperative; the failure may result in complete unsafe operation and possible multiple deaths).

2.4.2 Recursive Rework

Recursive rework refers to the concept defects found in a product that has been previously reworked. Reworked products can still be defective from the same issue identified previously or new ones. Dealing with recursive rework is complex because of the probability of failure change every time the product is reworked. Reworked products are more likely to be defective than a product that has not been reworked. This is due to the amount of handling and assembly and disassembly that the product must go through when reworked.

2.5 Cost Estimation

Product cost estimation is critical for any business. This process normally occurs when a new product is being designed. The product cost estimation refers to having the ability to predict all the cost that will be related with manufacturing a product. This prediction incorporates the entire manufacturing process starting from raw material, through the manufacturing process, and until the final product is completed [Chang, 2013 and Mital, 2014]. Once a product is being manufactured the cost estimation is not changed even though the manufacturing process generates scrap and rework.

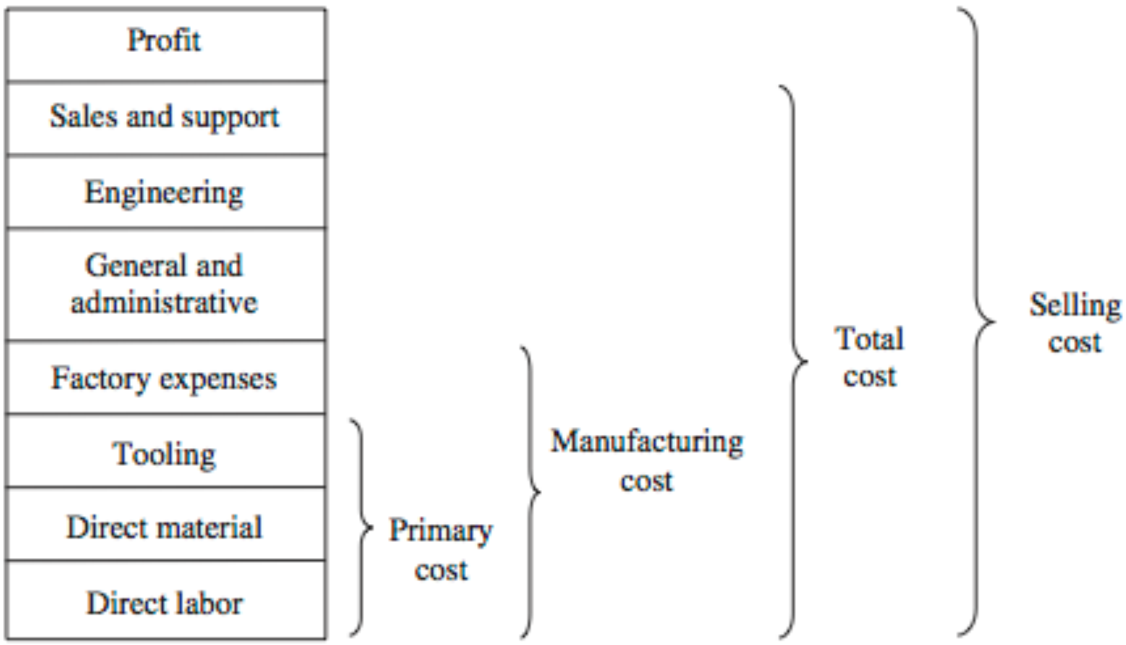


Figure 2.4: Product cost estimation structure.

The cost structure of any product is commonly divided into eight factors. Figure 2.4 shows the factors and the classification of each one. The primary cost is composed of the direct labor, direct material and tooling. These cost and the factory expenses consist of 40% of the total cost of a product. Direct labor refers to the cost of the workers that perform the job of transforming the raw material into the new product. The direct materials are those materials used for the creation of the product or part. The tooling refers to only tools that are used directly for the transformation of the product, not for maintenances or other related activities. The Manufacturing cost and total cost are considered to be indirect costs. Overhead and indirect costs cannot be associated clearly, or directly, with a single step of the manufacturing process. Only Manufacturing cost is considered in this study.

Process simulation, a strategy for cost estimation, uses time as the basic measurement. In addition to estimating Value Added (VA) Cost, Non-Value Added (NVA) Cost and Holding cost, this study adds the cost of energy consumption to the product.

Many different cost estimation techniques are used depending on the stage of the product development, complexity and accuracy required. One of the most common rules of thumb for cost estimation is the “1-3-9 rule” [Zienkiewicz, 1987]. This rule specifies that if the material required to produce a part is $1.00, the manufacturing cost will be $3.00, and the selling price should be $9.00. This approach is very rough but is a good way to calculate cost when little information is available and the estimate is not very critical.

Qualitative and Quantitate estimation methods are also used for product cost estimation. Qualitative cost estimation methods are based on comparative analysis of different products. One method used for this is regression analysis, which can predict cost efficiently with historical data. On the other hand, Quantitative techniques are based on the current product design, its features and the manufacturing processes that will be used. The operation-based approach is an example that can be used to estimate cost. The operation-based approach calculates the time preforming the entire manufacturing process and then calculates cost from these data.

2.5.1 Value Added Cost

VA is a term used widely in the Manufacturing industry due to the use of Lean methodology. Taiichi Ohno defines VA as “… anything other than the minimum amount of equipment, materials, parts, and working time absolutely essential to production.” [Ohno, 1988]. Utilizing the VA Cost approach applies the elements of Direct Labor, Direct Materials and Tooling in the cost element. It is important to mention that these elements refer only to the first time the product is being manufactured, if a defect was detected during a QC inspection (during the process or at the end) the rework performed to the product cannot be considered as VA due to the fact that it the work is being performed during a 2nd or 3rd time.

2.5.2 Non-Value Added Cost

NVA is considered as any cost that is not in the VA category. For manufacturing companies, this NVA cost is identified as any type of waste in their process [Womack, 2010]. Lean considers the 8 different types of waste in any process; these are:

- Transport: Moving people, products and information.
- Inventory: Storing parts, pieces, and documentation ahead of requirements.
- Motion: Bending, turning, reaching, lifting.
- Waiting: For parts, information, instructions, equipment.
- Over production: Making more than is immediately required.
- Over processing: Tighter tolerances or higher-grade materials than are necessary.
- Defects: Rework, scrap, incorrect documentation.
- Skills: Underutilizing capabilities, delegating tasks with inadequate training.

The Defects waste category includes any rework performed to the product. This is one of the main emphasis areas for this work. During the process of cost estimation using Simulation, all of these NVA cost are combined together with the exception of Waiting, which is categorized as a Holding cost.

2.5.3 Holding Cost

Holding cost in manufacturing and business management is considered to be the expenditure required to keep a product either as Raw material, WIP or Finished good [Johnson, 1974]. It is useful to think of food as an example to understand this concept. Some foods require staying at a certain temperature in order not to go bad, the cost of keeping these goods under those conditions is considered to be the holding cost of the product.

2.5.4 Energy Consumption Cost

The study of energy consumption has been focused mainly on methods that measure the amount of energy being used. These methods can include any type of energy and are not restricted to electrical energy. For this study, the energy consumption being measured is strictly electrical and is easily measured.

Energy consumption cost is currently calculated as an overhead cost. This is due to the fact that currently energy usage is not estimated. Most studies aim to create smart and sustainable buildings; their focus is on estimating electrical energy consumption for new buildings. They

seek to estimate how much energy a building will consume throughout a certain time period. This causes manufacturing companies to add the cost of energy/electricity used once it is billed without any further analysis. This study seeks to include energy consumption as a direct cost to the product. Efforts have been made in manufacturing improvement process to include energy as a critical measurement of improvement. An example of this is the creation of Sustainable Value Stream Mapping (SVSM), which includes not only VA and NVA activities but also energy consumption for these activities [Rother, 2003]. With these new tendencies, it is clear that energy consumption (kWh) is a critical factor that must be considered for product cost estimation.

2.6 Reworkability Definition

Reworkability is defined as how easily a product can be reworked. The easier it is to rework a product the higher its reworkability score. Reworkability scores are subjective and depend on the user's knowledge. Some of the possible approaches for obtaining significant subjective values are: ranking methods, rating methods, questionnaire methods, interviews, checklist and more [Kirvesoja, 1995]. A rating method for reworkability gives a score by adding points depending on how well the product follows the 17 Design for Disassembly guidelines to make a product easy to disassemble [Chiodo, 2005]. As the manufacturing process advances, it becomes more difficult to disassemble the product because of many different factors depending on each product. Some examples of these factors are: number of components included in the product, permanent processes done to the product (sealing, molding, grinding, etc.), critical process such as chemical of physical changes, etc. If some of the processes are more critical than others, weights might be included at each process to make this differentiation. If weights are included it is important that weights are between zero and one and the summation of all weights is equal to one.

Defining the reworkability score of the product at each station is critical in order to find the correct breakeven point between reworkability and cost. The use of a disassembly modeling process is recommended for this purpose. The disassembly process suggested by this

methodology is the direct graph. This disassembly modeling allows the user to easily identify the levels of the disassembly. Reworkability is directly related to these levels. As the disassembly process increases in level, the reworkability must increase. For this model the disassembly process can be understood as a top-bottom flow; and the assembly process as a bottom-top flow. The assembly process starts at the highest level of the disassembly direct graph were only components exist. This is the point where the maximum reworkability is obtained. As the assembly process continues the levels of the disassembly decrease until the entire product is manufactured. This modeling is important due to the fact that if at any point the assembly process does not change disassembly level, the reworkability must not change, or only change at a minimum rate. The significant changes on reworkability score must be shown when the process changes from one disassembly level to the next.

2.7 Different Types of Process Simulation

Process simulation refers to the development of a simulated environment in order to develop and test different scenarios. This environment can be physical or virtual. Virtual environments, developed through process simulation software are very common in manufacturing setting in order to test "what-if" scenarios. This allows the user to make decisions on whether to implement changes in their process in order to obtain a benefit; it also allows the user to test new processes before they have been developed in order to identify problem or opportunity areas that can be improved [Kelton, 2000]. The benefits of computer simulation are that they can easily been changed for testing, cost is significant lower than developing a trial and error process, and the time required is also significantly lower compared to physical simulations.

Discrete event simulation is used for most manufacturing process excluding processes such as petroleum refinement or chemical production, where continuous simulation must be used. Discrete event simulation reflects processes where changes can be identified at a specific point in time. These types of simulation are used in order to recreate the manufacturing processes that will be evaluated in this study [Morgan, 1984].

2.8 Description of Genetic Algorithm

Once the estimations and relationships have been identified, the objective is to optimize the system and reduce the error. This can be done utilizing different optimization techniques. This study considers the application of GA for a multi-objective problem, in order to provide the user with optimal solutions for QC strategy; GA is a stochastic method that will optimize the result by creating a Pareto front of optimal solutions. The current problem being analyzed will not develop a single optimal solution because it is a multi-objective optimization. The goal is to minimize cost (and energy consumption), and maximize output.

GA follows the genetic process of humans, and the evolution process. A population of possible solutions is develops first. The second step is a selection process were only the best solutions are selected. A third step is performed called cross over; this refers to the creating new solutions from the ones selected previously. These solutions are called children, and are a new generation of possible solutions. A fourth and final step is to mutate some of the solutions in order to not fall into local solutions and explore the entire universe of possible solutions. Once these steps are performed, they are repeated again until the stopping criteria are met. These stopping criteria can be a certain amount of iterations, or no increase in optimal solutions [Tseng, 2014].

GA mimics the evolutionary processes by using natural selection to identify optimal solutions. Figure 2.5 describes this process step by step [Dieterle, 2003]. The approach of GA was selected due to its:

- Feasibility for multi-objective optimization problem.
- Fast convergence on stochastic objective functions.
- Low risk of finding local optimal.
- Significant factors identified previously with ANOVA testing will be used in the GA.
- Post-Pareto analysis can be performed using Trade-off Analysis (ToA).

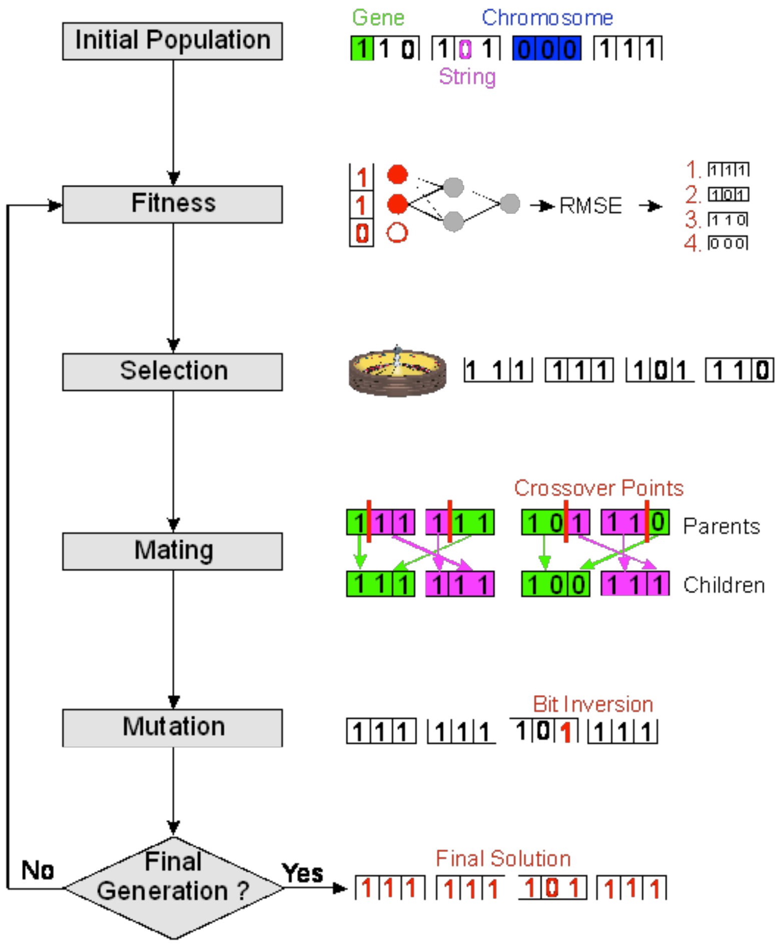


Figure 2.5: GA process steps.

2.9 Summary

Chapter 2 presented a background and introduced the terms and topics that were used in order to develop the methodology to address the study two objectives. The main two main gaps identified in the literature review were: (1) product cost estimation that includes only the manufacturing process is product specific and does not include energy consumption; the second gap identified was (2) the lack of research in the area of rework optimization including QC strategy.

Chapter 3: Proposed Methodology

3.1 Introduction

Chapter 3 presents the proposed methodology and the steps taken in order to develop it. It is divided in the two main objectives, which are cost estimation and Optimal QC strategy. Each of the subsections presents the methodology used in order to address the specific identified objectives.

3.2 Objective 1: Total Direct Product Cost Estimation

3.2.1 General Model for Calculating Direct Product Cost

In order to develop a general mathematical model for the estimation of cost and energy according to quality, the process, and models to calculate these parameters must be understood separately and then included in one general model. The mathematical models for the estimation of cost and energy consumption are based on process simulation methods for discrete and stochastic processes [Banks, 2005]. These models are better applied for off-line rework station and assuming all defects can be reworked.

The framework proposed in order to develop the general mathematical model is shown in Figure 3.1. The inputs of the system are the required product specifications in order to develop the simulation model. Once the model is developed, several iterations must be performed with different sigma levels at the quality inspection station. The statistical analysis is performed for each sigma level. With all this information available, the user is able to establish a Quality-Cost relationship.

The objective of the general model is to develop a cost estimation mathematical model that includes energy consumption as a direct cost and energy consumptions are being included in sustainable efforts such as Green Manufacturing. This model is based on main cost estimation concept: Direct material + Direct labor + Overhead cost [Ostwald, 2004]. Energy consumption is playing a role in Lean Manufacturing (Ex. SUS-VSM [Faulkner, 2014]) [Rusinko, 2007].

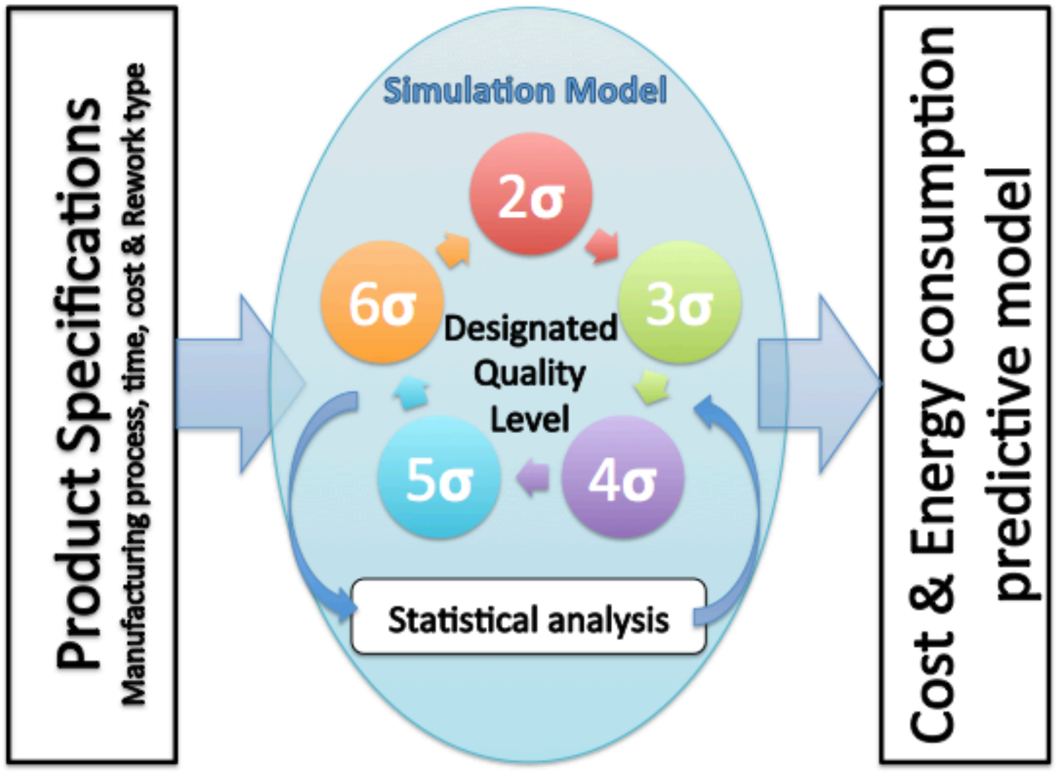


Figure 3.1: Cost estimation conceptual framework.

3.2.2 Energy Consumption and Environmental Cost

In order to establish and understand environmental cost a clear scope must be defined. Environmental cost depends directly on the environmental impact that a process or products have. This impact can be negative or positive in different cases. Examples of negative impacts are CO_2 gases emitted to the environment, Green House Gases (GHG) emitted, contamination of water or soil through liquid contaminants, etc. Positive impacts are harder to find unfortunately, but some example are products that can filter and clean water or air, or that while creating the product clean air or water is recycled to the environment. As broad as these impacts can be, a cost estimation model cannot include all of them. The most common one, and the one that will be used to establish environmental cost is the cost of CO_2 per ton.

The United States Environmental Protection Agency (EPA) has extensive study on how to estimate and calculate the cost of one ton of CO_2 to the environment. This cost is known as the Social Cost of Carbon (SCC). The SCC is an estimation of the economic damage that an

emission of one ton of CO_2 can cause to the environment [IWGSCC, 2013]. The SCC estimation tries to include factors such as human health, agricultural impact, changes in environmental climate, etc. It is merely impossible to include all impacts that CO_2 can have over the environment but the SCC is an excellent approximation. It is very likely that the SCC underestimates the cost due to this factor, but it is still a useful estimate in order to include an environmental cost on cost estimation methodologies.

Table 3.1 shows the estimates of the SCC per year. The EPA has been successful on estimating this cost since it first started in 2010. Thanks to these efforts there has been a variety of rulemaking in order to impact and reduce the carbon dioxide impact in the environment. These rulemaking has directly impact carbon dioxide emissions and has benefit society environmental conditions.

Table 3.1: SCC estimates updated per year [Interagency working group, 2013].

Social Cost of CO_2, 2015-2050 [a] (in 2011 Dollars)

Year	Discount Rate and Statistic			
	5% Average	3% Average	2.5% Average	3% 95th percentile
2015	$12	$39	$61	$116
2020	$13	$46	$68	$137
2025	$15	$50	$74	$153
2030	$17	$55	$80	$170
2035	$20	$60	$85	$187
2040	$22	$65	$92	$204
2045	$26	$70	$98	$220
2050	$28	$76	$104	$235

[a] The SCC values are dollar-year and emissions-year specific.

In order to estimate the amount of tons of CO_2 that is generated by any process, a life cycle can be developed. Life Cycle Assessments (LCA) is common for products when the environmental impact needs to be calculated. This process consists of estimating the impact in a cradle to grave overview [Curran, 1996]. LCA's calculate the total carbon footprint that a product leaves to the environment over it total life span. This process can be used also to

calculate any process (such as a rework or repair processes). For this study the total carbon footprint is not required due to the cost estimation. The carbon footprint does include the amount of tons of CO_2 that the process generates, and this is the data that will be used in order to estimate cost.

3.2.3 Cost Estimation of Energy Consumption and Rework Processes

3.2.3.1 Cost Estimation Without Energy Consumption

The total cost per product using process simulation is calculated by adding the VA cost, plus the NVA cost, plus the Waite time, at each of the manufacturing stations; divided by the total number of good products produced. These three costs are shown in equation 1. They represent the costs of direct labor, direct material and overhead cost [Maher, 2006]. Equations 2 and 3 show how Vale added and Wait time are calculated.

$$TC = \frac{\left[\sum_{i=1}^{N}(VA_i + NVA_i + W_i)\right]}{N} \quad (1)$$

where

TC = Total product cost [USD]

VA = VA cost [USD]

NVA = NVA cost (Rework) [USD]

W = Wait cost [USD]

E = Total Energy cost [USD]

S = Amount of work stations [ea]

N = Number of good products [ea]

i = Manufacturing station

$$VA = (t_{mb} * C_{mb}) + (t_{ob} * C_o) \quad (2)$$

where

t_{mb} *= time machine is busy [hour]*

c_{mb} = cost of machine busy [$ / hour]

t_{ob} = time operator is busy [hour]

c_o = cost of operator [$ / hour]

$$W = Q * C_h \tag{3}$$

where

Q = Queue time [hour]

C_h = Holding cost [USD]

When equation 1 is expanded for the first server (Ex. Machine or process) in order to identify cost and time separately equation 4 is derived. Equation 5 shows the equation used for the any other server (S), other than the first one. This equation is used also for the rework station to calculate the cost.

$$(VA_1 + NVA_1 + W_1) = VA_0 + NVA_0 + (t_{mb} * C_{mb}) + (t_{mi} * C_{mi}) + [(t_{ob} + t_{oi}) * C_o] \tag{4}$$

where

VA_0 = Initial VA cost [USD]

NVA_0 = Initial NVA cost [USD]

t_{mb} = Time the Machine is Busy [hours]

C_{mb} = Cost of the Machine being Busy [USD]

t_{mi} = Time the Machine is Idle [hours]

C_{mi} = Cost of the Machine being Idle [USD]

t_{ob} = Time the Operator is Busy [hours]

t_{oi} = Time the Operator is Idle [hours]

C_0 = Cost of the operator per a period of time (Ex. By hour, by shift, etc.) [USD]

$$TC = \frac{\left[\sum_{i=1}^{S}((t_{mb} * C_{mb})_i + (t_{mi} * C_{mi})_i + [(t_{ob} + t_{oi}) * C_o]_i)\right]}{N} \tag{5}$$

3.2.3.2 Cost Estimation Including Rework

Can a generalized mathematical model predict accurately the total cost and energy consumption of a manufacturing line that includes rework? In order to answer this question many factors must be taken into consideration and have a solid true foundation. In order to include rework in the cost estimation it is essential to understand the times of rework process change. This is due to the fact that the rework stations firs encounters problems that might not know exactly how to fix, but as time goes on, repeating problems occur and the rework time pero part must decrease.

At rework stations the cost is calculated differently than the regular process because a learning curve process is assumed [Yelle, 1979]. This assumption is based on the fact that every time quality levels vary, new defects can occur and due to this the operators must learn how to rework each individual defect. Equation 6 shows the model that will be used in order to estimate the rework time (tR) of each defective product including a learning curve. Figure 3.2 illustrates the time percentage change for the rework process as more products are being reworked. This graph shows only 50 points and it has an exponential distribution that will never reach 1.0, but after 25 points (Ex. Reworked products) the time difference is less than 0.1%.

$$t_R = 1 + e^{\left(-\frac{N}{10}\right)} \tag{6}$$

where

t_R = *Time of rework [hours / piece]*

N = Number of parts [ea]

When calculating the total cost of the system, the Initial product costs, the processing cost and the rework cost must be considered. Equation 7 is the compilation of all of these factors. Not

only are the process cost (used in equation 4) calculated but also the rework processing costs. Equation 7 can be used for any number of workstations (N) and any amount of rework parts (R).

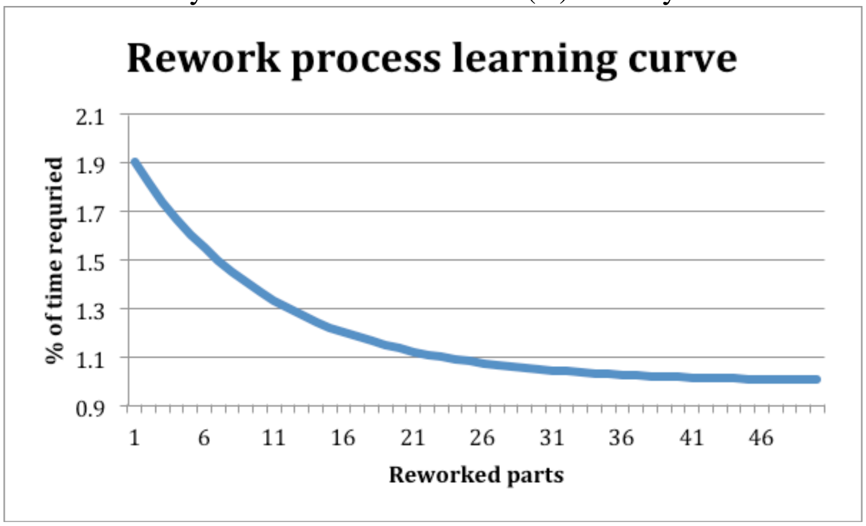


Figure 3.2: Rework learning curve.

$$TC = VA_0 + NVA_0 + \frac{\sum_{i=1}^{S}\{X+Y+Z\}_i + \sum_{i=1}^{R}\{X+Y+Z\}_i}{N} \quad (7)$$

where

$$X = t_{mb} * C_{mb}$$

$$Y = t_{mi} * C_{mi}$$

$$Z = (t_{ob} + t_{oi}) * C_o$$

In the equation, the terms of ‘X’, ‘Y’ and ‘Z’ are used in order to simplify the equation. These terms can be substituted in equation 7 and same result would be obtained. Equation 8 shows the NVA calculation applies only for the Rework station(s).

$$NVA = \{(t_{mb} * C_{mb}) + (t_{mi} * C_{mi}) + [(t_{ob} + t_{oi}) * C_o]\}_{RS} + \sum_{i=1}^{S}[(t_{mi} * C_{mi}) + (t_{oi} * C_o)] \quad (8)$$

3.2.3.3 Cost Estimation Including Energy Consumption

In order to include the energy in the cost estimation equation previously presented, it must first be calculated separately. The total energy per product consumed is calculated based on the same formula used for calculating cost (equation 7). There are four factors that change between cost and energy estimation. The first factor is that there is no VA or NVA energy. The second factor is that instead of cost, energy is being evaluated in the equation. The third is that there is no learning curve involved in the rework station. The fourth and final factor is that there is no operator involved when calculating energy. Equation 8 shows the condensed total energy cost and Equation 10 is the equation expanded that is used to calculate energy usage for the process.

$$E = (TE * EC) \tag{9}$$

where

TE = Total Energy consumed [kWh]

EC = Energy Cost [$/kWh]

$$TE = \frac{\Sigma_{i=1}^{S}\{(t_{mb}*E_{mb})+(t_{mi}*E_{mi})\}_i+\Sigma_{i=1}^{R}\{(t_{mb}*E_{mb})+(t_{mi}*E_{mi})\}_i}{N} \tag{10}$$

One the total energy consumption has been estimated (TE) by product in kWh, it can be added to the cost estimation by including the cost of energy usage ($/kWh). This cost varies depending on the country and region, and in some cases even depending on the size and the type of product being manufactured. Equation 11 shows Energy consumption formula being used.

$$TE = (t_{mb} * E_{mb}) + (t_{mi} * E_{mi}) \tag{11}$$

w*here*

E_{mb} *= Energy consumed when machine is busy [kWh].*

E_{mi} *= Energy consumed when machine is idle [kWh].*

Equation 12 shows the condensed equation used for product cost estimation and equation 13 is the expanded to calculate cost including all factors being evaluated. All the terms have been defined previously.

$$TC = VA_0 + NVA_0 + \sum_{i=1}^{S}(VA_i + NVA_i + W_i + E_i) \quad (12)$$

$$TC = VA_0 + NVA_0 + \frac{\sum_{i=1}^{S}\{X+Y+Z\}_i + \sum_{i=1}^{R}\{X+Y+Z\}_i}{N} + (TE * EC) \quad (13)$$

where

$EC = Energy\ cost\ per\ kWh\ [USD\ /\ kWh]$

3.3 Objective 2: Quality Control Strategy for Manufacturing Processes

The second objective of this study is to be able to define and optimal QC strategy. This means that the user must be able to understand the benefits and disadvantages of selecting one or many rework stations thought out the process, and their effect depending on the location of each one. Figure 3.3 illustrates the steps required in order to achieve this objective that are explained in detail in the following sections of this chapter.

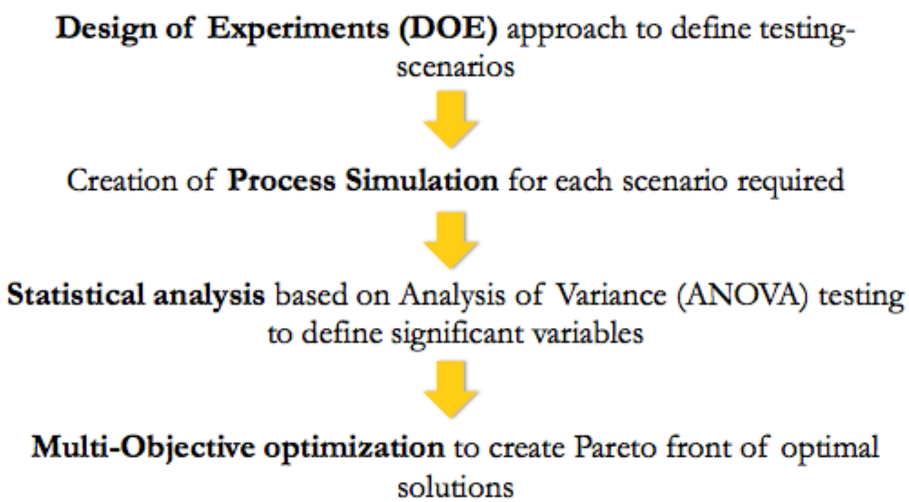


Figure 3.3: Optimal QC methodology steps.

3.3.1 Design of Experiments Inputs and Outputs

For the DOE section, a two-step process was followed. This process has the objective, as in all DOE, to identify the significant factors of a process [Anderson, 2000]. The first step was to develop a screening DOE by using a fractional factorial in order to reduce the amount of replications from 758 and reduce it to 16. This fractional factorial design allows a statistical analysis to be performed to identify significant factors depending on the each of the response variables [Cochran, 1957]. The use of fractional factorial design allows the user to perform fewer simulations on Arena® and obtain a result faster. The second step is the use of a full factorial design that allows the clear identification of the significant factors identified in the fractional factorial process [Goupy, 2007]. This second step can be understood as a verification run of the previous fractional factorial experiment. The use of the full factorial design was selected because there are no limits in number of factors to evaluate, there are no limit in number of levels per factor, identification of interaction between variables is possible and when using 2 levels per factor, this indicated linear relationship and the use of more levels are required for non-linear relationships, and the full factorial experiment also reduces error variance compared to other approaches.

Equations 14, 15 and 16 show the response (outputs) being evaluated. These equations where initially considered in order to identify the critical factors. They represent Total cost per product, Product cycle time and Average resource utilization respectively.

$$TC = VA_0 + NVA_0 + \sum_{i=1}^{S}(VA_i + NVA_i + W_i + E_i) \tag{14}$$

$$CT = \sum_{i=1}^{S}(VA_i + NVA_i + W_i) \tag{15}$$

$$\overline{RU} = \sum_{i=1}^{S} \left(\left\{ \frac{max[t_{mb}, t_{ob}]}{T_t} \right\}_i \right) \tag{16}$$

w*here*

T_t *= Total simulation run time [hour]*

RU = Average resource utilization [percentage]

The user must define the critical factors in the process. For this study an example of the possible factors and their levels is presented. For the initial screening DOE a total of 8 factors was considered. 6 factors contained 2 levels (minimum and maximum) and 2 factors had 3 levels. Factors with 2 levels being considered where:

- Probability Density Function (PDF) used for input: Constant or Triangular
- PDF for process: Constant or Triangular
- Input time rate: Low and High (Low = 1 pcs. / hour, High = 2 pcs. / hour)
- Process time rate: Low and High (Low = 1 pcs. / hour, High = 2 pcs. / hour)
- QC time rate: Low and High (Low = 1 pcs. / hour, High = 2 pcs. / hour)
- Rework time rate: Low and High (Low = 1 pcs. / hour, High = 2 pcs. / hour)
- Number of rework stations: Low and High (Low = 1 Finish Good QC, High = 6 QC sub-workstations)
- Process Quality sigma level: Low and High (Low = 2-sigma: 69.1% yield, High = 5-sigma: 99.9%)

3.3.2 Process Simulation Capabilities

The use of process simulation is a powerful tool used in order to compare different scenarios [Kelton et al., 1998], such as different quality levels in a manufacturing setting. It is a tool that allows the user to understand the logic and visualize what is happening in the system as different factors change in it. With this capability and complementing them with statistical analysis, it is possible to estimate and/or predict most factors that are important for the user.

These factors can vary significantly from cycle time, breakdown times, cost, utilization of resources and more. The use of process simulation for energy consumption estimation is not common, but it is possible through programming using SIMAN language.

Decision-making is main concept and objective behind using simulation, testing of different scenarios, and trend analysis. When considering multiple factors it is not a simple process in order to identify and take the best decision [Gwo-Hshiung, 2010]. Due to this, having the ability to predict cost and energy immediately after knowing the quality level of a process, become key for management decision-making.

One main motivation of this study is to provide manufacturing companies with a simple but effective model in order to estimate cost and energy usage of their processes. This model could be used on real time applications in order to make decision regarding process control and quality continues improvement. It also allows the users to compare different quality strategies that include (or not) rework processes.

3.3.2.1 Utilized Sigma Levels

Sigma levels are used to compare different processes on their level of quality because it is not process or product specific. It is the determination of amount of defects per million opportunities (dpmo). An opportunity is specified as a single characteristic that can cause a product to be considered defective [Maxey, 2012]. Table 3.2 specifies the comparison between the sigma level, defect rate and the yield of the process.

Table 3.2: Process sigma levels.

Sigma Level	Defect Rate	Yield
2 σ	308,770 dpmo	69.1 %
3 σ	66,811 dpmo	93.33 %
4 σ	6,210 dpmo	99.38 %
5 σ	233 dpmo	99.977 %
6 σ	3.44 dpmo	99.99966 %

3.3.2.2 Simulation Assumptions

Simulation assumptions are critical in order to understand what is being evaluated and what is out of the scope of the project. It is merely impossible to include all parameters, and constraints of a real life system into a computer simulation. The objective is to utilize these assumptions in order to understand the changes in parameters being evaluated with every "what-if" scenario performed. The general assumptions being used for process simulation for this study are the following:

- Demand of product does not change during the simulation time being evaluated.
- All inputs, such as product demand, are based on PDF in order to include randomness into the system.
- Breaks and Failures of machines are specified in case-to-case bases, and also follow PDF for time and amount of pieces produced.
- Performances measurements are calculated after several iterations of the simulation, and use a 95% significance level.
- Operators have specific break times and schedule and it is assumed that they are working at 100% efficiency during work periods.
- Energy consumption is considered to be constant per part.
- There is no energy failures considered during the simulation process.

3.3.3 Experimental Design Setup

In order to generate a conclusion on weather quality sub-workstations are better and 1 single finish good inspection an experiment must be developed. This experiment will be based on the use of computer process simulation with Arena® software. This software performs Montecarlo simulation for any process. In this case, manufacturing process will be simulated and evaluated including the rework stations. The following sections present how the analysis will be performed and the input and output variables to be used.

3.3.3.1 Establish Parameters for Comparison

The first step in the experiment being performed is to establish which parameters will be used in the simulation and compared for every scenario tested. These parameters are the basis in order to develop the simulation, modify it to develop "what-if" scenarios, and establish the outputs that will be compared in order to draw conclusions.

3.3.3.2 Simulation Creation

In order to develop the simulation, there are three basic components that must be included. The first one is the process architecture, or layout. This is defined as the steps of how the product is being manufactured. Examples of this are manufacturing lines in series, parallel or combination of both. These structures are known as job-shops or flow-shops. Both structures will be included in the experiment in order to confirm conclusion drawn from any specific architecture structure. The second and third components are the input variables used and the process parameters; these will be explained in the following sections.

3.3.3.3 Input Process Variables

In order to develop the simulation several process variables must be identified and established. These process variables are programed in the system at different stages and will follow different PDF depending on specific testing scenarios. The following list shows the process variables and their definition:

- Inter arrival time: The time between arrivals of entities in the system. This in normally considered as the demand of the product.
- Entities per arrival: The amount of product received for each arrival. This refers to the fact that products or demand can be batched in groups of 2 or more.
- System architecture: How the manufacturing process is arranged. Examples of this are job-shops or flow-shops. This architecture will also change in order to test the difference between having a single final goods quality inspection, or several sub-workstations throughout the entire manufacturing line.

- Initial cost: Initial cost refers to VA and NVA cost inquired before the manufacturing process begins. This is attributed mostly to raw materials cost and transportation costs respectively.
- Holding cost: This is the cost required to have the product "in-house" as inventory (including WIP).

3.3.3.4 Process Parameters

The process parameters presented in this section are the key elements in the simulation that will be changed for every test scenario in order to identify trends and draw conclusions from them. These are the process parameters that will be considered:

- Process time: This is the amount of time that is required for a product to be processed at that specific station. This time is for manufacturing processes, quality inspection process and rework processes.
- Process energy: Refers to the amount of electric energy required in order to perform a task at a specific workstation.
- Process resource(s): This is what is used in the process to perform the process specific to that workstation. Resources can be people, tools or equipment.
- Decision variable: This is used to separate the good parts from bad parts. This study will use only percentages instead of PDF to specify the percentage of product that must go to a rework process.

3.3.3.5 Simulation Process Outputs for Analysis

The outputs of the process are the key parameters that will evaluate in order to identify trends and draw conclusions. These conclusions in tend to prove which input and process parameters affect significantly the process output. Process outputs are commonly known as Key Performance Indicators in manufacturing.

- Total output: Refers to the amount of product produced during the simulation period.

- Total energy consumption: Is the amount of electric energy required in order to generate a finished good.
- Total product cost: Is the cost inquired in the process in order to generate one product. This cost includes NVA cost, VA cost, holding cost, and energy consumption cost.
- WIP: Is the amount of product that currently being produced during a specific time period. This is also considered as inventory for finance purposes.
- Resource utilization: Percentage of time that the resources is being utilized to produce a product.
- Queue time: The time a product has to wait in line before it can be processed at the next workstation because the resources of the required workstation are busy with a previous product.
- Cycle time: It is the average time that a part takes from when it enters the system until it leaves including any wait times, processing time at each workstation and rework time if it is required.

3.3.3.6 Testing Scenarios

Several "what-if" scenarios will be generated in order to test the hypothesis that using one single finished good inspection process is statistically different than using several sub-workstations to control quality. The parameters that will be changed for these testing scenarios are the following:

- System Architecture: It will consider 1 single finished goods quality inspection versus 1 or more quality sub-workstations during the process.
- Quality sigma-level: Refers to the percentage of good products produced. This sigma level will change between 2 and 6 in order to identify trends in cost and energy consumption.

3.3.4 Simulation Data Acquisition Procedure

The data acquisition process is simple and computer based. It is performed by the Arena® Simulation software. During the simulation processing time, the software records every parameter being evaluated for every single change in the system. Due to the fact that this is a discrete event simulation process, parameter changes occur only at specific points in time.

3.3.5 Simulation Data Processing

Once all the data has been generated with the use of the simulation package different steps and/or considerations must be performed with the data. The following section explains in detail what these steps are.

3.3.5.1 Production Output

Production output refers to the amount of product produced after a certain amount of time. This amount of time is specified in order to achieve steady state in the simulation. All test scenarios use the same simulation time due to the fact that if time changes, increases or decreases, the amount of products produces will also increase or decrease.

3.3.5.2 Product Cost

The total product cost is calculated by the summation of all holding, processing and energy cost throughout the process. The average cost per product will vary for every test scenario due to the changes in the layout of the process, the quality sigma level of the process, and the system input specifications.

3.3.5.3 Analysis of Variance Testing

The Analysis of Variance test (ANOVA) is commonly used statistical test in order to compare 2 sets of data in order to establish if their means are significantly different of not [Montgomery, 2012]. The user defines the significant level but commonly a 95% is used. This means that there is a 5% error probability on the statistical analysis being performed. The ANOVA of a single factor is called a One-way ANOVA. This statistical test is used when

analyzing different sets of data where only one factor is being changed a time. This test will be sued during this study to understand the difference in costs of system when changing the sigma level of the process.

ANOVA testing is selected due to the fact that the objective is to test if means are equal for every test-scenario. Identifying this is critical in order to point out the significant factors. Balanced ANOVA is used in order to test effect of different “treatments”. N-way multi-variant ANOVA will be used as well if required. It is important to test every factor independently and test all possible interaction between factors.

Using the Tukey’s and/or Fisher LSD method as required will also develop the comparison of the populations. These two methods allow a clear comparison between populations in order to identify if they are significantly different or not [Maxwell, 2004]. This is critical in order to obtain correct results and analyses if the factors being evaluated, and their change, generates 2 different populations or not.

3.3.5.4 Regression Analysis

Regression analysis is performed in order to develop a statistical estimation of relationship between the input and process variables, and the process outputs for the different test case scenarios. The creation of the regression analysis will develop predictive equations that will allow the estimation of process out puts at with different conditions. This will develop easy and more visual representations of the relationship of variables.

3.3.6 Feasible Optimization Approach

Once the results have been obtained from the DOE and significant factors identified, and optimization must occur in order to propose an optimal QC strategy for the specific manufacturing line. In order to do so, the several objectives that are important must be included and a process to optimize them must be followed. Due to this objective a multi objective optimization GA has been selected.

3.3.6.1 Multi Objective Optimization for Identifying Optimal Quality Control strategy

In optimization problems, most the time an optimal solution is desired, but not always feasible. Multi-objective optimization refers to the optimization problems were, as there name implies, are multiple objectives that the user desires to be optimized. In most cases these objective functions contradict each other and that is why several possible solutions are generated. Multi-objective problems develop a Pareto front of solutions [Sayyad, 2013]. User decides which optimal solution fits best their needs, or a post-pareto analysis can be performed. Illustration 3.1 shows an example of a 3D Pareto front.

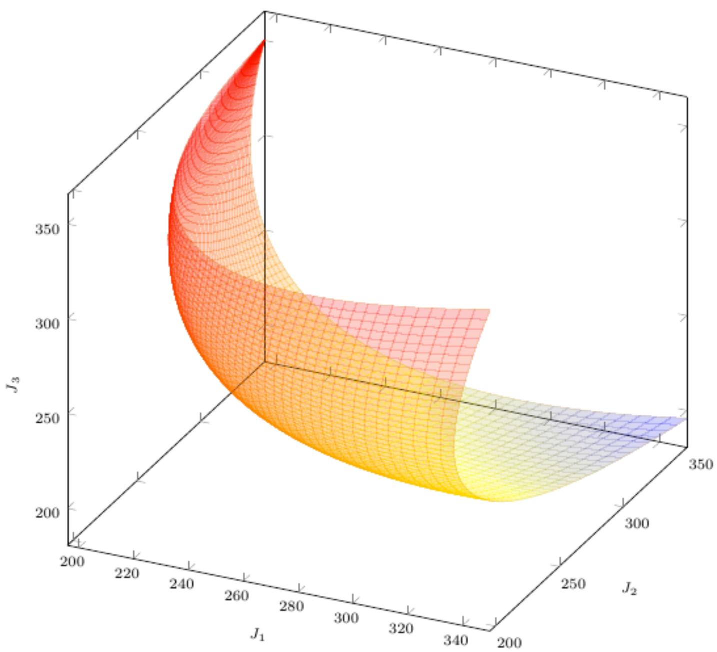


Illustration 3.1: Example of a 3D Pareto front [Stack-exchange, 2016].

Objective functions can vary and are unique to each multi objective optimization problem being solved. The initial proposed equations that will be used for the multi objective optimization process have the following objectives:

- Minimize total cost per product:

$$Min(TC) = VA_0 + NVA_0 + \sum_{i=1}^{S}(VA_i + NVA_i + W_i + E_i) \tag{17}$$

- Minimize product cycle time:

$$Min(CT) = \sum_{i=1}^{S} (VA_i + NVA_i + W_i) \tag{18}$$

- Maximize average resource utilization:

$$Max(\overline{RU}) = \sum_{i=1}^{S} \left(\left\{ \frac{max[t_{mb}, t_{ob}]}{T_t} \right\}_i \right) \tag{19}$$

All optimization process is subject to constraints, but in this example, since the intention is to generalize the optimization process only the non-negative constraint is considered:

Subject to:

IF $NVA_i = 0$ *then* $VA_i \neq 0$;

IF $NVA_i \neq 0$ *then* $VA_i = 0$;

3.4 Summary

Chapter 3 addressed the methodology used to tackle the gaps identified in Chapter 2. This methodology consists in creating a mathematical model that can estimate product cost generically, and includes energy consumption. This cost model also includes rework stations by utilizing learning curves in the estimation. A general cost estimation model that can be used in process simulation, and optimization process is developed.

Chapter 3 also presents the approach in order to generate an optimal QC strategy. This strategy includes rework stations throughout the manufacturing line. The amount of rework stations and location is identified using a GA. Combining the cost estimation model, the simulation process estimations and the GA as steps in the methodology is what allows this study to propose an optimal QC strategy.

Chapter 4: Computational Results and Discussion

Chapter 4 presents a set of several case studies that present the application of the proposed methodology for both objectives presented previously. In particular, Objective 1 has three case studies, and Objective 2 has two case studies. The three case studies for the first objective show how the general cost estimation model that includes energy consumption was obtained and is used. The two case studies for the second objective present the methodology used in order to estimate reworkability and a complete example that generates an optimal QC strategy. Finally, the results obtained by the GA are verified.

4.1 Objective 1: Cost Estimation Mathematical Model Proposed

4.1.1 Case 1 – Manufacturing Process of Solar Panels

This case study will concentrate on solar panel assembly. Different sigma levels will be used in order to identify the change in cost per product when more defective products are found in the process. Solar Panels are an array of several solar cells place together in order to generate electricity. Solar cells are photovoltaic (PV) cells many formed by silicon crystals that have the capability of transforming solar radiation into electricity [Boyle, 2012.]. Solar Panels use Solar cells in order to generate more electricity and obtain a higher energy output [DiLabio, 1998]. The Solar Panel can consist normally from 4 to 60 solar cells arranged in a rectangular form. These Panels input solar radiation and provide electricity as output.

The assembly process of Solar Panel can be easily explained in 5 steps [Solar-World Americas, 2014; Venegas, 2014]. This assembly can be done either automatically using robots or manually. The entire assembly process takes approximately 1 hour plus 25 hours for the silicon curing process. The steps for the assembly are:

1. Stringing cells into solar panels: Solar cells are arranged thought out the entire solar panel.
2. Soldering: The solar cells are soldered first in series and then in parallel. The arrangement depends on the amount of solar cells used for the entire panel.

3. Framing, Junction box and Connectors assembly: The solar panels are covered and laminated with Ethylene vinyl acetate (EVA-hard polymer) to protect the solar cell, framed using a frame (normally a rigid plastic or aluminum), sealed using silicon and finally the Junction box and connectors are assembled on the back of the panel.
4. Silicon curing: The solar panel is left for 24 hours so that the silicon can dry properly.
5. Inspection and shipping: Final inspection for QA is performed and shipping of the panel to the customer performed at this final step.

4.1.1.1 Simulation Model

The assembly process for the solar panel being used for the simulation model is the same as the one described in the previously. Figure 4.1 illustrates the assembly process overview used for the simulation model.

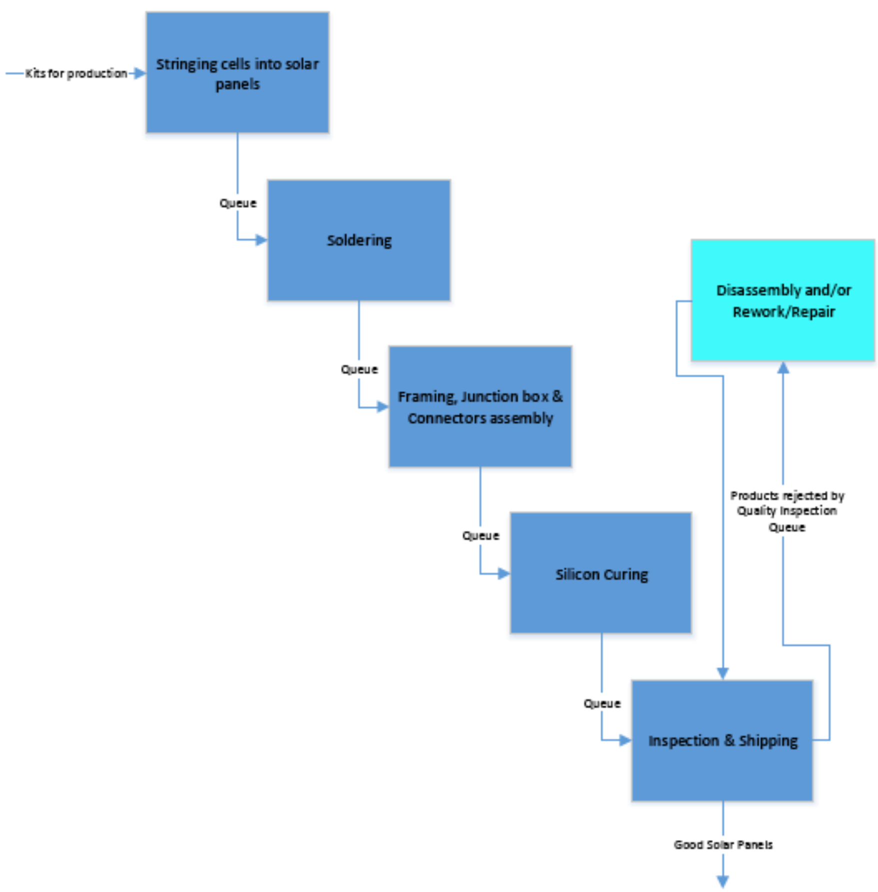


Figure 4.1: Overview of Simulation model.

The simulation model is a Dynamic, Discrete and Stochastic model. The assembly starts with the input of the kits containing all the parts required for the solar panel, and then it goes through the five-assembly process including the QA stage. The product at the QA stage is either accepted and shipped to the customer, or rejected and sent to the rework station. The products in the rework operation are disassembled and reassembled at the same stage and send directly to the quality inspection section again.

The parameters and assumptions used to develop the simulation model are presented in Table 4.1. The simulation model was developed in ARENA® software.

Table 4.1: Simulation parameters and assumptions.

Parameters		
Entities	Solar Panel	All entities are equal and go through the same process, with equal processing times. Initial VA cost of $50, and $1.5/hour of holding cost are assigned.
	Reworked solar panel	Entities that are rejected at inspection and are reworked. Holding cost is changed to $2.5/hour.
Resources	Operator 1	Used for the stringing cells into solar panels operation. Schedule based capacity of 8 hours with 15 minutes break after 3.75 hours and 30 minute break after 6 hours of work. Cost for busy and idle time is equal ($12/hr.).
	Robot	Used for the soldering operation. Fixed based capacity of 1 with pre-empt robot failures with a exponential probability of 50 hours; and maintenance scheduled after 25 cycles for 30 minutes. Cost for busy ($0.5/hr.), cost per use ($1), and no cost assigned when idle.
	Operator 2	Used for the framing, junction box and connectors assembly operation. Same conditions as operator 1 are used.
	Quality Inspector	Used for the inspection and shipping operation. Same conditions as operator 1 are used, except for cost ($15/hr.).
Events	Arrivals	Solar panels kits arrive to the assembly line with an exponential distribution with mean of 4 hours. They arrive in batches of 5 kits.
	Departures	Solar panels leave the system as soon as they pass the quality and shipping inspection process.

Processes	Stringing cells into solar panel	The duration of this process follows a Triangular distribution of (8, 10, 13) minutes per solar panel.
	Soldering	The duration of this process follows a Constant distribution of 3 minutes per solar panel.
	Framing, junction box and connectors assembly	The duration of this process follows a Triangular distribution of (20, 25, 27) minutes per solar panel.
	Silicon curing	The delay time of this process follows a constant distribution of 24 hours per solar panel.
	Inspection and shipping	The duration of this process follows a Triangular distribution of (8, 10, 17) minutes per solar panel.
	Rework station	The duration of this process follows a Uniform distribution of (3, 45) minutes per solar panel. The Rework Operator performs the operation.
Run parameters	Replication length and iterations	The replication length used is 120 Days and 12 replicates.
	Warm-up period	The warm-up period was defined to 2,500 hours to establish steady state.
Assumptions	All buffers for each station have infinite capacity.	
	A single queue is formed in front of each process.	
	All queues are First-In-First-Out (FIFO) rule.	
	No transfer delays are considered between stations.	
	The Inspection and shipping station, detects all defects without knowing in which station is was done.	
	Statistical independence probability is considered for all the time process and defective decision parameter.	
	The system is in steady state and balanced (no changes over time for capacity and process times).	
	Each day consist of only 8 hours considering breaks (1 shift, 7.25 productive hours).	
	All indirect cost to the process such as overhead cost or indirect labor is not considered.	
	Cost of extra materials at the rework station is not considered.	
	All solar panels can be reworked after detecting a defect.	
	Overhead cost of resources is not included. Due to this, a sigma 6 level process is not more expensive (before production) than a sigma 2 level process.	

4.1.1.2 Computational Results

The computational results from the process simulation at sigma level 2 and 6 were obtained and analyzed. The same data was collected for all other sigma levels, and was evaluated. Tables 4.2 and 4.3 illustrate the performance measures of the simulation with the

extreme sigma levels. Even though that not all the parameters are used for the statistical analysis, they allow the user to identify the differences from each simulation.

Table 4.2: Computational results from simulation using 2-sigma quality level.

Per Panel		Average	Half width	Minimum	Maximum
Process times (Min)	VA	1,489.02	0.06	1,480.69	1,498.18
	Rework Time	35.12	0.45	3.00	252.27
	Total Rework	1,700.19	11.89	1,501.25	2,495.69
	Total Non-Rework	1,631.18	12.95	1,656.17	2,464.24
System Cost (USD)	VA	98.04	0.71	119.08	375.96
	Rework	87.81	1.12	7.50	630.68
	Total Rework	278.15	3.68	130.24	1,366.84
	Total Non-Rework	101.59	0.32	96.39	122.99
Solar cells reworked		513.83	22.14	455	555
Resource Utilization (%)	Operator 1	23.76	1.0	21.12	26.02
	Operator 2	56.32	2.0	50.31	61.78
	Quality Insp.	37.89	2.0	33.79	40.64
	Rework Op.	21.49	1.0	19.09	23.30
	Robot	6.23	0.1	5.56	6.82
Overall System cost (USD)		143,547	**Total output (Panels)**		1,166

Table 4.3: Computational results from simulation using 6-sigma quality level.

Per Panel		Average	Half width	Minimum	Maximum
Process times (Min)	VA	1,488.77	0.06	1,481.29	1,497.92
	Rework Time	0.00	0.00	0.00	0.00
	Total Rework	0.00	0.00	0.00	0.00
	Total Non-Rework	1,640.10	18.62	1,482.23	2,558.81
System Cost (USD)	VA	98.02	0.02	96.13	100.26
	Rework	0.00	0.00	0.00	0.00
	Total Rework	0.00	0.00	0.00	0.00
	Total Non-Rework	101.80	0.47	96.34	125.42
Solar cells reworked		0.00	0.00	0	0
Resource Utilization (%)	Operator 1	24.74	1.00	21.43	27.10
	Operator 2	58.59	3.00	50.69	64.59
	Quality Insp.	27.13	1.00	23.24	29.74
	Rework Op.	0.00	0.00	0.00	0.00
	Robot	6.48	0.01	5.62	7.08
Overall System cost (USD)		84,951	**Total output (Panels)**		1,208

4.1.1.3 Statistical Analysis

In order to develop a clear estimation between the sigma level of the process and the cost change, the cost per solar panel produced was calculated for each simulation performed, using the average value:

1. System estimate with 0 defective:
    a. System cost: $84,951
    b. Total Solar panel out of the system: 1,208
    c. Cost per solar panel produced: $70.32
2. System estimate with a 6-sigma level:
    a. System cost: $84,951
    b. Total Solar panel out of the system: 1,208
    c. Cost per solar panel produced: $70.32
3. System estimate with a 5-sigma level:
    a. System cost: $83,912
    b. Total Solar panel out of the system: 1,188
    c. Cost per solar panel produced: $70.63
4. System estimate with a 4-sigma level:
    a. System cost: $82,796
    b. Total Solar panel out of the system: 1,148
    c. Cost per solar panel produced: $72.12
5. System estimate with a 3-sigma level:
    a. System cost: $89,488
    b. Total Solar panel out of the system: 1,149
    c. Cost per solar panel produced: $77.88
6. System estimate with a 2-sigma level:
    a. System cost: $143,547
    b. Total Solar panel out of the system: 1,166

c. Cost per solar panel produced: $123.11

System cost reflects a change between 4 and 3 Sigma and an extreme increase between 3 and 2 Sigma. Solar panels produced shows an unexpected tendency due to the increase between 3 and 2 Sigma; this is due to the fact that more products are being reworked, but the extreme variability of the rework process allows more solar panels to be produced. The cost per solar panel graph illustrates slight increases; the only dramatic change is from 3 to 2 Sigma level.

Solar panels produced analysis

Solar Panels Produced Analysis

The statistical analysis was performed using a significant level of 5%. The residuals evaluation of the Solar Panels produced by the system reflect that values are randomly distributed and are normally distributed.

One-way ANOVA: S.P. Produced versus Sigma Level

```
Source        DF      SS    MS     F      P
Sigma Level    5   41573  8315  1.34  0.260
Error         66  410528  6220
Total         71  452101

S = 78.87   R-Sq = 9.20%   R-Sq(adj) = 2.32%


                                  Individual 95% CIs For Mean Based on
                                  Pooled StDev
Level     N    Mean  StDev  ----+---------+---------+---------+-----
2        12  1168.1   72.0        (----------*----------)
3        12  1153.9   77.7    (----------*-----------)
4        12  1148.2   72.7   (----------*----------)
5        12  1187.6   82.1             (----------*----------)
6        12  1208.1   83.9                  (----------*----------)
Infinit  12  1208.1   83.9                  (----------*----------)
                            ----+---------+---------+---------+-----
                             1120      1160      1200      1240

Pooled StDev = 78.9
```

Figure 4.2: ANOVA for solar panels produced.

Since the required assumptions are true, this allows the ANOVA analysis illustrated in Figure 4.2. They reflect that the amount of Solar panels produced by the system do not change

significantly from one Sigma level to the next. This reflects that the system has an efficient rework process.

System Cost Analysis

The statistical analysis was performed using a significant level of 5%. The residuals evaluation of the overall system cost reflects that values are randomly distributed and are normally distributed. This allows the ANOVA analysis illustrated in Figure 4.3. They reflect that System cost only has a significant variation when moving from a 2 Sigma level to a 3 Sigma level.

One-way ANOVA: System cost versus Sigma Level

```
Source       DF           SS          MS       F      P
Sigma Level   5  34332849828  6866569966  343.00  0.000
Error        66   1321278101    20019365
Total        71  35654127928

S = 4474   R-Sq = 96.29%   R-Sq(adj) = 96.01%


                              Individual 95% CIs For Mean Based on Pooled StDev
Level     N    Mean  StDev      +---------+---------+---------+---------
2        12  143547   6906                                     (-*)
3        12   89488   4008         (-*)
4        12   82796   3600      (*-)
5        12   83912   3662       (*)
6        12   84951   3872       (*-)
Infinit  12   84951   3872       (*-)
                                +---------+---------+---------+---------
                              80000    100000    120000    140000

Pooled StDev = 4474
```

Figure 4.3: ANOVA for System cost.

Cost per Solar Panel Analysis

The statistical analysis was performed using a significant level of 5%. The residuals evaluation of the cost per Solar Panel reflects that values are randomly distributed and are normally distributed. This allows the ANOVA analysis illustrated in Figure 4.4. They reflect that cost per Solar panel has a significant variation when moving from a 2 Sigma level to a 3 Sigma level, and from 3 Sigma level to 4 Sigma level. A change from sigma level 4 to 5 is also identified, but not sufficient to be considered significant.

One-way ANOVA: Cost per S.P. versus Sigma Level

```
Source       DF        SS       MS        F      P
Sigma Level   5  26157.06  5231.41  1273.10  0.000
Error        66    271.21     4.11
Total        71  26428.26

S = 2.027   R-Sq = 98.97%   R-Sq(adj) = 98.90%


                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level     N    Mean  StDev  ----+---------+---------+---------+-----
2        12  123.00   2.39                                    (*)
3        12   77.68   2.23       (*)
4        12   72.20   1.48   (*)
5        12   70.78   2.05  (*)
6        12   70.43   1.95  (*)
Infinit  12   70.43   1.95  (*)
                            ----+---------+---------+---------+-----
                               75        90       105       120

Pooled StDev = 2.03
```

Figure 4.4: ANOVA for cost per solar panel.

4.1.1.4 Regression Analysis for Cost Model of Manufacturing of Solar Panels

A regression analysis was performed in order to develop a model with a 5% error to calculate the cost per product depending on the sigma level the manufacturing line has. The equation obtained from the regression analysis allows the user to calculate their cost without the need of performing the simulation repeatedly. If process sigma changes from day-to-day, or even hour-to-hour, it is possible to estimate cost product with this equation. A coefficient of determination (R-Sq) of 99.0% is achieved. Equation 20 represents this regression analysis.

$$C_p = 391.5 - \left(1452 * \log_{10}\sigma_L\right) + \left(2189 * \left[\log_{10}\sigma_L\right]^2\right) - \left(1098 * \left[\log_{10}\sigma_L\right]^3\right) \qquad (20)$$

where

C_P = *Cost of Production [USD]*

In order for the previous regression model to work for any product, a normalized version of the equation is required. Dividing it by the lowest cost normalized all the data collected from

the simulations of the cost for the solar panels. The same regression analysis was performed, utilizing logarithmic values and a cubic regression. Figure 4.5 shows the results from this regression. Finally equation 21 is developed once the values are normalized and the cost of the product is included in the equation.

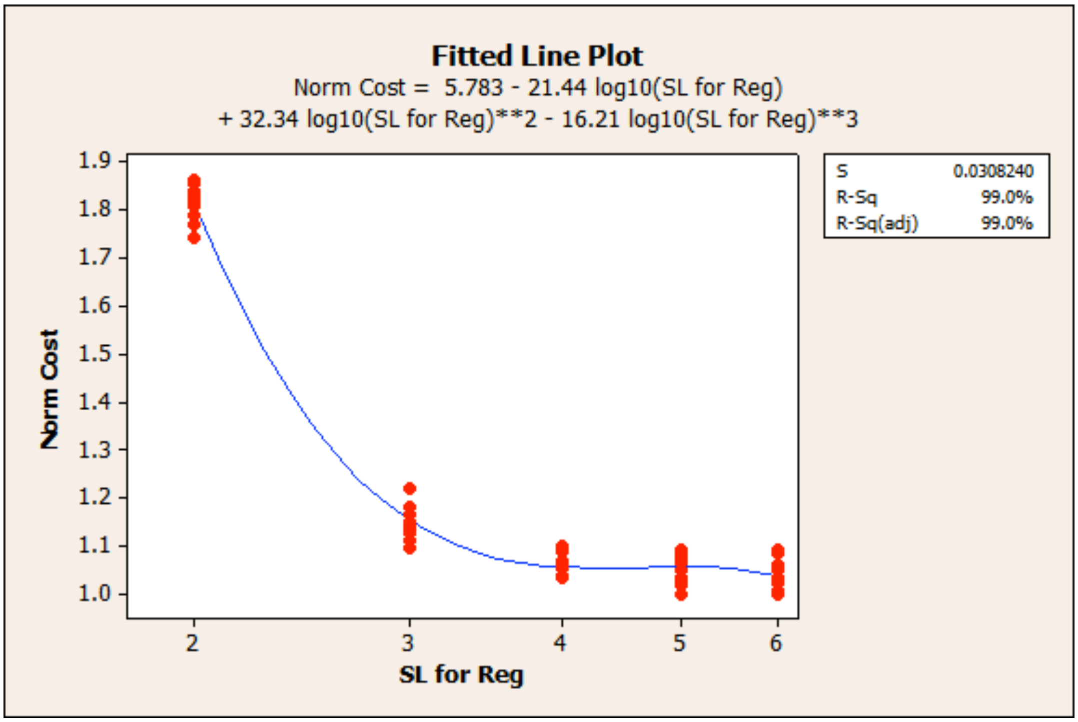


Figure 4.5: Regression analysis with normalized cost values.

$$C_p = P_C * \{5.783 - (21.44 * \sigma_L) + (32.34 * [\log_{10} \sigma_L]^2) - (16.21 * [\log_{10} \sigma_L]^3)\} \qquad (21)$$

where

P_C = *Product Cost [USD]*

4.1.1.5 Conclusion

This study illustrates the changes in cost of an overall solar panel manufacturing system has sigma level changes on the final inspection of the process. This study concentrates only con cost changes for the manufacturing process. It does not consider cost of customer complaints or any type of loss of opportunity cost. It also works under the premise that all defective Solar

panels can be reworked and sold as good products for the same price and with the same quality level.

The regression analysis performed allows the user to estimate cost of their product depending on their quality level. The main contribution of this work is creating the generalized model to estimate this cost. Even though it is a general model depending on product type and cost; it is specific on the type of rework process for the product. If there is more than only a final quality inspection, or the rework is not done offline, the proposed methodology and model will not be very accurate.

4.1.2 Case 2 – Product Cost Estimation Including Environmental Cost

This cost estimation model is intended to be very general and applicable for most manufacturing processes. Due to this reason simplicity and robustness are some key elements that must be achieved with the model. The model only incorporates direct and indirect costs, and a proposed cost called Environmental cost. It is also applicable during the different stages of the manufacturing process and not only once the final product is completed.

4.1.2.1 Assumptions to Develop Cost Estimation Model

In order to develop a cost estimation model that has the ability to derive cost at different stages of the manufacturing process including rework, several assumptions must be made:

- The manufacturing processes that include mores that 1 stage are connected in series.
- Distance between stations and transportation are not included.
- Inspection and decision about an accepted or reject product is done at the end of each station.
- Material required for production is always available. This means that manufacturing time per station is not affected by material not being available.
- Off-line rework (including inspection) is performed after each station when required.
- Cost is different per station, per defect and per rework required process.

- All products and different defects type can be rework. If the entire product or subassembly must be scrapped, then it is completely replaced.
- Cost and type of rework are the same for each criticality level per manufacturing station.

4.1.2.2 Cost Estimation Model of Total Direct Product Cost

The cost estimation model consists of three main sections; each with a specific cost associate to it. The first section is the direct cost. This cost relates to any material or labor that is required in order to perform the rework and the re-inspection of the product. The second section consists of the indirect cost. These costs are also known as the overhead cost and consist of all the cost required to rework the part but that are not direct costs. Some example of this are cost of energy required to run the facility, cost of engineers and supervisors, cost of rent for the facility, etc. The third and final section of the model is the environmental cost. This cost relates to the cost that is caused to the environment due to CO_2 tons emitted.

These three aspects of the cost estimation model, direct, indirect and environmental cost, are the highest level of cost estimation method. They are braked down into more specific sections depending on the step of the process the defect is found, and on the criticality of the defect. Equation 22 specifies the top level cost estimation. Equations 23, 24 and 25 specify the more detail cost.

$$C_T = D + I + E \tag{22}$$

$$D = D_L + D_M \tag{23}$$

$$I = I_{CH} * I_T \tag{24}$$

$$E = SCC * T_{CO2} \tag{25}$$

where

C_t *Total Cost [USD]*

D	*Direct Cost [USD]*
I	*Indirect Cost [USD]*
E	*Environmental Cost [USD]*
D_L	*Direct Labor [USD]*
D_M	*Direct Materials [USD]*
I_{CH}	*Indirect cost per hour [USD]*
I_T	*Indirect time required [USD]*
SCC	*Social Cost of* CO_2 *per ton [USD]*
T_{CO2}	*Tons of* CO_2 *produced [Metric tons]*

The cost estimation model requires a concrete process in order to work correctly with the assumptions mentioned previously. This process is illustrated in Figure 4.6.

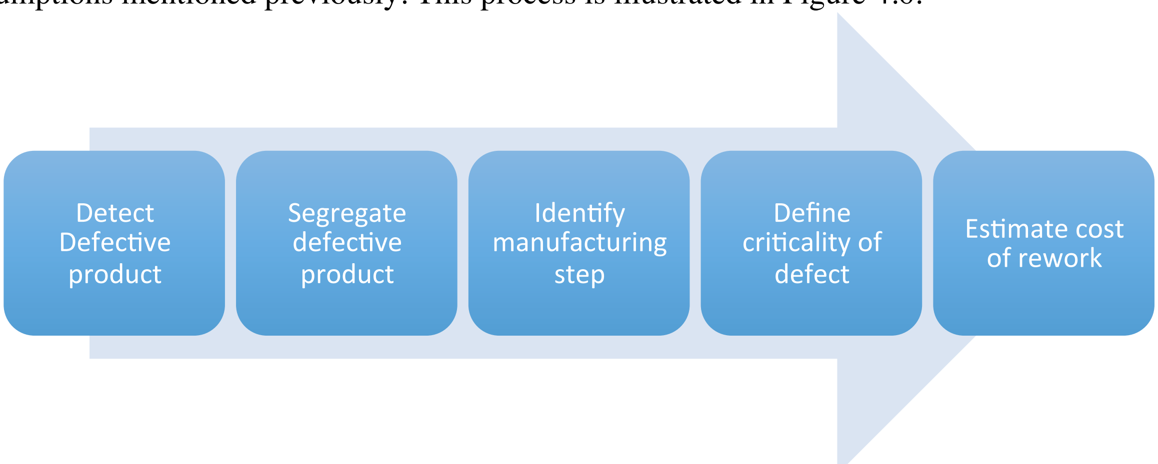


Figure 4.6: Cost estimation methodology.

The 5^{th} steps of the cost estimation methodology are required and may not be performed in the specific order presented in Figure 4.6, but all steps must be performed in order to estimate cost. This proposed methodology does not deal with the process of how to detect a defective product nor which characteristics must be achieved to consider it as defective. This detection is what initiates the cost estimation process and there is no need of any estimation if no defect is

found. Once the defect has been detected, it must be segregated in order to perform the cost estimation and the off-line rework process (as established as one of the assumptions). The identification of the manufacturing step and the criticality of the defect must be performed in order to estimate the cost. If the product is identified at a later stage of the rework, a higher cost is required due to disassembly or a more complex rework. Criticality of the defect is also directly proportional to the defect; higher criticality of defect means higher rework cost.

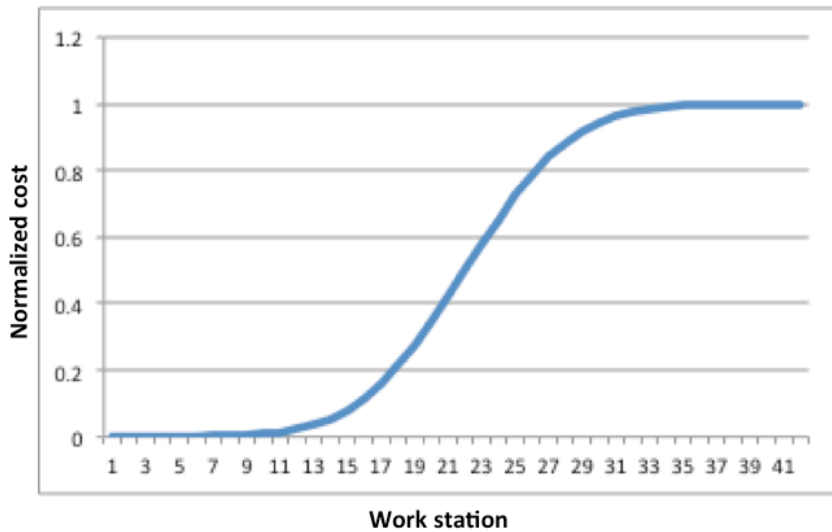


Figure 4.7: Cumulative normal distribution cost.

The cost of the product during the manufacturing process is assumed to follow a cumulative normal distribution function. This function is illustrated on Figure 4.7, where a total of 42 steps are considered for the manufacturing process (X-axis) and the cost goes from 0 to 1 (which represents the total cost). Utilizing this function shape allows the methodology to assign less cost when the product is barely beginning the manufacturing process, the cost increase significantly as it goes through the middle stages where most transformation is done, and finally low cost is assigned for final process which normally are aesthetic, packaging and/or quality testing.

The cost estimation increase for the criticality of defect is expected to increase linearly. The FMEA severity rating has 6 different levels; this implies that every time criticality of the

defect increases a level, the cost also increases a 17% for the rework. The cost estimation for each defect must be calculated individually and is very specific case-by-case basis. In order to estimate a general case the following general equation can be used (Equation 26):

$$C_T = (D_L + D_M) + (I_{CH} * I_T) + (SCC * T_{CO2}) \tag{26}$$

Equations 27, 28, 29 and 30 are specific to Direct Material cost, Direct Labor cost, and Indirect cost per hour:

$$D_L = (\%\ due\ to\ defect\ criticality\ level) * (\%\ of\ work\ already\ performed) * (\%\ of\ cost\ from\ D_L) * (Total\ product\ cost) \tag{27}$$

$$D_M = (\%\ due\ to\ defect\ criticality\ level) * (\%\ of\ cost\ already\ incured) * (\%\ of\ cost\ from\ D_M) * (Total\ product\ cost) \tag{28}$$

$$I_{CH} = \frac{(\%\ of\ cost\ from\ I) * (Total\ product\ cost)}{(Hours\ required\ to\ manufacture\ product)} \tag{29}$$

$$T_{CO2} = (Total\ amount\ of\ CO_2\ of\ the\ process) * (\%\ of\ work\ already\ performed) \tag{30}$$

4.1.2.3 Theoretical Numerical Example to Test Cost Estimation Mathematical Model

In order to use the proposed model, a simple numerical example was developed. This example does not reflect any specific real life product or manufacturing process, and it serves the only purpose of exemplifying the methodology.

Assume that a product is being manufactured which contains 42 steps in the process. The cost of the process follows a normal cumulative distribution. The cost due to criticality of the defect is almost linear with the first 5 criticality levels increasing the cost by a factor of 15% and the last criticality defect a factor of 25%. The increments of cost for this example are based on

the total cost of production of the product. For this example, in order to make it easy, a total cost of $100.[00] will used for the calculations. A 30% of this amount is attributed to direct labor, 40% to direct materials, and the rest to indirect costs. The total manufacturing process takes 21 hours. The rework is expected to last for 3 hours. The total amount of CO_2 emissions for this process is 0.5 tons for the total process. Depending on the step where the defect is identified, the emissions of CO_2 are calculated linearly. The 3% average SCC will be used. Equation 31, 32, 33, 34 and 35 will be used for the cost estimation calculation.

The following calculations are done assuming a defect of severity level III is found at station 20 of the manufacturing process. This is a simple example that can be used for any severity and station:

$$D_L = (0.45) * \left({}^{20}/_{42}\right) * (0.30) * (100) = 6.428 \quad (31)$$

$$D_M = (0.45) * (0.2742) * (0.40) * (100) = 4.9356 \quad (32)$$

$$I_{CH} = \frac{(0.3)*(100)}{(21)} = 1.428 \quad (33)$$

$$T_{CO2} = (0.5) * \left({}^{20}/_{42}\right) = 0.238 \quad (34)$$

$$C_T = (6.428 + 4.9356) + (1.428 * 3) + (39 * 0.238) = 24.9296 \quad (35)$$

Considering this hypothetical example, a defect of criticality III is found after 48% of the manufacturing is complete; a total cost of $24.[93] must be added to the total cost of the product due to the rework required. As the criticality of the defect increases, and/or the process advances, the cost of rework also increases. Assuming the same defect is found on the last station of the process, the cost increases to $55.[28]. The calculations are shown below. Knowing this

relationship and being able to estimate the rework cost, manufacturers can make decisions faster and more accurate on the decision of reworking vs. scrapping a product.

$$C_T = (13.5 + 18) + (1.428 * 3) + (39 * 0.5) = 55.284 \quad (36)$$

4.1.2.4 Conclusion

This work illustrates how estimate the cost of a rework process once the total cost of the product is known, the time required for the rework is known and the amount of CO_2 emissions are also known. The model incorporates the basic cost estimation factors such as direct and indirect cost, but also considers a new proposed environmental cost to the estimation.

The cost of a rework increases directly proportionally to the step of the manufacturing process where the defect is found, and to the criticality of this defect. These two aspects are the ones that drive the cost of rework up or down. The objective of this model is not to reduce the cost of the rework, but to give a fast cost calculation method for the required rework. Manufacturers can use this tool as a decision making tool.

This model is the first step in order to develop a complete, robust and efficient cost estimation mechanism for rework processes. The future work that must be performed is to include more factors into the environmental cost. Currently only tons of CO_2 emissions are used, but factors such as GHGs and soil and water contamination must also be included to develop a robust model.

Overall the model does fulfill the requirement of calculating a rework cost for a defective product found in a manufacturing process. The cost includes the direct, indirect and environmental cost, and allows the user to estimate the total rework cost. This cost can be used as a decision making tool for manufacturing companies in order to decide to rework or scrap any defective process. The benefit of this model is that it can be applied in most manufacturing settings due to its simplicity.

4.1.3 Case 3 – Single server methodology example

This is a single server process with the off-line rework station. This is the simplest system that can be evaluated, and even though not very realistic, it does allow the approach to be proven. The process shown in Figure 4.8 and explained previously will be followed.

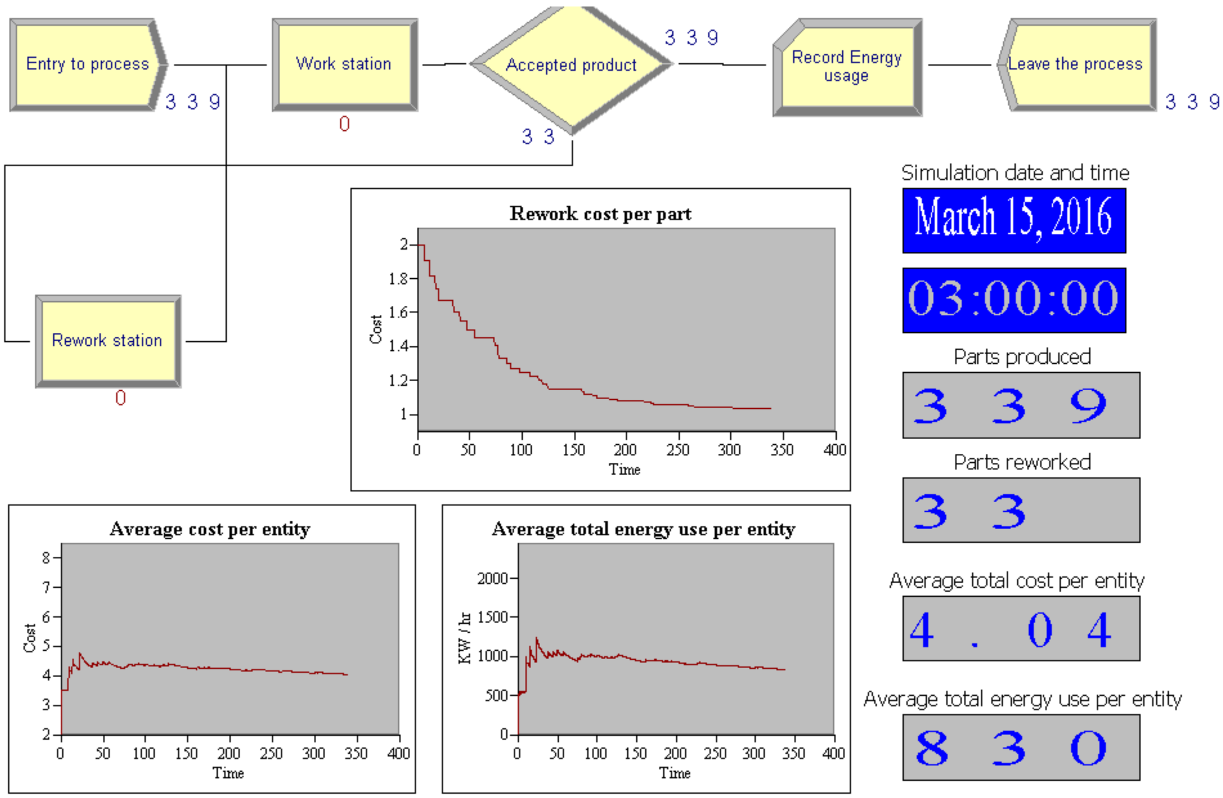


Figure 4.8: System dashboard presenting key performance indicators, and showing process steady state.

The process simulation is developed in the Arena software. Figure 4.8 shows the process being modeled. It consists of a single server that uses 1 machine and 1 operator with an offline rework station with the same configuration as the server. This is the simplest system possible in order to shows the system dashboard where the user can see the change of the parameters being evaluated as time advances.

After the simulation has been completed the WIP is analyzed to evaluate if a warm-up time is required. In the current example a warm-up period is not required, Figure 4.9 shows the

graph of WIP. To define the stopping criteria the graphs of cost per entity and average total cost per entity are evaluated. The stopping criterion was defined to be 400 hours, because the graphs show steady state conditions for the system. The amount of iterations was calculated to be 4.9 for this example.

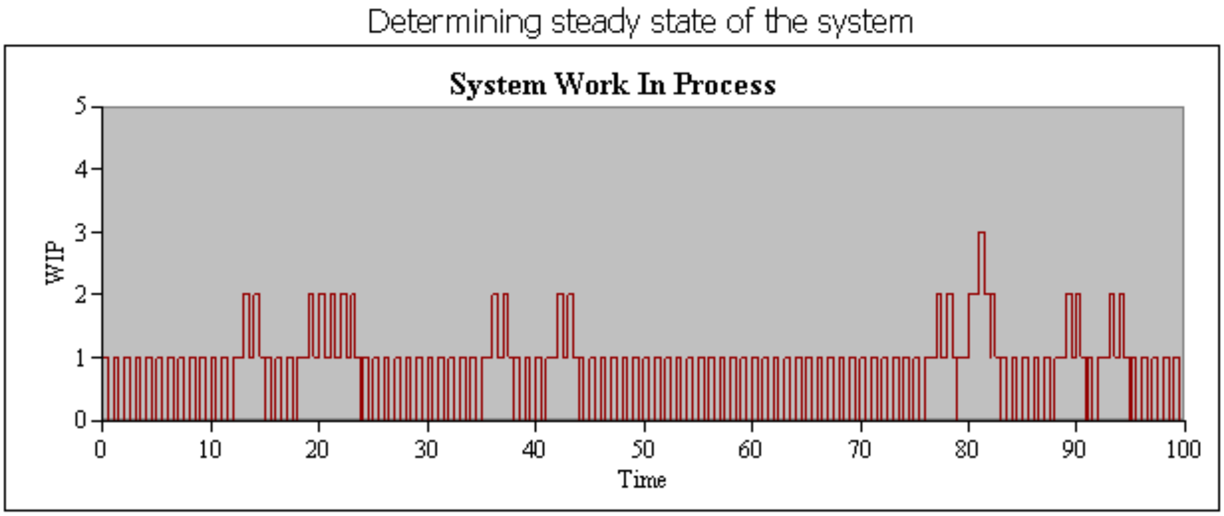


Figure 4.9: WIP for the system on the first 100 hours.

Several simulations were ran for the quality levels of 69.1%, 93.33%, 99.38%, 99.977%, 99.99966% (representing sigma levels from 2σ to 6σ [Michael, 2004]) and 100%. The simulation time per run was less than one minute. Once the reports for each simulation are generated, an ANOVA is developed to evaluate the statistical difference between the quality levels.

Figure 4.10 shows the Box plot obtained from the ANOVA analysis for Cost, Energy and Total Output (calculated using equations 1, 5 and 6). Cost and Energy usage are clearly different for sigma's 2 and 3 and equal for 4 and higher; whereas Output mean changes, but there is no statistical difference in populations. The p-values for total cost and energy usage were less than 0.005 for both parameters, for total output, the p-value obtained were 0.159, which supports the conclusion drawn previously.

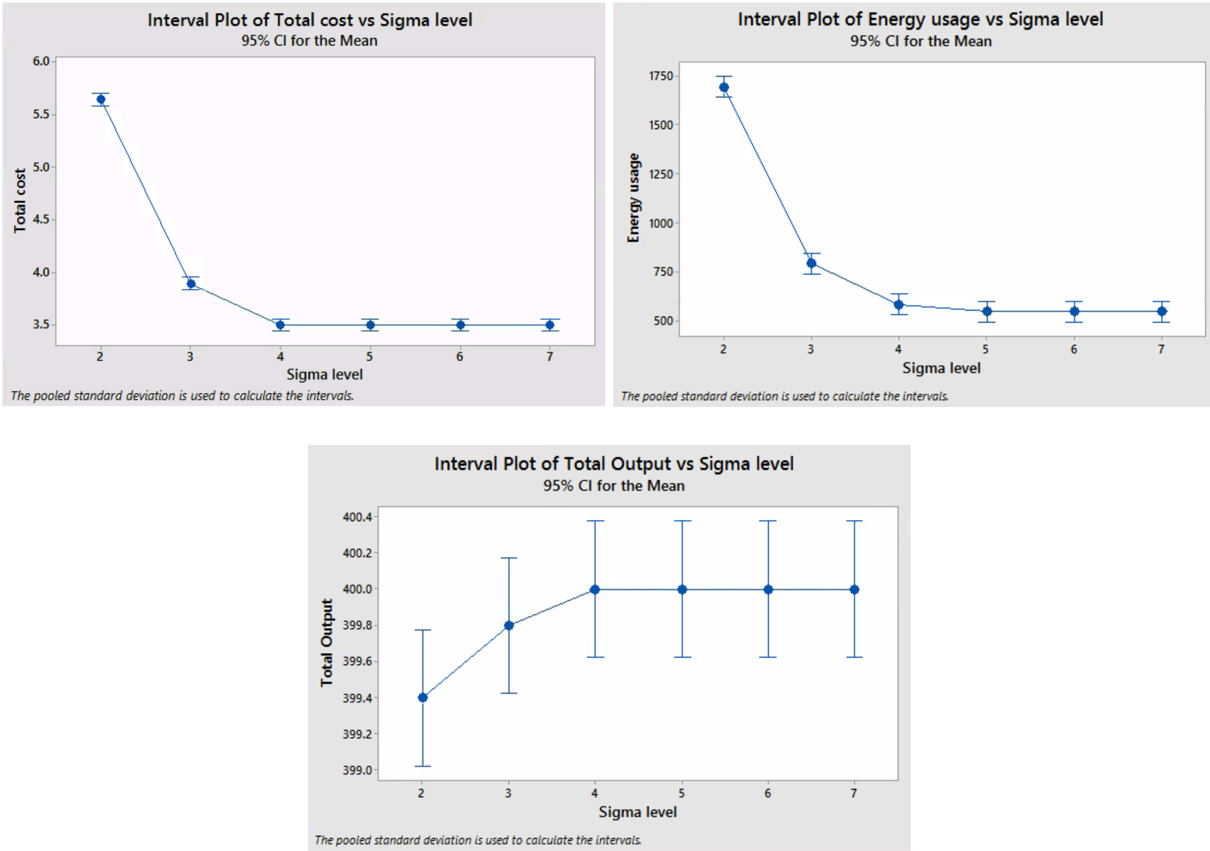


Figure 4.10: Box plot for considered parameters.

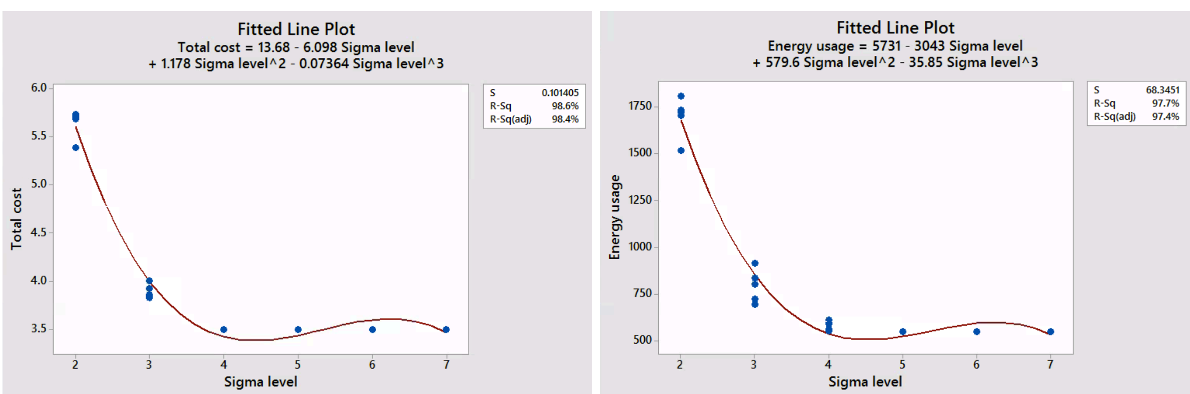


Figure 4.11: Linear regression for considered parameters.

After identifying that only cost and energy consumption change significantly depending on Sigma level, the linear regression analysis is performed on these two parameters. Figure 4.11 shows the linear regression performed using a cubic equation resulting on a R-Square value of

98.6% and 97.4% for cost and energy respectively. With the equations set for the current simulation, the equation can be normalized in order to generalize the trend for cost and energy usage. Equation 37 is the result from this normalization for total cost and equation 38 is for total energy usage

$$TC = P_C * (2.359 - 1.043\sigma + 0.2010\sigma^2 - 0.01255\sigma^3) \quad (37)$$

$$TE = P_C * (3.172 - 1.684\sigma + 0.3207\sigma^2 - 0.01984\sigma^3) \quad (38)$$

This can be used for any system with the same architecture as the on presented before. This system is known as a single server manufacturing process. P_C on equations 37 and 38 represents the product cost (assuming no defects or rework) for which the estimation is being used. The regression analysis performed allows the user to estimate cost and energy usage of their product depending on their designated quality level.

4.2 Objective 2: Optimal Quality Control Strategy Determination

4.2.1 Case 4 – Cost and Reworkability Breakeven Point

The EnSeal laparoscopic device is a Medical device manufactured by Johnson and Johnson®. This device is used for many different types of laparoscopic surgeries with the main intention to cut and seal (thru cauterization) vessels up to 7mm in diameter. The product is shown on illustration 4.1. This specific case study is based on the work done under the thesis "Identification of Rework station location to reduce Cost and enhance Reworkability using Design for Disassembly [Saavedra, 2012].

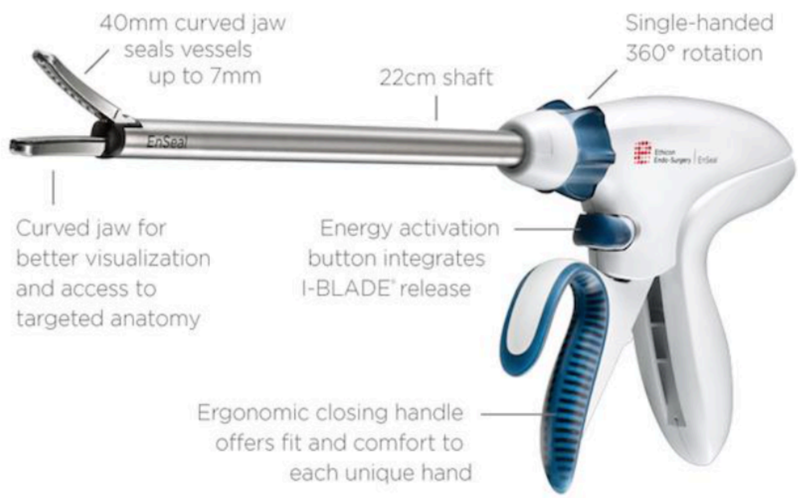


Illustration 4.1: EnSeal laparoscopic surgical device [Ethicon, 2010].

The manufacturing process of the EnSeal devices is manufactured in two steps. The first step is to assembly the shaft of the knives and the second step is to assemble the entire device. Figure 4.12 shows the first part of the process, which is the assembly of the shaft. This process is mostly manual but requires extreme precision because the assembly and the inspections are done using microscopes because the parts being assembled are particularly small.

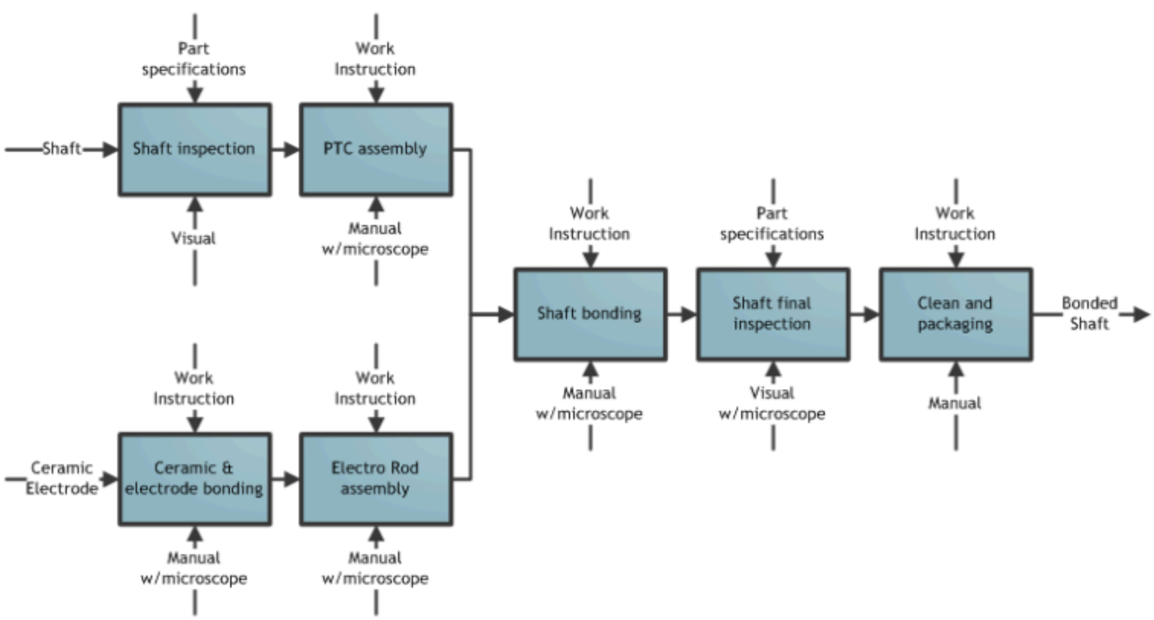


Figure 4.12: EnSeal shaft assembly process.

Figure 4.13 shows the second part of the process, which is the assembly of the instrument. This assembly begins with the shaft subassembly produced in the first section of the process. This process is not put together because it is manufactured in different assembly lines.

Figure 4.14 shows a layout of the entire production line and how it is that the two assembly lines are interconnected. The bolded section of the assembly line is the shaft manufacturing line (fist part of entire manufacturing process) and the part that is not bolded corresponds to the second part of the assembly, which is the instrument assembly. Two different manufacturing lines are shown (Line 108 and Line 109), for purpose of this methodology only one assembly line will be considered.

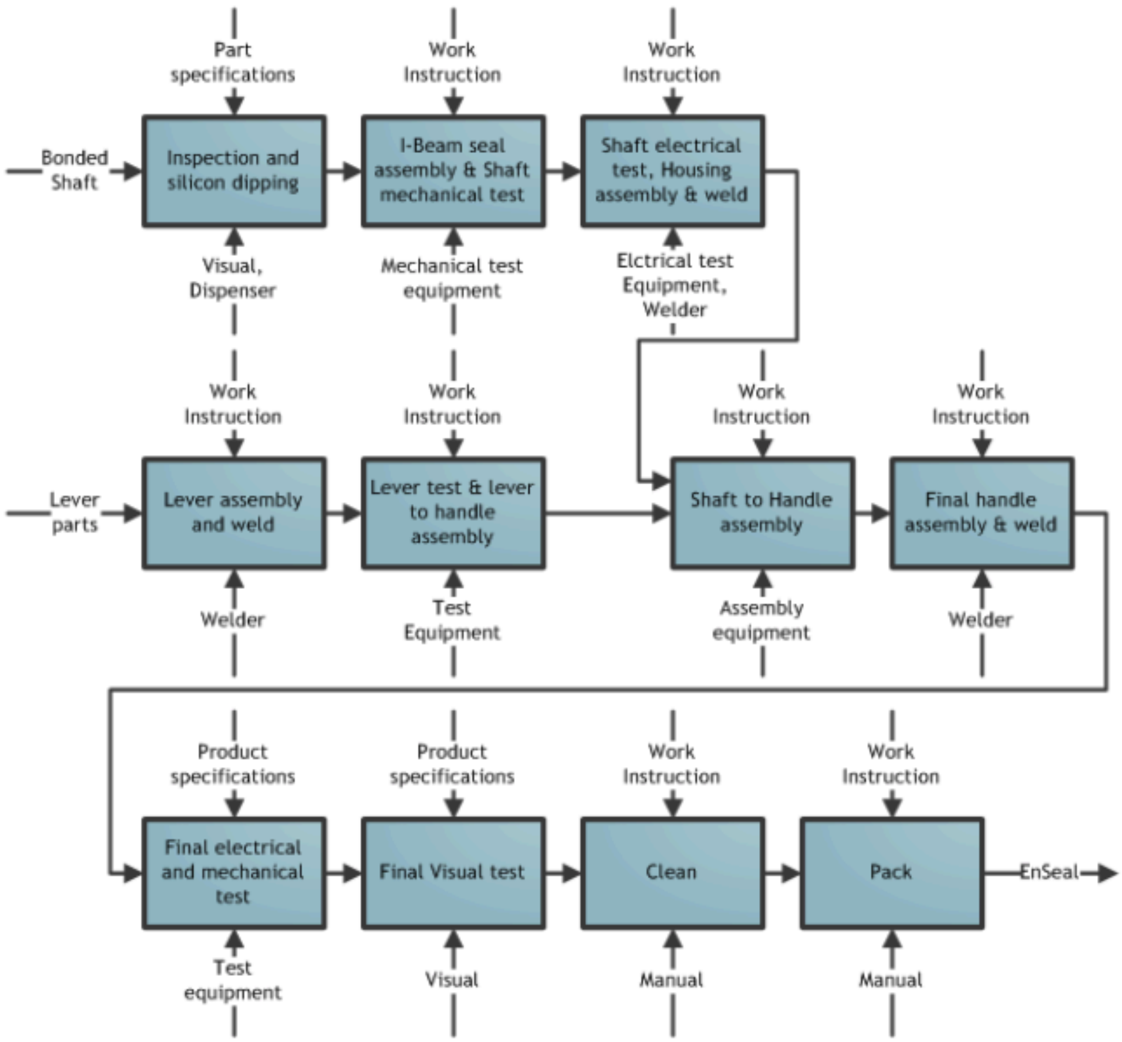


Figure 4.13: EnSeal instrument assembly process.

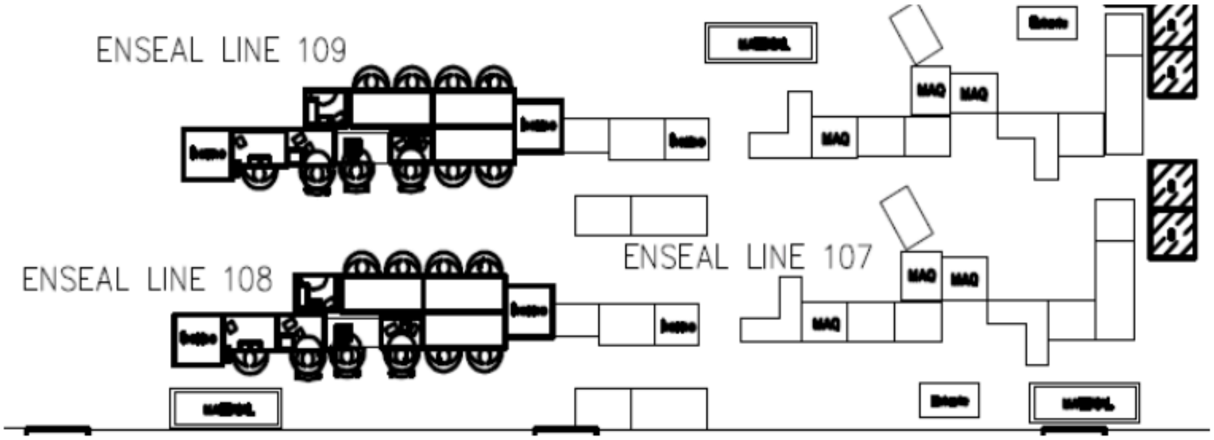


Figure 4.14: EnSeal assembly line layout.

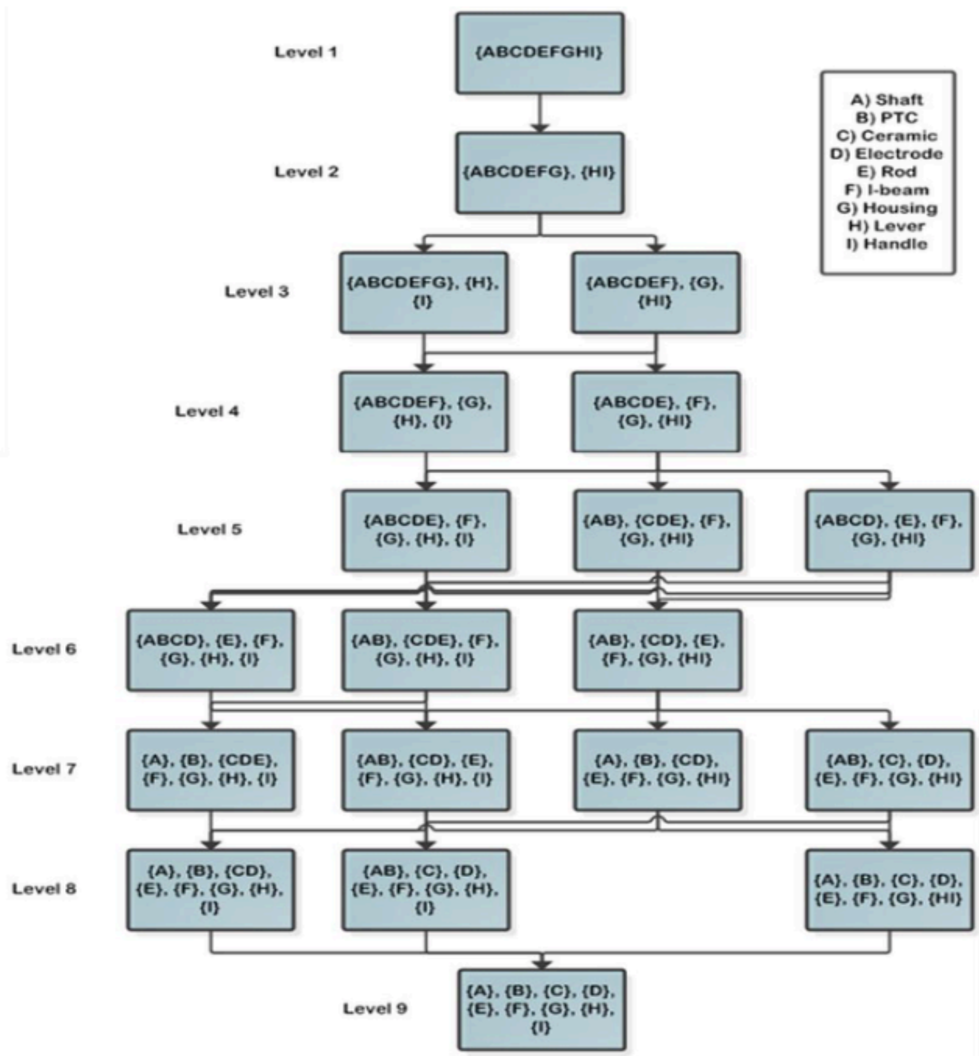


Figure 4.15: EnSeal direct graph disassembly model.

The Disassembly modeling must be performed before calculating the reworkability score at each step of the process. This provides the information on how many different disassembly levels there are of this process. The identification of all of these levels will facilitate the calculation of the reworkability scores of each workstation. Figure 4.15 shows the disassembly model using the direct graph methodology.

In order to obtain the optimal single rework station location the methodology on Figure 4.16 was followed. The first step of the methodology is to identify all the process steps of the assembly process. Figures 4.12 and 4.13 show all the steps. The second step is to calculate the cost of the product in each of these steps. The cost shown in Table 4.4 are not the real costs of manufacturing this product, they are close estimates. Due to company policies the exact cost cannot be used.

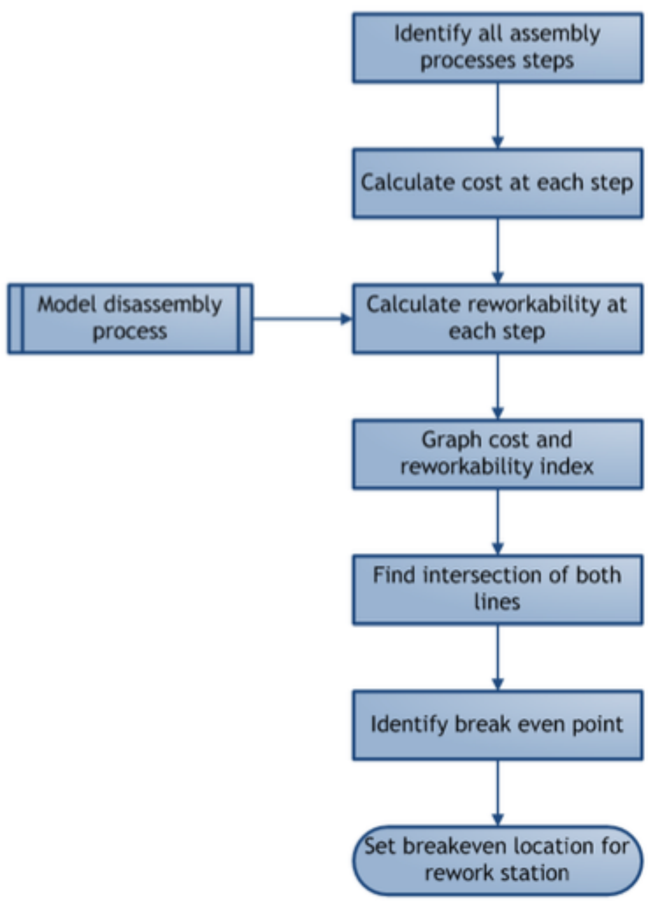


Figure 4.16: Methodology steps to find rework station location.

Table 4.4: Assembly process steps cost of EnSeal device.

Process step	Approximate cost USD
Shaft Inspection	$0.05
PTC Assembly	$0.75
Ceramic / Electrode Bonding (TRIO)	$0.60
Electro Rod Assembly	$2.00
Bonding Shaft	$1.25
Shaft Final Inspection	$0.05
Shaft Clean and Pack	$0.05
Bonded Shaft Inspection & Silicone Dipping	$0.10
I-Beam Seal Assembly & Shaft Mechanical Test	$2.15
Shaft Electrical Test Housing Assembly and Weld	$3.85
Lever Assembly & Weld	$2.50
Lever Test & lever to Handle Assembly	$1.30
Shaft to Handle Assembly	$0.75
Final Handle Assembly & Weld	$3.10
Final Electrical & Mechanical Test	$1.00
Final Visual Test	$0.10
Clean	$0.05
Pack	$0.35
Total	**$20.00**

The third step is to calculate the reworkability of each step of the process using the 14 guidelines of design for disassembly. The same assumptions used in the trocars example for parallel operations apply also for this assembly process. Weights of this process have been assigned according to designer and company experience and priorities. Table 4.5 shows the calculation of the reworkability of the assemblies' stations 1 and 2. Table 4.6 shows the equations used to calculate the reworkability scores. In this example there are some steps of the process were the scores of the reworkability do not change because those steps are of inspection of cleaning only and the product is not being affected. If these processes could be done before

the breakeven point between the reworkability and cost, a mayor benefit could be obtained. In many cases this is not possible, but if during the design of the production process this can be achieved it should be done.

Table 4.5: Reworkability of EnSeal device at station 1 and 2.

		Station 1		Station 2	
17 disassembly guidelines	Weight	Score	Reworkability Score	Score	Reworkability Score
Are all access points obvious or indicated on the product?	1	10	0.192307692	10	0.192307692
Are joints and fasteners easily accessible?	3	10	0.576923077	10	0.576923077
Is part able to disassemble maintaining product stability?	5	10	0.961538462	10	0.961538462
Are all joining elements of equal type?	4	10	0.769230769	9	0.692307692
Is destructive technique safe and will not harm people or affect reusable components?	5	10	0.961538462	10	0.961538462
Can reusable parts be cleaned easily and without damage?	5	10	0.961538462	10	0.961538462
Are incompatible materials easily separated?	4	10	0.769230769	9	0.692307692
Are all component interfaces simple and reversibly separable?	2	10	0.384615385	10	0.384615385
Is the product or system organized into hierarchical modules by aesthetic, repair, and end-of-life protocol?	3	10	0.576923077	10	0.576923077
Are reusable/swappable platforms, modules, and components implemented?	5	10	0.961538462	10	0.961538462
Does the product have only the minimal number of parts it requires?	3	10	0.576923077	10	0.576923077
Are compatible adhesives, labels, surface coatings, pigments, etc used?	4	10	0.769230769	9	0.692307692
Is only one disassembly direction without reorientation required?	2	10	0.384615385	10	0.384615385
Are all joints separable by hand or only a few, simple tools required?	1	10	0.192307692	10	0.192307692
Is the number and length of operations for detachment minimized?	2	10	0.384615385	10	0.384615385
Are materials marked in molds with types and reutilization protocols?	1	10	0.192307692	10	0.192307692
Is a shallow or open structure used for easy access to subassemblies?	2	10	0.384615385	10	0.384615385
Total Reworkability score at production station 'j'	52	170	10	167	9.769230769

Table 4.6: Reworkability of EnSeal device at station 1 and 2.

	17 disassembly guides	Weight	Score	Reworkability Score
1	Are all access points obvious or indicated on the product?	W_a	S_a	$S_a * \left(\frac{W_a}{\sum W_i}\right) = R_a$
2	Are joints and fasteners easily accessible?	W_b	S_b	$S_b * \left(\frac{W_b}{\sum W_i}\right) = R_b$
3	Is part able to disassemble maintaining product stability?	W_c	S_c	$S_c * \left(\frac{W_c}{\sum W_i}\right) = R_c$
4	Are all joining elements of equal type?	W_d	S_d	$S_d * \left(\frac{W_d}{\sum W_i}\right) = R_d$
5	Is destructive technique safe and will not harm people or affect reusable components?	W_e	S_e	$S_e * \left(\frac{W_e}{\sum W_i}\right) = R_e$
6	Can reusable parts be cleaned easily and without damage?	W_f	S_f	$S_f * \left(\frac{W_f}{\sum W_i}\right) = R_f$
7	Are incompatible materials easily separated?	W_g	S_g	$S_g * \left(\frac{W_g}{\sum W_i}\right) = R_g$
8	Are all component interfaces simple and reversibly separable?	W_g	S_g	$S_g * \left(\frac{W_g}{\sum W_i}\right) = R_g$
9	Is the product or system organized into hierarchical modules by aesthetic, repair, and end-of-life protocol?	W_k	S_k	$S_k * \left(\frac{W_k}{\sum W_i}\right) = R_k$
10	Are reusable/swappable platforms, modules, and components implemented?	W_l	S_l	$S_l * \left(\frac{W_l}{\sum W_i}\right) = R_l$
11	Does the product have only the minimal number of parts it requires?	W_m	S_m	$S_m * \left(\frac{W_m}{\sum W_i}\right) = R_m$
12	Are compatible adhesives, labels, surface coatings, pigments, etc used?	W_o	S_o	$S_o * \left(\frac{W_o}{\sum W_i}\right) = R_o$
13	Is only one disassembly direction without reorientation required?	W_p	S_p	$S_p * \left(\frac{W_p}{\sum W_i}\right) = R_p$
14	Are all joints separable by hand or only a few, simple tools required?	W_q	S_q	$S_q * \left(\frac{W_q}{\sum W_i}\right) = R_q$
15	Is the number and length of operations for detachment minimized?	W_s	S_s	$S_s * \left(\frac{W_s}{\sum W_i}\right) = R_s$
16	Are materials marked in molds with types and reutilization protocols?	W_t	S_t	$S_t * \left(\frac{W_t}{\sum W_i}\right) = R_t$
17	Is a shallow or open structure used for easy access to subassemblies?	W_u	S_u	$S_u * \left(\frac{W_u}{\sum W_i}\right) = R_u$
	Total Reworkability score at production station ‘j’	$\sum_{i=0}^{i=n} W_i$	$\sum_{i=0}^{i=n} S_i$	$\sum_{i=0}^{i=n} R_i$

The following step is to calculate the intersection between the two lines (cost and re-workability). In order to do this both index must be calculated. Table 4.7 shows the summary of the coast and reworkability scores and the calculated index for both factors. Figure 4.17 illustrates the data obtained from the Table 4.7 in a graph. This graph allows easily identifying the intersection point of both factors in order to determine the optimal rework station location.

Table 4.7: Summary of cost and reworkability for EnSeal.

				Index	
Station	Cost	Cum. Cost	Reworkability	Cost	Reworkability
1	$0.10	$ 0.10	10	0.001618	1
2	$2.75	$ 2.85	9.769230769	0.046117	0.976923077
3	$5.60	$ 8.45	9.192307692	0.136731	0.919230769
4	$4.20	$ 12.65	8.865384615	0.204693	0.886538462
5	$5.25	$ 17.90	7.942307692	0.289644	0.794230769
6	$0.10	$ 18.00	7.942307692	0.291262	0.794230769
7	$0.15	$ 18.15	7.557692308	0.293689	0.755769231
8	$0.90	$ 19.05	7.480769231	0.308252	0.748076923
9	$7.80	$ 26.85	6.615384615	0.434466	0.661538462
10	$10.85	$ 37.70	6.615384615	0.610032	0.661538462
11	$7.45	$ 45.15	5.673076923	0.730583	0.567307692
12	$3.30	$ 48.45	5.076923077	0.783981	0.507692308
13	$2.75	$ 51.20	4.519230769	0.828479	0.451923077
14	$9.10	$ 60.30	3.692307692	0.975728	0.369230769
15	$1.00	$ 61.30	3.692307692	0.991909	0.369230769
16	$0.10	$ 61.40	3.692307692	0.993528	0.369230769
17	$0.05	$ 61.45	3.692307692	0.994337	0.369230769
18	$0.35	$ 61.80	3.384615385	1	0.338461538
Total/Max	$61.80		10		

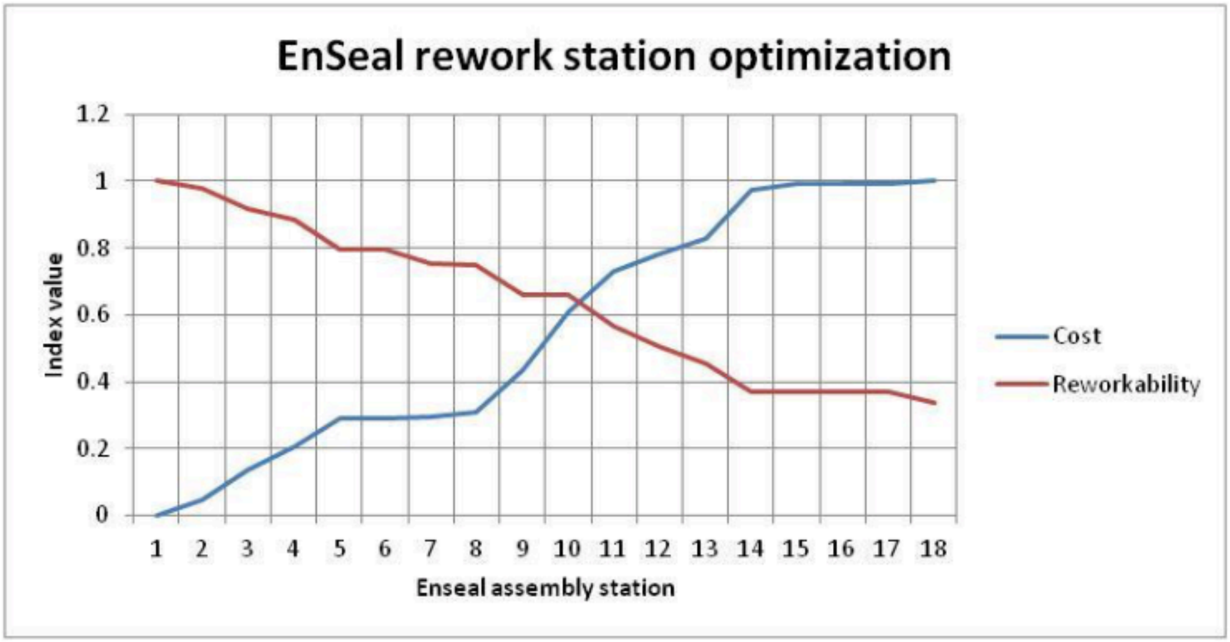


Figure 4.17: Graph of EnSeal rework station.

All of these calculations were done using the Microsoft Excel® software. As the methodology implies the rework station must be placed after the 10th station of the process. The 10th station is "Shaft Electrical Test Housing Assembly and Weld"; and after this station comes the Lever assembly and welding process. What this implies is that there is no point on reworking the assembly after it has been welded. This is because the reworkability of the product is too high and it becomes more costly and complex to rework the product at the manufacturing facility than to scrap it. The product can be reworked or recycled after it has been scraped but it would not be done as part of the assembly process to recuperate parts or components of the defective product.

4.2.2 Case 5 – Design of Experiment Solar Panels Test and Optimal Amount and Location of Rework Stations

The manufacturing process of Solar panels presented in case study 1 is used in order to test the entire methodology developed and proposed in this study. Figure 4.18 shows the simulation model for this manufacturing process. Discrete event Simulation is used for this case study for the time based process simulation. The software used for the process simulation is Arena® due to its robustness for discrete event simulation. This manufacturing process shows the

6 main stations used for solar panel manufacturing. For the final optimization process all 20 stations that include sub-assemblies are considered.

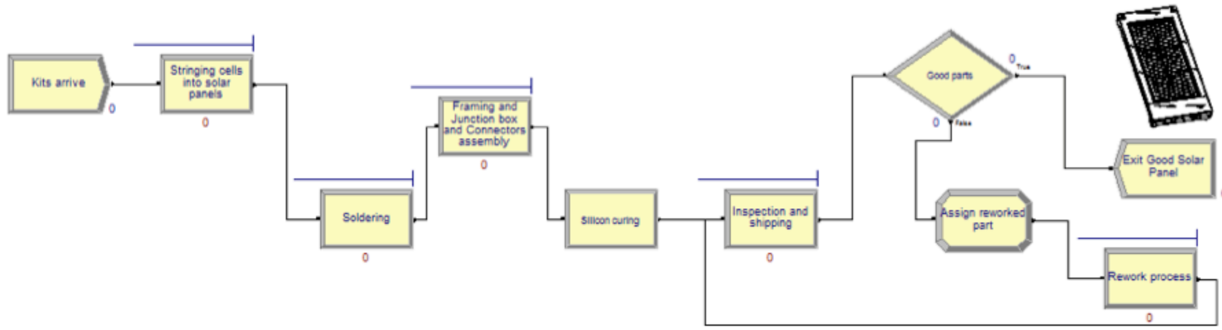


Figure 4.18: Process simulation for solar cell manufacturing process.

The first step of the methodology is to develop a screening DOE in order to identify the significant factors that affect the response variables that have been selected as critical for the manufacturing process. The factors being evaluated are the Input PDF, the Process PDF, the Input rate (pcs. / hr.), Process rate (pcs / hr.), QC workstation rate (pcs. / hr.), the Number of rework stations, and the Quality Sigma Level. The response variables selected are Cycle time (hours), cost (USD) and resource utilization (%). A fractional factorial was developed and the required simulation runs are presented in Table 4.8. The triangular distributions used were TRIA (0.9, 1, 1.1) and TRIA (1.8, 2, 2.2); and the sigma level of 2 represent a yield of 69.1% while a 6 sigma is 99.977% yield.

Table 4.9 shows the results obtained for the simulations for each of the required combinations for the Fractional Factorial. Appendix 1 contains two full reports from the simulation performed. The Fractional Factorial design uses a Resolution of IV in order to estimate the main effects of two factors interaction. This does evaluate the two-factor effect, but these may be combined with other two factors interaction.

Table 4.8: Fractional factorial simulation runs.

Input PDF	Process PDF	Input rate	Process rate	QC rate	Rework rate	No. Rework stations	Quality Sigma level
Constant	Constant	1	1	1	1	1	2
Triangular	Constant	1	1	1	2	6	5
Constant	Traingular	1	1	2	1	6	5
Triangular	Traingular	1	1	2	2	1	2
Constant	Constant	2	1	2	2	6	2
Triangular	Constant	2	1	2	1	1	5
Constant	Traingular	2	1	1	2	1	5
Triangular	Traingular	2	1	1	1	6	2
Constant	Constant	1	2	2	2	1	5
Triangular	Constant	1	2	2	1	6	2
Constant	Traingular	1	2	1	2	6	2
Triangular	Traingular	1	2	1	1	1	5
Constant	Constant	2	2	1	1	6	5
Triangular	Constant	2	2	1	2	1	2
Constant	Traingular	2	2	2	1	1	2
Triangular	Traingular	2	2	2	2	6	5

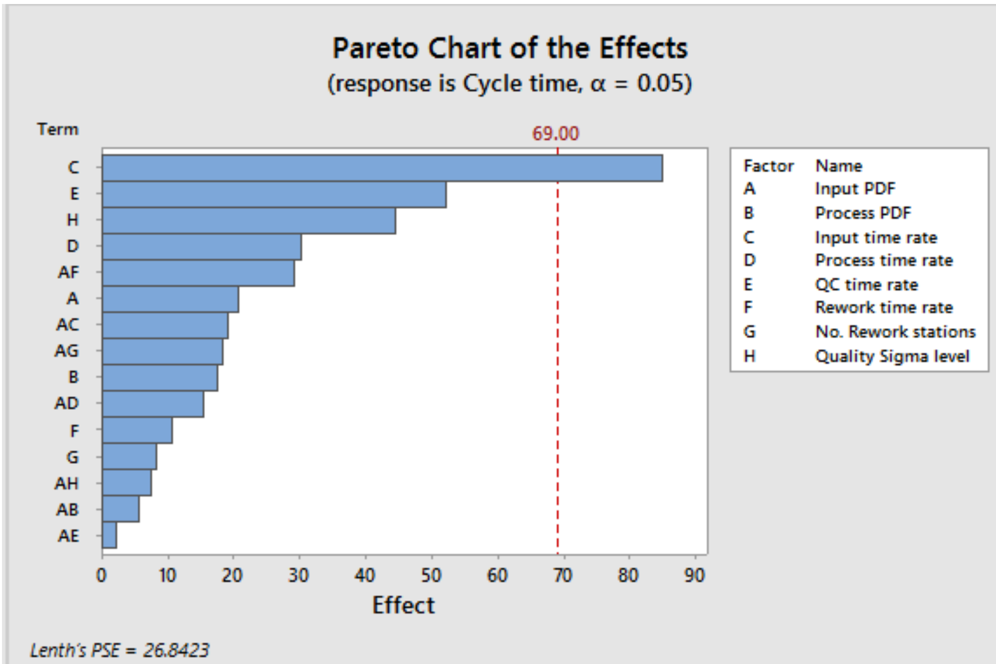
Table 4.9: Fractional factorial response factors results.

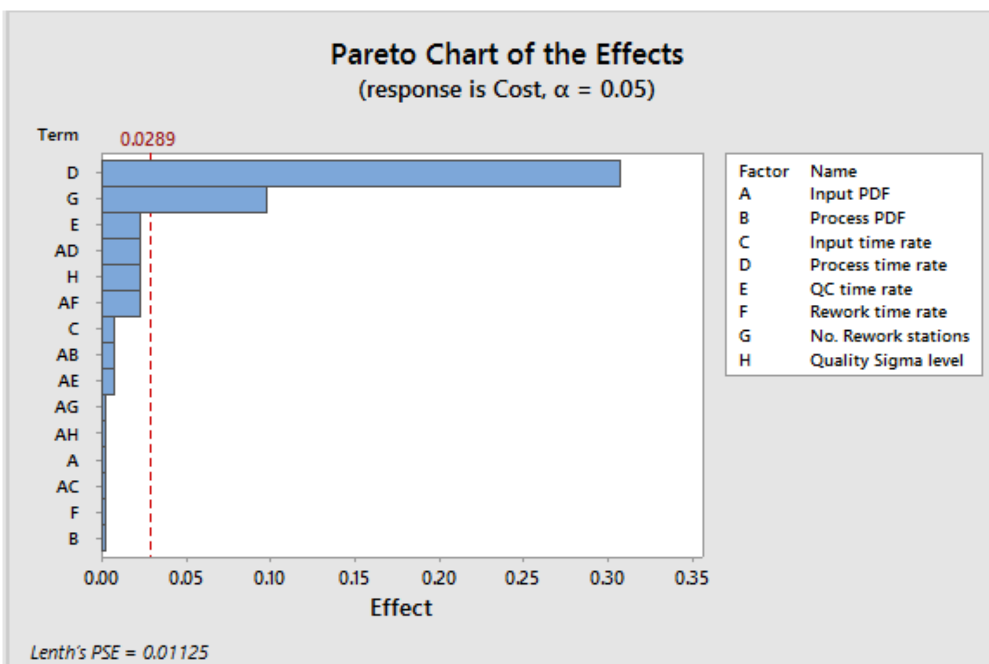
RunOrder	Cycle time	Cost	Resource utilization
1	79.7801	0.38	0.9075
2	12.3036	0.3	0.6583
3	135.3747	0.3	0.5183
4	147.4948	0.43	0.9025
5	113.4015	0.3	0.5818
6	8.2945	0.4	0.4975
7	6.9928	0.35	0.4362
8	23.4367	0.3	0.5368
9	130.5	0.7	0.865
10	199.9433	0.6	0.5611
11	151.7667	0.6	0.7575
12	131.05	0.65	0.7987
13	18	0.6	0.4922
14	15.8517	0.72	0.8912
15	95.106	0.75	0.8812
16	27.1956	0.6	0.725

Note: Cycle time in hours, Cost in %, and Resource utilization in %.

The statistical analysis is performed on the results obtained in order to verify if any of the factors considered initially are significant. Figure 4.19 shows the analysis where the significant factors can be identified clearly. The only significant factors identified were Input rate time, Process time rate, and Number of rework stations. Appendix 2 presents the Tukey's pairwise

comparison and the Fisher LSD analysis used in order to validate the significant factors identified by the factorial DOE. The Resource utilization response did not reflect any of the factors as significant. Due to this, it was eliminated from the Full Factorial DOE developed to analyze the significant factors.





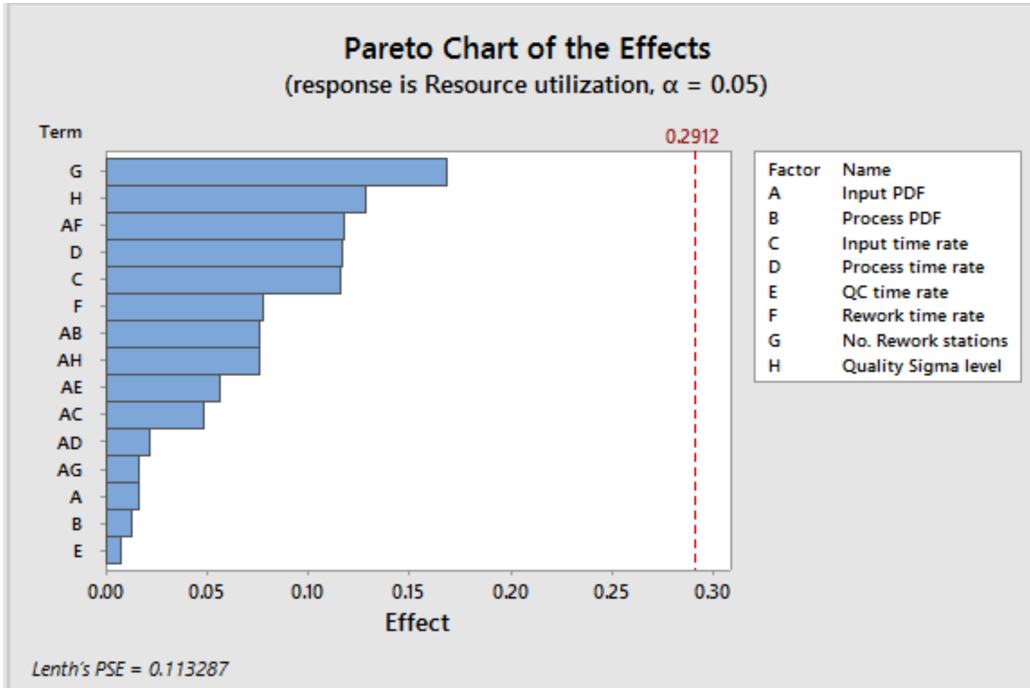


Figure 4.19: Significant factors from Fractional Factorial.

Table 4.10: Full Factorial design and results.

Input rate	Process rate	No. Rework stations	Cycle time	Cost
1	1	1	79.7801	0.38
1	1	6	12.3036	0.3
1	1	6	135.3747	0.3
1	1	1	147.4948	0.43
2	1	6	113.4015	0.3
2	1	1	8.2945	0.4
2	1	1	6.9928	0.35
2	1	6	23.4367	0.3
1	2	1	130.5	0.7
1	2	6	199.9433	0.6
1	2	6	151.7667	0.6
1	2	1	131.05	0.65
2	2	6	18	0.6
2	2	1	15.8517	0.72
2	2	1	95.106	0.75
2	2	6	27.1956	0.6

Note: Cycle time in hours, and Cost in %

Table 4.10 presents the Full Factorial design developed in order to evaluate the significant factors identified versus the response variables of Cycle time and cost. Figure 4.20 shows the relationship between the results obtained of cost and Cycle time in order to identify any relationship. As seen in the graph, no relationship was found. Table 4.11 shows the optimal parameters to minimize cost and cycle time independently. To develop the Full Factorial design the parameters of Input PDF (Triangular), Process PDF (Triangular), Process time rate (1.5), QC time rate (1.5), Rework time rate (1.5), and Sigma level of 3 (93.31%) were not changed.

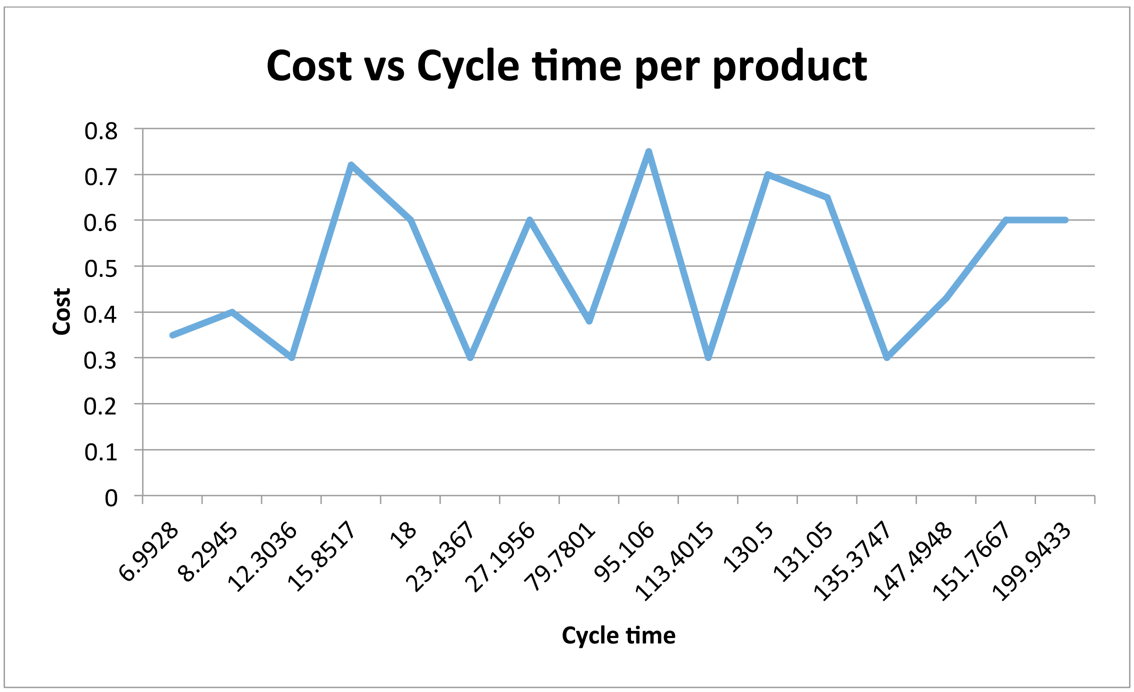


Figure 4.20: Cost versus cycle time relationship.

Table 4.11: Optimal parameters to minimize cycle time and cost.

Input time rate	Process time rate	No. Rework stations	Cycle time	Cost
2	1	1	6.9928	0.35
1	1	6	12.3036	0.3
2	1	6	23.4367	0.3
2	1	6	113.4015	0.3
1	1	6	135.3747	0.3

Note: Cycle time in hours, and Cost in %

Figure 4.21 demonstrates that Cost has the Quality sigma level and the Number of reworks stations as significant factors. This means that these two factors must be considered when trying to optimize the process. On the other hand, Figure 4.21 also shows that there are no significant factors for Cycle time. This means that no factors are required in the optimization process.

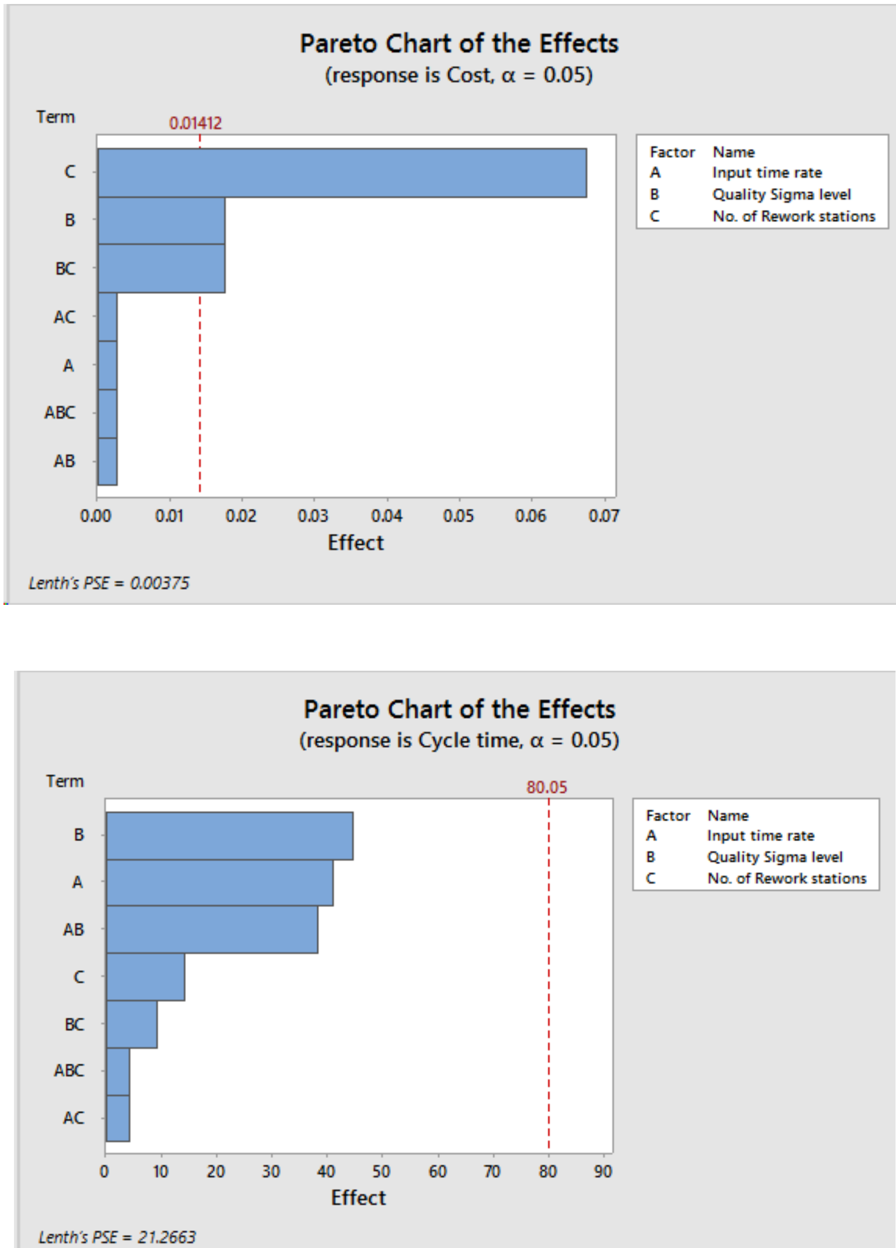


Figure 4.21: Significant factors from Full Factorial Design.

The final step of the process was to develop the multi objective optimization process. This was achieved by using GA technique. The process followed in order to identify the optimal location of the rework station in the solar panel manufacturing line is described. This optimization considers the sub-assemblies of the Aluminum frame, solar glass, both encapsulate, the cells, the back sheet and the junction box as in-house assemblies. This develops a manufacturing process of 20 stations. Illustration 4.2 shows the order of how these sub components are assembled. Figure 4.22 shows the flow chart that the algorithm uses in order to achieve and propose optimal solutions.

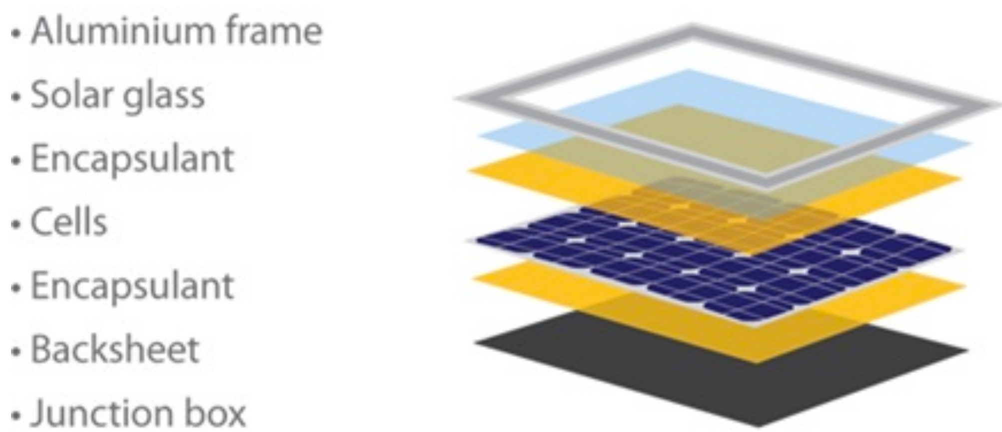


Illustration 4.2: Components assembly order [Sun grid, 2016].

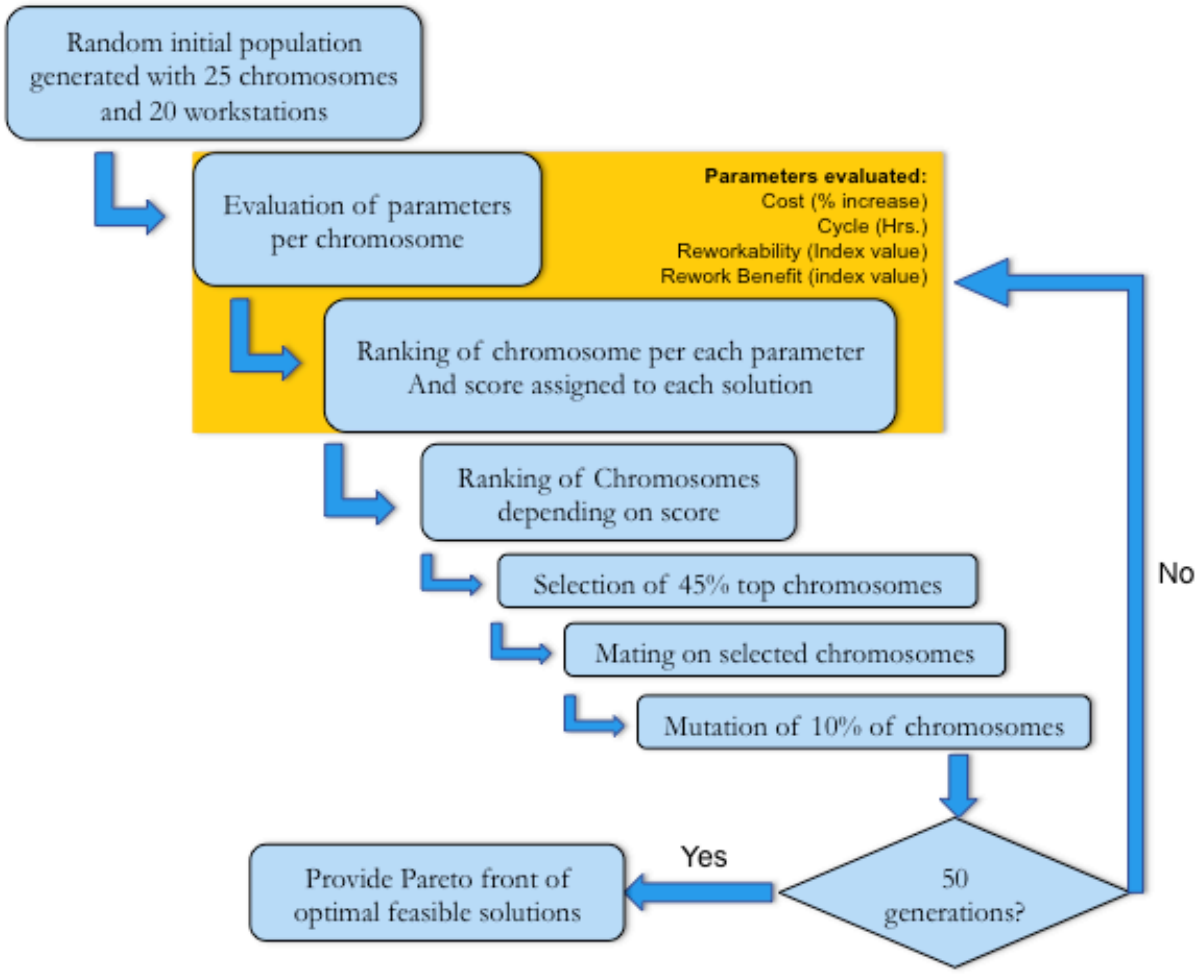


Figure 4.22: Flow chart of GA used to obtain optimal QC strategy Pareto front.

In order to generate possible solutions the four objective functions are evaluated. The equations are shown for Cost (Equation 39), Cycle Time (Equation 40), Reworkability (Equation 41 and 43) and Rework benefit (Equation 42).

$$Min(TC) = VA_0 + NVA_0 + \sum_{i=1}^{S} (VA_i + NVA_i + W_i + E_i) \tag{39}$$

$$Min(CT) = \sum_{i=1}^{S} (VA_i + NVA_i + W_i) \tag{40}$$

$$R_i = \sum_{i=1}^{i=n} \left[S_i * \left(\frac{W_i}{\sum W_i} \right) \right] \tag{41}$$

$$Max(R_U) = \sum_{i=1}^{i=n} R_i \tag{42}$$

where

S	*Reworkability score [index value 1 to 10]*
W	*Weight to specific DfD factor [index value 1 to 10]*
R	*Reworkability [index value 1 to 10]*
i	*Work station*

$$Max(RB) = \sum_{i=0}^{i=n} (R_i * WS_i) \tag{43}$$

where

RB	*Reworkability Benefit [index value]*
WS	*Weight to specific location of rework station [index value 1 to n]*

The GA is considered an unconstrained GA. This implies that usual constraints found in optimization models are not present. In order for the multi-objective GA to work due to this nature, is the need of having trade off conflicting objectives. These conflicting objectives are the ones that generate different non-dominant solutions. The objectives of minimizing cost and cycle time would incline the algorithm to provide solutions with zero rework stations. On the other hand the reworkability index would provide an optimal solution with a rework station at each workstation of the manufacturing process.

Table 4.12: 1st GA generation.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0	0	0	0	1	0	1	0	1	1	0	1	1	0	0	1	0	1	1	0
1	1	0	0	1	1	1	0	1	1	0	0	1	1	0	0	0	1	0	1
0	1	0	0	1	1	0	1	0	1	0	0	1	0	0	1	1	1	1	1
0	1	0	1	0	1	0	1	1	1	0	0	0	1	1	0	0	1	0	1
1	1	0	0	1	0	0	0	0	1	1	1	1	0	0	1	1	0	0	0
1	0	1	0	1	1	0	1	0	1	0	0	0	0	0	0	0	1	0	1
1	1	0	0	0	0	0	1	0	0	1	1	1	0	1	0	1	0	0	1
0	0	1	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	0	0
0	1	0	1	1	0	1	0	0	1	1	1	0	0	1	0	1	1	0	1

The first step of the GA is to generate a random initial population with 20 chromosomes that represent each of the manufacturing stations; the initial population is shown in Table 4.12. A zero is used to reflect that there is no rework station for that workstation, while a one signifies that a rework station is placed. Table 4.13 shows the evaluation of each of possible solutions. This evaluation uses Cost (% increase from product cost) and Cycle time (hrs.) as parameters that must be minimized, and Reworkability (index value) and Rework benefit (index value) as values that must be maximized.

Table 4.13: 1st GA generation evaluation.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Parameter	Points cost	Points cycle time	Points Reworkabiity	Rework benefit	Total points
1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	182	1	1	20	20	42
0	1	1	0	0	1	0	0	0	1	1	1	0	1	1	1	0	1	1	1	146	8	5	13	19	45
0	0	0	1	0	1	1	0	0	1	0	0	1	1	1	1	0	1	1	1	142	14	9	7	18	48
1	0	1	1	0	0	0	1	0	0	1	1	1	0	1	1	1	1	1	0	137	5	4	15	17	41
0	0	0	0	0	0	0	0	1	1	1	0	0	1	1	1	0	1	1	1	132	20	15	1	16	52
0	1	0	0	1	1	1	0	0	0	1	1	0	1	1	0	1	0	1	1	128	10	8	11	15	44
1	0	1	1	1	0	0	1	1	0	1	0	1	0	1	1	0	1	0	1	123	3	3	18	14	38
0	1	1	0	0	1	0	0	1	0	1	1	1	1	1	1	0	1	0	0	119	7	7	14	13	41
1	1	1	0	1	0	0	0	1	0	1	0	0	1	1	0	1	0	1	1	116	6	6	16	12	40
0	0	0	0	0	0	1	1	0	1	1	0	0	1	1	1	1	1	0	0	116	17	14	4	11	46
1	1	1	0	1	0	1	1	0	0	1	1	1	0	0	1	1	0	1	0	114	2	2	19	10	33
1	0	0	0	1	1	1	1	0	0	0	1	1	0	0	0	0	1	1	1	109	11	12	10	9	42
1	1	0	0	0	0	0	1	1	1	0	1	1	1	0	0	1	0	1	0	105	9	11	12	8	40
0	0	0	0	1	1	0	1	0	0	0	1	0	1	1	0	0	1	0	1	98	18	18	3	7	46
1	0	1	1	0	0	0	0	0	0	1	1	1	0	1	1	0	0	0	1	95	13	13	8	6	40
1	1	0	0	1	1	1	0	1	1	1	0	0	0	1	0	1	0	0	0	83	4	10	17	5	36
0	1	1	0	0	0	1	1	0	0	1	1	0	0	0	0	0	1	0	1	81	15	17	6	4	42
0	1	0	1	1	1	0	0	0	1	0	0	1	1	0	0	0	0	0	1	74	12	16	9	3	40
0	0	0	0	1	1	0	0	1	0	1	1	0	0	0	0	0	0	1	0	62	19	20	2	2	43
1	1	0	0	0	0	1	1	0	0	1	0	0	1	0	0	0	0	0	0	43	16	19	5	1	41

From this first generation a selection process is developed in order to sort the best solutions from the entire population. Figure 4.23 shows the initial distribution, and after 50 generations, of the solutions when comparing cost versus rework benefit. It is easily identifiable

that the solutions tend to converge to one optimal location. The algorithm does go through cross over and mutation every generation in order to avoid getting "stuck" in a local optimal and not identifying better solutions because the entire search space was not evaluated. This does not play a significant role for small operations, but operations that might require above 50 workstations, mutation is critical. A 30% of the population is selected to pass directly to the new generation, from here, the cross over is performed, and only 5% goes through a single point mutation.

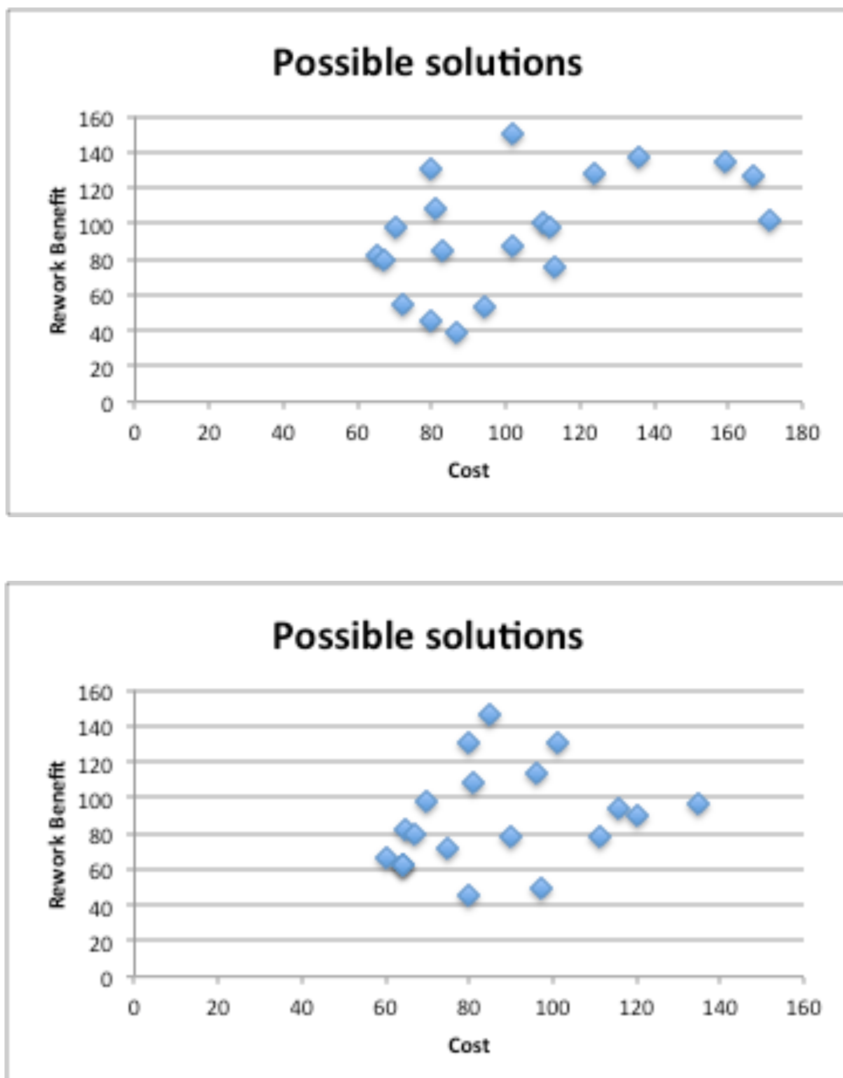


Figure 4.23: Solutions plot for first and after fifty generations.

Table 4.14 has the optimal solutions compared to including rework stations after each step, or having only one final rework station. This is where the benefit and the balance of between both approaches are valuable and observable. Appendix 3 presents the programing used in order to generate the GA.

Table 4.14: Optimal solution comparison.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Cost	Cycle time	Reworkability	Rework benefit
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	210	20	210	210
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	20
0	0	0	0	0	0	1	0	1	1	1	1	1	1	0	1	1	1	1	0	85	11	85	146
1	1	0	0	0	0	0	0	1	1	1	0	1	1	1	0	1	1	0	1	101	11	101	130

Note: Cycle time in hours, Cost in %, Reworkability and Rework benefit are index values

4.3 Genetic Algorithm Results Verification

In order to verify if the results of the GA are optimal all of the possible solutions were evaluated. This process was done manually and becomes unfeasible as the number of workstations increases. With a total of 10 workstations 1,024 different options are feasible. Since there is no single optimal solution, Table 4.15 and 4.16 presents the optimal solution for Cost, Cycle Time, Reworkability and Rework benefit. The amount of options increases exponentially when more workstations are added to the process. For example, for 15 workstations, a total of 32,768 solutions would have to be evaluated making this process unfeasible.

Table 4.15: Optimization of individual values versus multi-objective optimization.

1	2	3	4	5	6	7	8	9	10	Cost	Cycle time	Reworkability	Rework benefit
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	1	1	11	10
0	0	0	0	0	0	0	0	1	0	2	1	12	9
0	0	0	0	0	0	0	1	0	0	3	1	13	8
1	1	1	1	1	1	1	1	1	1	55	10	155	55
1	1	1	1	1	1	1	1	1	0	54	9	144	45
1	1	1	1	1	1	1	1	0	1	53	9	143	46
1	1	1	1	1	1	1	0	1	1	52	9	142	47
1	0	0	1	0	1	1	1	1	0	31	6	91	35
0	0	1	0	1	0	1	1	1	0	23	5	73	32
0	1	0	0	0	1	1	0	1	0	20	4	60	24
0	1	0	0	1	0	1	1	0	0	22	4	62	22

Note: Cycle time in hours, Cost in %, Reworkability and Rework benefit are index values

When comparing the four best solutions obtained from the GA after ten generations at the bottom of Table 4.15, it can be seen that the results that the GA provides are optimal results and reduces the estimation burden. Utilizing multi objective optimization allows the user to find a solution that is a compromise between the different response variables. This solution focuses on all variables and not just tries to optimize one. Table 4.16 presents the possible solutions when a manual evaluation is performed. These solutions are selected by obtaining the average values of cost, cycle time, reworkability and rework benefit. The average value of cost is 27.5, for cycle time 5, for reworkability 77.5, and rework benefit 27.5. The solutions obtained from the GA are close to average values for each factor.

Table 4.16: Manual selection of optimal solution.

1	2	3	4	5	6	7	8	9	10	Cost	Cycle time	Reworkability	Rework benefit
0	0	1	1	0	1	1	1	0	0	27	5	77	28
0	0	1	1	1	0	1	0	1	0	27	5	77	28
0	0	1	1	1	1	0	0	0	1	27	5	77	28
0	1	0	0	1	1	1	1	0	0	27	5	77	28
0	1	0	1	0	1	1	0	1	0	27	5	77	28
0	1	0	1	1	0	0	1	1	0	27	5	77	28
0	1	0	1	1	0	1	0	0	1	27	5	77	28
0	1	1	0	0	1	0	1	1	0	27	5	77	28
0	1	1	0	0	1	1	0	0	1	27	5	77	28
0	1	1	0	1	0	0	1	0	1	27	5	77	28
0	1	1	1	0	0	0	0	1	1	27	5	77	28
1	0	0	0	1	1	1	0	1	0	27	5	77	28
1	0	0	1	0	1	0	1	1	0	27	5	77	28
1	0	0	1	0	1	1	0	0	1	27	5	77	28
1	0	0	1	1	0	0	1	0	1	27	5	77	28
1	0	1	0	0	0	1	1	1	0	27	5	77	28
1	0	1	0	0	1	0	1	0	1	27	5	77	28
1	0	1	0	1	0	0	0	1	1	27	5	77	28
1	1	0	0	0	0	1	1	0	1	27	5	77	28
1	1	0	0	0	1	0	0	1	1	27	5	77	28

Note: Cycle time in hours, Cost in %, Reworkability and Rework benefit are index values

The computational times required for the GA to run are presented in Table 4.17. It can be seen in the table how the computational time changes when the amount of chromosomes increase

or the amount of workstations increases. The full enumeration computational time is also presented when using to 10 workstations. This proves that the GA provides a feasible optimal solution by reducing the computational time.

Table 4.17: Computational time comparison.

No. of Chromosomes	No. of Generations	Computational time (hrs.)
25	5	0.2
25	50	1.8
100	5	0.3
100	50	1.9
1,024	1	3.1

4.4 Sensitivity Analysis of Genetic Algorithm solution

In order to understand better the impact of adding or eliminating a rework station in the process, a sensitivity analysis was performed. Tables 4.18 and 4.19 show the change in cost, cycle time, reworkability and rework benefit when a single rework station are added through out the manufacturing line.

Table 4.18 shows the changes when a single rework station is added in different locations of the manufacturing line. It can be observed that the cost and the cycle time increase in an exponential form while the reworkability decrease linearly and rework benefit increases linearly. Table 4.19 shows the changes when an additional rework station is added. The same tendencies can be observed as the ones mentioned for table 4.18.

Table 4.18: Sensitivity analysis for rework station location.

1	2	3	4	5	6	7	8	9	10	Cost	Cycle time	Reworkability	Rework benefit
1	0	0	0	0	0	0	0	0	0	1	1	20	1
0	1	0	0	0	0	0	0	0	0	2	1	19	2
0	0	1	0	0	0	0	0	0	0	3	1	18	3
0	0	0	0	1	0	0	0	0	0	6	2	16	5
0	0	0	0	0	0	1	0	0	0	8	3	14	7
0	0	0	0	0	0	0	1	0	0	10	3	13	8
0	0	0	0	0	0	0	0	1	0	12	4	12	9
0	0	0	0	0	0	0	0	0	1	14	5	11	10

Table 4.19: Sensitivity analysis for amount of rework stations.

1	2	3	4	5	6	7	8	9	10	Cost	Cycle time	Reworkability	Rework benefit
1	0	0	0	0	0	0	0	0	0	10	1	20	1
1	1	0	0	0	0	0	0	0	0	19	2	39	3
1	1	1	0	0	0	0	0	0	0	27	3	57	6
1	1	1	1	1	0	0	0	0	0	40	5	90	15
1	1	1	1	1	1	1	0	0	0	49	7	119	28
1	1	1	1	1	1	1	1	0	0	52	8	132	36
1	1	1	1	1	1	1	1	1	0	54	9	144	45
1	1	1	1	1	1	1	1	1	1	55	10	155	55

4.5 Summary

Chapter 4 presented several case studies that demonstrated the use of the proposed mathematical model for cost estimation and the methodology to identify an optimal QC strategy for solar panels manufacturing process including in-house component manufacturing. The last section showed the GA results verification where the difference between optimizing only one objective verses optimizing all objectives is clear. The algorithm provides an advantage, because without it, the user would have to go through the entire 1,024 possible combinations in order to select the best one manually. The computational time for the GA is greatly smaller than the full enumeration. It was also proven that the solutions provided by the GA are non-dominate solutions, meaning that they are better than others in one specific objective but worst in others. This is why a single optimal solution cannot be obtained.

Chapter 5: Conclusions and Recommendations for Future Work

Chapter 5 is a recapitulation of the intent of the study, the conclusion obtained by the methodology proposed, the contribution of this methodology and recommendations for future study. The methodology provides optimal solutions that can be used by the user in order to establish an optimal QC strategy in a Manufacturing environment.

5.1 Conclusions

This study focused on two main objectives. The first objective was to develop a mathematical model that can estimate cost for manufacturing products. This cost was calculated using initially process simulations. The intent was to calculate the cost of the product at different quality sigma levels. This mathematical model also allows the user to avoid having to modify simulations and or re-calculating cost every time the yield of the process is increased or reduced. This objective was achieved. A model was developed and tested against the manufacturing of solar panels. This model was further modified in order to include a critical cost parameter that is energy usage. This parameter is not considered in previous work because it is not simple to calculate and represents, around 6% to 11% of the total direct cost of the product. The manufacturing industry, due to its continues improvement process, is moving towards automation of their processes. The direct usage cost of this equipment is energy and that is why this parameter must and was considered for the direct cost calculations. The findings for each case study were the following:

- Case study 1: The methodology followed was able to generate a generic cost estimation model for direct product cost as quality sigma level changes in the process.
- Case study 2: The calculations of the energy consumption in the solar panel manufacturing setting showed that energy represents an 8% of the direct cost for Solar Panel manufacturing process.
- Case study 3: The single server case study proved that the methodology and equation obtained in case study 1 are applicable in different scenarios.

- Case study 4: The methodology shows how to calculate the reworkability index used in the GA for the QC optimization.
- Case study 5: Shows the comprehensive example of Solar panel manufacturing process was a final optimal QC control strategy obtained through the use of the GA.

Objective 2 was to develop a methodology that can provide an optimal QC strategy for how many rework stations and at what points of the manufacturing line must they be placed in order to provide the most benefit to any company. This objective was achieved first through the use of DOE in order to identify significant values, then the use of GA in order to evaluate all the possible solutions. The DOE phase initially started with eight factors that could affect the response variables of the process. These factors were considered and an initial screening DOE using fractional factorial method was performed. The analysis used three response variables to be evaluated. After the initial screening, a full factorial design was used to evaluate the remaining three factors against only two of the response variables. Once it was shown that these were the significant variables to be considered, they were used in the optimization process. GA was applied in order to evaluate possible solutions of quantity and location of rework stations. GA provides the user with optimal solutions that can be prioritized depending on the specific requirements of the user. The algorithm provides a chromosome that tells the user how many rework stations and where on the manufacturing line they must be placed in order to minimize cost and cycle time, while maximizing reworkability and rework benefit.

In order to evaluate the benefit of using GA, an analysis was presented on the difference of evaluating all possible solutions versus utilizing the GA optimization process. A full enumeration can be evaluated manually but this is extremely time consuming; for only 5 workstations, the manual evaluation can take up to 6 hrs. GA provides a fast and efficient way of determining an optimal solution for the QC strategy as proven in table 4.7.

5.2 Contributions

This study contributes to several different areas because of the two main objectives that were pursued. Thanks to the cost estimation objective, contributions to the areas of mathematical modeling and cost estimation are achieved. The main contribution in the study is a stepping-stone of creating a culture where energy consumption is considered a direct cost of the product. Once the manufacturing industry understands and adopts this mentality, significant improvements can be achieved in the areas of sustainable and green manufacturing. Manufacturing industries have a culture of continues improvement and cost reductions; if energy begins to play a significant role in cost, efforts to reduce the usage will be made. This does not only provide a benefit to the company, but also to the environment because currently most energy still comes from pollutant sources such as coal energy generating companies.

The objective of creating a methodology that optimizes a quality strategy utilizing rework stations is the main contribution to the area of QC and QA. Most companies do not evaluate these possibilities because the focus is towards lean manufacturing or mass production. Lean manufacturing guides the companies towards zero defects and having rework stations at each step of the process. On the other hand mass production guides the industry towards low cycle times and 1 single rework station at the end. Finding a balance between these two approaches is the main contribution of this work. This balance cannot be singularly identified because the problem to solve is multi objective; but the methodology proposed does generate possible solutions from which the final user can select depending on specific priorities.

5.3 Recommendations for Future Work

The work performed was mostly theoretical and more concrete examples must be evaluated. In this work the study of Solar panels manufacturing was used to evaluate the methodologies used of cost estimation and QC strategy. Here are some possible topics that can expand in this area of study:

- Testing more case scenarios in different industries, outside the Green Energy Manufacturing industry. It would be interesting to see the results on this methodology in industries where the process is still very manually intensive. This would change the percentages currently identified for energy usage and challenge significantly this methodology.
- Many other optimization techniques can be used in order to optimize the QC strategy. New approaches such as Ant Colony optimization or Neural Networks can be used and then evaluated to see which one provides a better QC strategy.
    - The main challenge of doing this is that there is no need for these optimization methods for small process. If manufacturing processes only consist of 5 or 10 workstations, all the combinations can be evaluated and an optimization method is not required.
- The evaluation of the manufacturing steps of the process throughout the entire Supply chain of a product would be very interesting to evaluate. This can provide a new perspective of where rework stations should be implemented, instead of the current approach, which reflects only QC and rework stations once each company finishes manufacturing their specific sub assembly or product.

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Appendix 1

Factorial Simulation Runs 2 and 4

Appendix 1 shows the simulation reports obtained from the Arena® software. These reports not only contain the values used for the methodology but also specific resource utilization, cost, and cycle time specification.

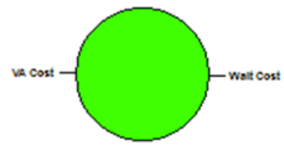
Unnamed Project

Replications: 1 Time Units: Hours

Key Performance Indicators

All Entities

	Average
Non-Value Added Cost	0
Other Cost	0
Transfer Cost	0
Value Added Cost	5,098
Wait Cost	2
Total Cost	5,100



All Resources

	Average
Busy Cost	4,696 *
Idle Cost	944
Usage Cost	0
Total Cost	5,640

* *these costs are included in Entity Costs above.*

System

	Average
Total Cost	6,044
Number Out	28

Unnamed Project

Replications: 1 Time Units: Hours

Entity

Time

VA Time	Average	Half Width	Minimum Value	Maximum Value
Entity 1	12.0000	(Insufficient)	12.0000	12.0000

NVA Time	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00

Wait Time	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.02356366	(Insufficient)	0.00	0.1187

Transfer Time	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00

Other Time	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00

Total Time	Average	Half Width	Minimum Value	Maximum Value
Entity 1	12.0236	(Insufficient)	12.0000	12.1187

Cost

VA Cost	Average	Half Width	Minimum Value	Maximum Value
Entity 1	155.00	(Insufficient)	155.00	155.00

NVA Cost	Average	Half Width	Minimum Value	Maximum Value
Entity 1	1.0000	(Insufficient)	1.0000	1.0000

Wait Cost	Average	Half Width	Minimum Value	Maximum Value
Entity 1	1.0236	(Insufficient)	1.0000	1.1187

Other Cost	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00

Transfer Cost	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00

Unnamed Project

Replications: 1 Time Units: Hours

Entity

Cost

Total Cost	Average	Half Width	Minimum Value	Maximum Value
Entity 1	157.02	(Insufficient)	157.00	157.12

Other

Number In	Value
Entity 1	40.0000

Number Out	Value
Entity 1	28.0000

WIP	Average	Half Width	Minimum Value	Maximum Value
Entity 1	10.2904	(Insufficient)	0.00	13.0000

Unnamed Project

Replications: 1 Time Units: Hours

Queue

Time

Waiting Time	Average	Half Width	Minimum Value	Maximum Value
Finshed Goods QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 1 QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 1 submodel.Queue	0.05619525	(Insufficient)	0.00	0.2081
Process 2 QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 2 submodel.Queue	0.00	(Insufficient)	0.00	0.00
Process 3 QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 3 submodel.Queue	0.00	(Insufficient)	0.00	0.00
Process 4 QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 4 submodel.Queue	0.00	(Insufficient)	0.00	0.00
Process 5 QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 5 submodel.Queue	0.00	(Insufficient)	0.00	0.00
Process 6.Queue	0.00	(Insufficient)	0.00	0.00

Cost

Waiting Cost	Average	Half Width	Minimum Value	Maximum Value
Finshed Goods QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 1 QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 1 submodel.Queue	0.05619525	(Insufficient)	0.00	0.2081
Process 2 QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 2 submodel.Queue	0.00	(Insufficient)	0.00	0.00
Process 3 QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 3 submodel.Queue	0.00	(Insufficient)	0.00	0.00
Process 4 QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 4 submodel.Queue	0.00	(Insufficient)	0.00	0.00
Process 5 QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 5 submodel.Queue	0.00	(Insufficient)	0.00	0.00
Process 6.Queue	0.00	(Insufficient)	0.00	0.00

Other

Unnamed Project

Replications: 1 Time Units: Hours

Queue

Other

Number Waiting	Average	Half Width	Minimum Value	Maximum Value
Finshed Goods QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 1 QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 1 Rework.Queue	0.00	(Insufficient)	0.00	0.00
Process 1 submodel.Queue	0.05619525	(Insufficient)	0.00	1.0000
Process 2 QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 2 Rework.Queue	0.00	(Insufficient)	0.00	0.00
Process 2 submodel.Queue	0.00	(Insufficient)	0.00	0.00
Process 3 QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 3 Rework.Queue	0.00	(Insufficient)	0.00	0.00
Process 3 submodel.Queue	0.00	(Insufficient)	0.00	0.00
Process 4 QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 4 Rework.Queue	0.00	(Insufficient)	0.00	0.00
Process 4 submodel.Queue	0.00	(Insufficient)	0.00	0.00
Process 5 QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 5 Rework.Queue	0.00	(Insufficient)	0.00	0.00
Process 5 submodel.Queue	0.00	(Insufficient)	0.00	0.00
Process 6.Queue	0.00	(Insufficient)	0.00	0.00
Rework.Queue	0.00	(Insufficient)	0.00	0.00

Unnamed Project

Replications: 1 Time Units: Hours

Resource

Usage

Instantaneous Utilization	Average	Half Width	Minimum Value	Maximum Value
Equipment 1	0.9903	(Insufficient)	0.00	1.0000
Equipment 2	0.9403	(Insufficient)	0.00	1.0000
Equipment 3	0.8903	(Insufficient)	0.00	1.0000
Equipment 4	0.8403	(Insufficient)	0.00	1.0000
Equipment 5	0.7903	(Insufficient)	0.00	1.0000
Equipment 6	0.7403	(Insufficient)	0.00	1.0000
Operator 1	0.9903	(Insufficient)	0.00	1.0000
Operator 2	0.9403	(Insufficient)	0.00	1.0000
Operator 3	0.8903	(Insufficient)	0.00	1.0000
Operator 4	0.8403	(Insufficient)	0.00	1.0000
Operator 5	0.7903	(Insufficient)	0.00	1.0000
Operator 6	0.7403	(Insufficient)	0.00	1.0000
QC equipment	0.7153	(Insufficient)	0.00	1.0000
QC equipment P1	0.9653	(Insufficient)	0.00	1.0000
QC equipment P2	0.9153	(Insufficient)	0.00	1.0000
QC equipment P3	0.8653	(Insufficient)	0.00	1.0000
QC equipment P4	0.8153	(Insufficient)	0.00	1.0000
QC equipment P5	0.7653	(Insufficient)	0.00	1.0000
QC Operator	0.7153	(Insufficient)	0.00	1.0000
QC Operator P1	0.9653	(Insufficient)	0.00	1.0000
QC Operator P2	0.9153	(Insufficient)	0.00	1.0000
QC Operator P3	0.8653	(Insufficient)	0.00	1.0000
QC Operator P4	0.8153	(Insufficient)	0.00	1.0000
QC Operator P5	0.7653	(Insufficient)	0.00	1.0000
Rework Equipment	0.00	(Insufficient)	0.00	0.00
Rework Equipment P1	0.00	(Insufficient)	0.00	0.00
Rework Equipment P2	0.00	(Insufficient)	0.00	0.00
Rework Equipment P3	0.00	(Insufficient)	0.00	0.00
Rework Equipment P4	0.00	(Insufficient)	0.00	0.00
Rework Equipment P5	0.00	(Insufficient)	0.00	0.00
Rework Operator	0.00	(Insufficient)	0.00	0.00
Rework Operator P1	0.00	(Insufficient)	0.00	0.00
Rework Operator P2	0.00	(Insufficient)	0.00	0.00
Rework Operator P3	0.00	(Insufficient)	0.00	0.00
Rework Operator P4	0.00	(Insufficient)	0.00	0.00
Rework Operator P5	0.00	(Insufficient)	0.00	0.00

Unnamed Project

Replications: 1 Time Units: Hours

Resource

Usage

Number Busy	Average	Half Width	Minimum Value	Maximum Value
Equipment 1	0.9903	(Insufficient)	0.00	1.0000
Equipment 2	0.9403	(Insufficient)	0.00	1.0000
Equipment 3	0.8903	(Insufficient)	0.00	1.0000
Equipment 4	0.8403	(Insufficient)	0.00	1.0000
Equipment 5	0.7903	(Insufficient)	0.00	1.0000
Equipment 6	0.7403	(Insufficient)	0.00	1.0000
Operator 1	0.9903	(Insufficient)	0.00	1.0000
Operator 2	0.9403	(Insufficient)	0.00	1.0000
Operator 3	0.8903	(Insufficient)	0.00	1.0000
Operator 4	0.8403	(Insufficient)	0.00	1.0000
Operator 5	0.7903	(Insufficient)	0.00	1.0000
Operator 6	0.7403	(Insufficient)	0.00	1.0000
QC equipment	0.7153	(Insufficient)	0.00	1.0000
QC equipment P1	0.9653	(Insufficient)	0.00	1.0000
QC equipment P2	0.9153	(Insufficient)	0.00	1.0000
QC equipment P3	0.8653	(Insufficient)	0.00	1.0000
QC equipment P4	0.8153	(Insufficient)	0.00	1.0000
QC equipment P5	0.7653	(Insufficient)	0.00	1.0000
QC Operator	0.7153	(Insufficient)	0.00	1.0000
QC Operator P1	0.9653	(Insufficient)	0.00	1.0000
QC Operator P2	0.9153	(Insufficient)	0.00	1.0000
QC Operator P3	0.8653	(Insufficient)	0.00	1.0000
QC Operator P4	0.8153	(Insufficient)	0.00	1.0000
QC Operator P5	0.7653	(Insufficient)	0.00	1.0000
Rework Equipment	0.00	(Insufficient)	0.00	0.00
Rework Equipment P1	0.00	(Insufficient)	0.00	0.00
Rework Equipment P2	0.00	(Insufficient)	0.00	0.00
Rework Equipment P3	0.00	(Insufficient)	0.00	0.00
Rework Equipment P4	0.00	(Insufficient)	0.00	0.00
Rework Equipment P5	0.00	(Insufficient)	0.00	0.00
Rework Operator	0.00	(Insufficient)	0.00	0.00
Rework Operator P1	0.00	(Insufficient)	0.00	0.00
Rework Operator P2	0.00	(Insufficient)	0.00	0.00
Rework Operator P3	0.00	(Insufficient)	0.00	0.00
Rework Operator P4	0.00	(Insufficient)	0.00	0.00
Rework Operator P5	0.00	(Insufficient)	0.00	0.00

Unnamed Project

Replications: 1 Time Units: Hours

Resource

Usage

Number Scheduled	Average	Half Width	Minimum Value	Maximum Value
Equipment 1	1.0000	(Insufficient)	1.0000	1.0000
Equipment 2	1.0000	(Insufficient)	1.0000	1.0000
Equipment 3	1.0000	(Insufficient)	1.0000	1.0000
Equipment 4	1.0000	(Insufficient)	1.0000	1.0000
Equipment 5	1.0000	(Insufficient)	1.0000	1.0000
Equipment 6	1.0000	(Insufficient)	1.0000	1.0000
Operator 1	1.0000	(Insufficient)	1.0000	1.0000
Operator 2	1.0000	(Insufficient)	1.0000	1.0000
Operator 3	1.0000	(Insufficient)	1.0000	1.0000
Operator 4	1.0000	(Insufficient)	1.0000	1.0000
Operator 5	1.0000	(Insufficient)	1.0000	1.0000
Operator 6	1.0000	(Insufficient)	1.0000	1.0000
QC equipment	1.0000	(Insufficient)	1.0000	1.0000
QC equipment P1	1.0000	(Insufficient)	1.0000	1.0000
QC equipment P2	1.0000	(Insufficient)	1.0000	1.0000
QC equipment P3	1.0000	(Insufficient)	1.0000	1.0000
QC equipment P4	1.0000	(Insufficient)	1.0000	1.0000
QC equipment P5	1.0000	(Insufficient)	1.0000	1.0000
QC Operator	1.0000	(Insufficient)	1.0000	1.0000
QC Operator P1	1.0000	(Insufficient)	1.0000	1.0000
QC Operator P2	1.0000	(Insufficient)	1.0000	1.0000
QC Operator P3	1.0000	(Insufficient)	1.0000	1.0000
QC Operator P4	1.0000	(Insufficient)	1.0000	1.0000
QC Operator P5	1.0000	(Insufficient)	1.0000	1.0000
Rework Equipment	1.0000	(Insufficient)	1.0000	1.0000
Rework Equipment P1	1.0000	(Insufficient)	1.0000	1.0000
Rework Equipment P2	1.0000	(Insufficient)	1.0000	1.0000
Rework Equipment P3	1.0000	(Insufficient)	1.0000	1.0000
Rework Equipment P4	1.0000	(Insufficient)	1.0000	1.0000
Rework Equipment P5	1.0000	(Insufficient)	1.0000	1.0000
Rework Operator	1.0000	(Insufficient)	1.0000	1.0000
Rework Operator P1	1.0000	(Insufficient)	1.0000	1.0000
Rework Operator P2	1.0000	(Insufficient)	1.0000	1.0000
Rework Operator P3	1.0000	(Insufficient)	1.0000	1.0000
Rework Operator P4	1.0000	(Insufficient)	1.0000	1.0000
Rework Operator P5	1.0000	(Insufficient)	1.0000	1.0000

Unnamed Project

Replications: 1 Time Units: Hours

Resource

Usage

Scheduled Utilization

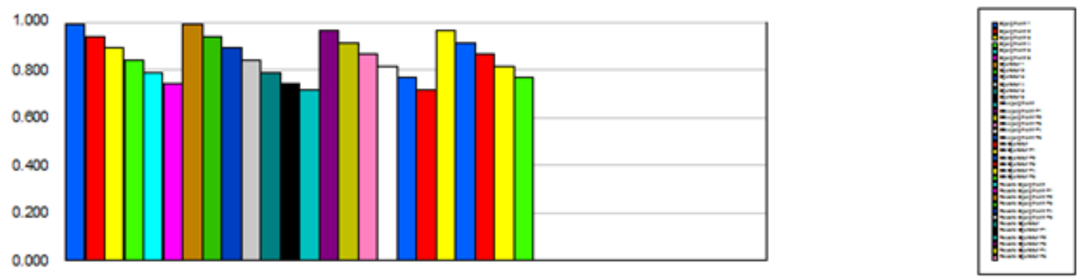
	Value
Equipment 1	0.9903
Equipment 2	0.9403
Equipment 3	0.8903
Equipment 4	0.8403
Equipment 5	0.7903
Equipment 6	0.7403
Operator 1	0.9903
Operator 2	0.9403
Operator 3	0.8903
Operator 4	0.8403
Operator 5	0.7903
Operator 6	0.7403
QC equipment	0.7153
QC equipment P1	0.9653
QC equipment P2	0.9153
QC equipment P3	0.8653
QC equipment P4	0.8153
QC equipment P5	0.7653
QC Operator	0.7153
QC Operator P1	0.9653
QC Operator P2	0.9153
QC Operator P3	0.8653
QC Operator P4	0.8153
QC Operator P5	0.7653
Rework Equipment	0.00
Rework Equipment P1	0.00
Rework Equipment P2	0.00
Rework Equipment P3	0.00
Rework Equipment P4	0.00
Rework Equipment P5	0.00
Rework Operator	0.00
Rework Operator P1	0.00
Rework Operator P2	0.00
Rework Operator P3	0.00
Rework Operator P4	0.00
Rework Operator P5	0.00

Unnamed Project

Replications: 1 Time Units: Hours

Resource

Usage



Unnamed Project

Replications: 1 Time Units: Hours

Resource

Usage

Total Number Seized

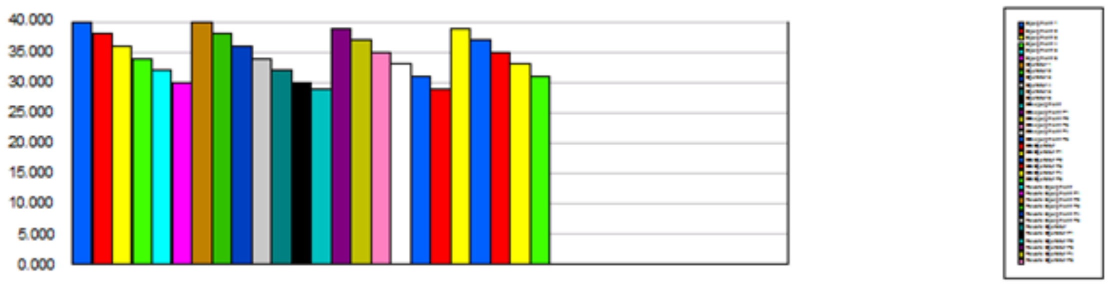
	Value
Equipment 1	40.0000
Equipment 2	38.0000
Equipment 3	36.0000
Equipment 4	34.0000
Equipment 5	32.0000
Equipment 6	30.0000
Operator 1	40.0000
Operator 2	38.0000
Operator 3	36.0000
Operator 4	34.0000
Operator 5	32.0000
Operator 6	30.0000
QC equipment	29.0000
QC equipment P1	39.0000
QC equipment P2	37.0000
QC equipment P3	35.0000
QC equipment P4	33.0000
QC equipment P5	31.0000
QC Operator	29.0000
QC Operator P1	39.0000
QC Operator P2	37.0000
QC Operator P3	35.0000
QC Operator P4	33.0000
QC Operator P5	31.0000
Rework Equipment	0.00
Rework Equipment P1	0.00
Rework Equipment P2	0.00
Rework Equipment P3	0.00
Rework Equipment P4	0.00
Rework Equipment P5	0.00
Rework Operator	0.00
Rework Operator P1	0.00
Rework Operator P2	0.00
Rework Operator P3	0.00
Rework Operator P4	0.00
Rework Operator P5	0.00

Unnamed Project

Replications: 1 Time Units: Hours

Resource

Usage



Cost

Unnamed Project

Replications: 1 Time Units: Hours

Resource

Cost

Busy Cost

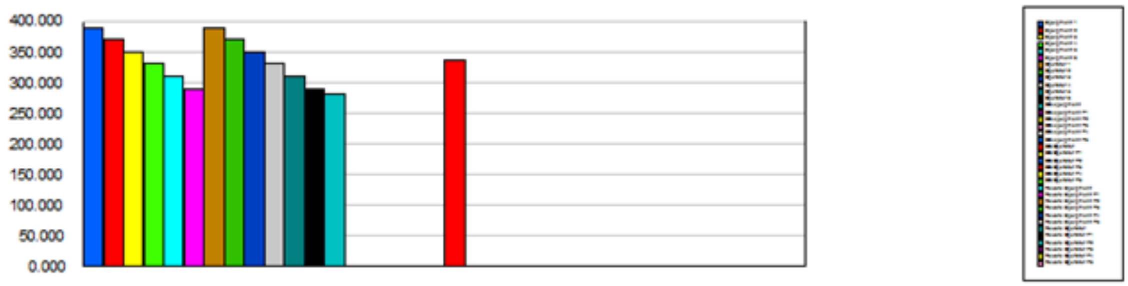
	Value
Equipment 1	390.00
Equipment 2	370.00
Equipment 3	350.00
Equipment 4	330.00
Equipment 5	310.00
Equipment 6	290.00
Operator 1	390.00
Operator 2	370.00
Operator 3	350.00
Operator 4	330.00
Operator 5	310.00
Operator 6	290.00
QC equipment	280.00
QC equipment P1	0.00
QC equipment P2	0.00
QC equipment P3	0.00
QC equipment P4	0.00
QC equipment P5	0.00
QC Operator	336.00
QC Operator P1	0.00
QC Operator P2	0.00
QC Operator P3	0.00
QC Operator P4	0.00
QC Operator P5	0.00
Rework Equipment	0.00
Rework Equipment P1	0.00
Rework Equipment P2	0.00
Rework Equipment P3	0.00
Rework Equipment P4	0.00
Rework Equipment P5	0.00
Rework Operator	0.00
Rework Operator P1	0.00
Rework Operator P2	0.00
Rework Operator P3	0.00
Rework Operator P4	0.00
Rework Operator P5	0.00

Unnamed Project

Replications: 1 Time Units: Hours

Resource

Cost



Unnamed Project

Replications: 1 Time Units: Hours

Resource

Cost

Idle Cost

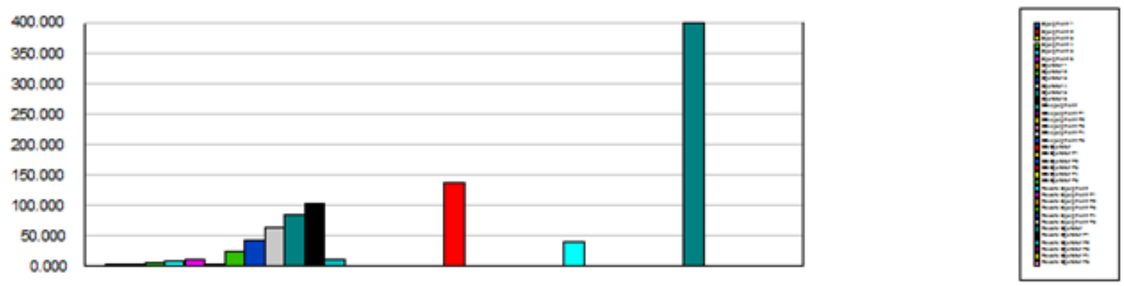
	Value
Equipment 1	0.3861
Equipment 2	2.3861
Equipment 3	4.3861
Equipment 4	6.3861
Equipment 5	8.3861
Equipment 6	10.3861
Operator 1	3.8610
Operator 2	23.8610
Operator 3	43.8610
Operator 4	63.8610
Operator 5	83.8610
Operator 6	103.86
QC equipment	11.3861
QC equipment P1	0.00
QC equipment P2	0.00
QC equipment P3	0.00
QC equipment P4	0.00
QC equipment P5	0.00
QC Operator	136.63
QC Operator P1	0.00
QC Operator P2	0.00
QC Operator P3	0.00
QC Operator P4	0.00
QC Operator P5	0.00
Rework Equipment	40.0000
Rework Equipment P1	0.00
Rework Equipment P2	0.00
Rework Equipment P3	0.00
Rework Equipment P4	0.00
Rework Equipment P5	0.00
Rework Operator	400.00
Rework Operator P1	0.00
Rework Operator P2	0.00
Rework Operator P3	0.00
Rework Operator P4	0.00
Rework Operator P5	0.00

Unnamed Project

Replications: 1 Time Units: Hours

Resource

Cost



Unnamed Project

Replications: 1 Time Units: Hours

Resource

Cost

Usage Cost

	Value
Equipment 1	0.00
Equipment 2	0.00
Equipment 3	0.00
Equipment 4	0.00
Equipment 5	0.00
Equipment 6	0.00
Operator 1	0.00
Operator 2	0.00
Operator 3	0.00
Operator 4	0.00
Operator 5	0.00
Operator 6	0.00
QC equipment	0.00
QC equipment P1	0.00
QC equipment P2	0.00
QC equipment P3	0.00
QC equipment P4	0.00
QC equipment P5	0.00
QC Operator	0.00
QC Operator P1	0.00
QC Operator P2	0.00
QC Operator P3	0.00
QC Operator P4	0.00
QC Operator P5	0.00
Rework Equipment	0.00
Rework Equipment P1	0.00
Rework Equipment P2	0.00
Rework Equipment P3	0.00
Rework Equipment P4	0.00
Rework Equipment P5	0.00
Rework Operator	0.00
Rework Operator P1	0.00
Rework Operator P2	0.00
Rework Operator P3	0.00
Rework Operator P4	0.00
Rework Operator P5	0.00

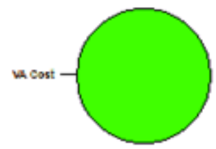
Unnamed Project

Replications: 1 Time Units: Hours

Key Performance Indicators

All Entities

	Average
Non-Value Added Cost	0
Other Cost	0
Transfer Cost	0
Value Added Cost	2,991
Wait Cost	0
Total Cost	2,991



All Resources

	Average
Busy Cost	2,851 *
Idle Cost	2,014
Usage Cost	0
Total Cost	4,865

* *these costs are included in Entity Costs above.*

System

	Average
Total Cost	5,006
Number Out	20

Unnamed Project

Replications: 1 Time Units: Hours

Entity

Time

VA Time	Average	Half Width	Minimum Value	Maximum Value
Entity 1	7.0262	(Insufficient)	6.8404	7.2298

NVA Time	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00

Wait Time	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00

Transfer Time	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00

Other Time	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00

Total Time	Average	Half Width	Minimum Value	Maximum Value
Entity 1	7.0262	(Insufficient)	6.8404	7.2298

Cost

VA Cost	Average	Half Width	Minimum Value	Maximum Value
Entity 1	150.55	(Insufficient)	146.65	154.82

NVA Cost	Average	Half Width	Minimum Value	Maximum Value
Entity 1	1.0000	(Insufficient)	1.0000	1.0000

Wait Cost	Average	Half Width	Minimum Value	Maximum Value
Entity 1	1.0000	(Insufficient)	1.0000	1.0000

Other Cost	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00

Transfer Cost	Average	Half Width	Minimum Value	Maximum Value
Entity 1	0.00	(Insufficient)	0.00	0.00

Unnamed Project

Replications: 1 Time Units: Hours

Entity

Cost

Total Cost	Average	Half Width	Minimum Value	Maximum Value
Entity 1	152.55	(Insufficient)	148.65	156.82

Other

Number In	Value
Entity 1	21.0000

Number Out	Value
Entity 1	20.0000

WIP	Average	Half Width	Minimum Value	Maximum Value
Entity 1	3.5131	(Insufficient)	3.0000	4.0000

Unnamed Project

Replications: 1 Time Units: Hours

Queue

Time

Waiting Time	Average	Half Width	Minimum Value	Maximum Value
Finshed Goods QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 1.Queue	0.00	(Insufficient)	0.00	0.00
Process 2.Queue	0.00	(Insufficient)	0.00	0.00
Process 3.Queue	0.00	(Insufficient)	0.00	0.00
Process 4.Queue	0.00	(Insufficient)	0.00	0.00
Process 5.Queue	0.00	(Insufficient)	0.00	0.00
Process 6.Queue	0.00	(Insufficient)	0.00	0.00

Cost

Waiting Cost	Average	Half Width	Minimum Value	Maximum Value
Finshed Goods QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 1.Queue	0.00	(Insufficient)	0.00	0.00
Process 2.Queue	0.00	(Insufficient)	0.00	0.00
Process 3.Queue	0.00	(Insufficient)	0.00	0.00
Process 4.Queue	0.00	(Insufficient)	0.00	0.00
Process 5.Queue	0.00	(Insufficient)	0.00	0.00
Process 6.Queue	0.00	(Insufficient)	0.00	0.00

Other

Number Waiting	Average	Half Width	Minimum Value	Maximum Value
Finshed Goods QC.Queue	0.00	(Insufficient)	0.00	0.00
Process 1.Queue	0.00	(Insufficient)	0.00	0.00
Process 2.Queue	0.00	(Insufficient)	0.00	0.00
Process 3.Queue	0.00	(Insufficient)	0.00	0.00
Process 4.Queue	0.00	(Insufficient)	0.00	0.00
Process 5.Queue	0.00	(Insufficient)	0.00	0.00
Process 6.Queue	0.00	(Insufficient)	0.00	0.00
Rework.Queue	0.00	(Insufficient)	0.00	0.00

Unnamed Project

Replications: 1 Time Units: Hours

Resource

Usage

Instantaneous Utilization	Average	Half Width	Minimum Value	Maximum Value
Equipment 1	0.5011	(Insufficient)	0.00	1.0000
Equipment 2	0.5096	(Insufficient)	0.00	1.0000
Equipment 3	0.5064	(Insufficient)	0.00	1.0000
Equipment 4	0.5003	(Insufficient)	0.00	1.0000
Equipment 5	0.5023	(Insufficient)	0.00	1.0000
Equipment 6	0.4943	(Insufficient)	0.00	1.0000
Operator 1	0.5011	(Insufficient)	0.00	1.0000
Operator 2	0.5096	(Insufficient)	0.00	1.0000
Operator 3	0.5064	(Insufficient)	0.00	1.0000
Operator 4	0.5003	(Insufficient)	0.00	1.0000
Operator 5	0.5023	(Insufficient)	0.00	1.0000
Operator 6	0.4943	(Insufficient)	0.00	1.0000
QC equipment	0.4991	(Insufficient)	0.00	1.0000
QC Operator	0.4991	(Insufficient)	0.00	1.0000
Rework Equipment	0.00	(Insufficient)	0.00	0.00
Rework Operator	0.00	(Insufficient)	0.00	0.00

Number Busy	Average	Half Width	Minimum Value	Maximum Value
Equipment 1	0.5011	(Insufficient)	0.00	1.0000
Equipment 2	0.5096	(Insufficient)	0.00	1.0000
Equipment 3	0.5064	(Insufficient)	0.00	1.0000
Equipment 4	0.5003	(Insufficient)	0.00	1.0000
Equipment 5	0.5023	(Insufficient)	0.00	1.0000
Equipment 6	0.4943	(Insufficient)	0.00	1.0000
Operator 1	0.5011	(Insufficient)	0.00	1.0000
Operator 2	0.5096	(Insufficient)	0.00	1.0000
Operator 3	0.5064	(Insufficient)	0.00	1.0000
Operator 4	0.5003	(Insufficient)	0.00	1.0000
Operator 5	0.5023	(Insufficient)	0.00	1.0000
Operator 6	0.4943	(Insufficient)	0.00	1.0000
QC equipment	0.4991	(Insufficient)	0.00	1.0000
QC Operator	0.4991	(Insufficient)	0.00	1.0000
Rework Equipment	0.00	(Insufficient)	0.00	0.00
Rework Operator	0.00	(Insufficient)	0.00	0.00

Unnamed Project

Replications: 1 Time Units: Hours

Resource

Usage

Number Scheduled	Average	Half Width	Minimum Value	Maximum Value
Equipment 1	1.0000	(Insufficient)	1.0000	1.0000
Equipment 2	1.0000	(Insufficient)	1.0000	1.0000
Equipment 3	1.0000	(Insufficient)	1.0000	1.0000
Equipment 4	1.0000	(Insufficient)	1.0000	1.0000
Equipment 5	1.0000	(Insufficient)	1.0000	1.0000
Equipment 6	1.0000	(Insufficient)	1.0000	1.0000
Operator 1	1.0000	(Insufficient)	1.0000	1.0000
Operator 2	1.0000	(Insufficient)	1.0000	1.0000
Operator 3	1.0000	(Insufficient)	1.0000	1.0000
Operator 4	1.0000	(Insufficient)	1.0000	1.0000
Operator 5	1.0000	(Insufficient)	1.0000	1.0000
Operator 6	1.0000	(Insufficient)	1.0000	1.0000
QC equipment	1.0000	(Insufficient)	1.0000	1.0000
QC Operator	1.0000	(Insufficient)	1.0000	1.0000
Rework Equipment	1.0000	(Insufficient)	1.0000	1.0000
Rework Operator	1.0000	(Insufficient)	1.0000	1.0000

Unnamed Project

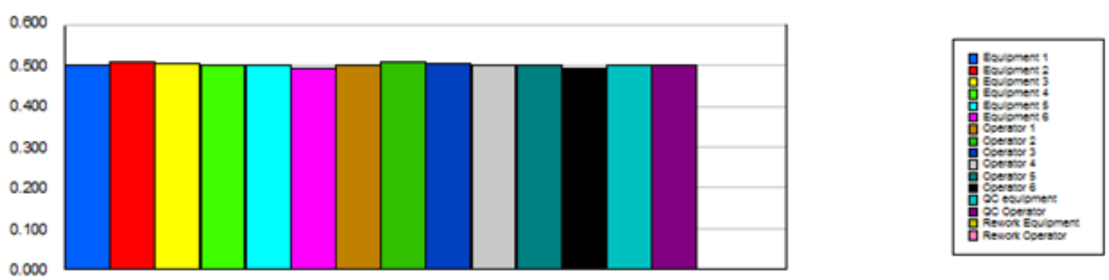
Replications: 1 Time Units: Hours

Resource

Usage

Scheduled Utilization

	Value
Equipment 1	0.5011
Equipment 2	0.5096
Equipment 3	0.5064
Equipment 4	0.5003
Equipment 5	0.5023
Equipment 6	0.4943
Operator 1	0.5011
Operator 2	0.5096
Operator 3	0.5064
Operator 4	0.5003
Operator 5	0.5023
Operator 6	0.4943
QC equipment	0.4991
QC Operator	0.4991
Rework Equipment	0.00
Rework Operator	0.00



Unnamed Project

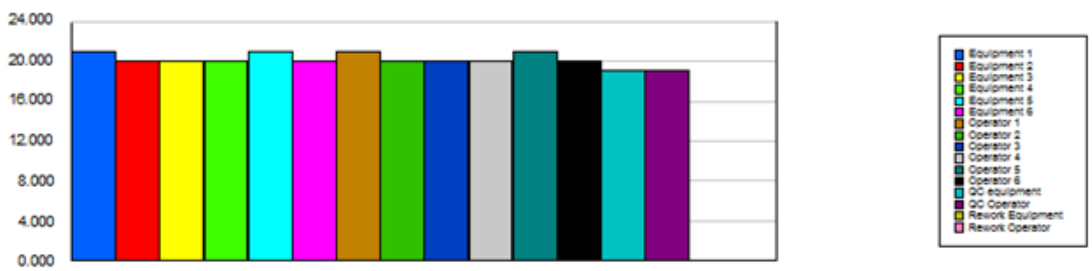
Replications: 1 Time Units: Hours

Resource

Usage

Total Number Seized

	Value
Equipment 1	21.0000
Equipment 2	20.0000
Equipment 3	20.0000
Equipment 4	20.0000
Equipment 5	21.0000
Equipment 6	20.0000
Operator 1	21.0000
Operator 2	20.0000
Operator 3	20.0000
Operator 4	20.0000
Operator 5	21.0000
Operator 6	20.0000
QC equipment	19.0000
QC Operator	19.0000
Rework Equipment	0.00
Rework Operator	0.00



Cost

Unnamed Project

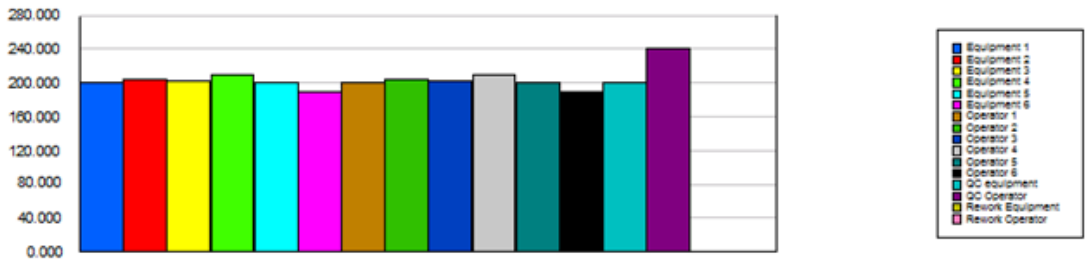
Replications: 1 Time Units: Hours

Resource

Cost

Busy Cost

	Value
Equipment 1	200.45
Equipment 2	203.86
Equipment 3	203.00
Equipment 4	209.29
Equipment 5	199.92
Equipment 6	188.92
Operator 1	200.45
Operator 2	203.86
Operator 3	203.00
Operator 4	209.29
Operator 5	199.92
Operator 6	188.92
QC equipment	200.00
QC Operator	240.00
Rework Equipment	0.00
Rework Operator	0.00



Unnamed Project

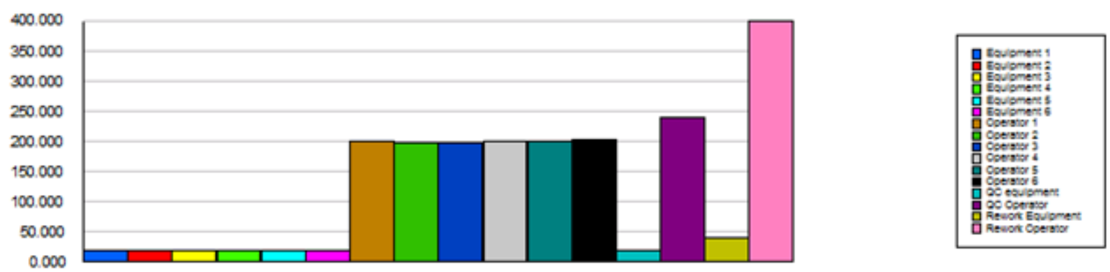
Replications: 1 Time Units: Hours

Resource

Cost

Idle Cost

	Value
Equipment 1	19.9547
Equipment 2	19.6145
Equipment 3	19.7458
Equipment 4	19.9883
Equipment 5	19.9069
Equipment 6	20.2287
Operator 1	199.55
Operator 2	196.14
Operator 3	197.46
Operator 4	199.88
Operator 5	199.07
Operator 6	202.29
QC equipment	20.0374
QC Operator	240.45
Rework Equipment	40.0000
Rework Operator	400.00



Unnamed Project

Replications: 1 Time Units: Hours

Resource

Cost

Usage Cost

	Value
Equipment 1	0.00
Equipment 2	0.00
Equipment 3	0.00
Equipment 4	0.00
Equipment 5	0.00
Equipment 6	0.00
Operator 1	0.00
Operator 2	0.00
Operator 3	0.00
Operator 4	0.00
Operator 5	0.00
Operator 6	0.00
QC equipment	0.00
QC Operator	0.00
Rework Equipment	0.00
Rework Operator	0.00

Appendix 2

Tukey and Fisher LSD analysis

Appendix 2 contains the results obtained from Minitab® in order to evaluate if the populations are statistically different. Tukey and Fisher LSD methods are used.

Input Rate

Cycle Time

Tukey Pairwise Comparisons

```
Grouping Information Using the Tukey Method and 95% Confidence

Input
time
rate    N   Mean  Grouping
1       8  123.5  A
2       8   38.5    B

Means that do not share a letter are significantly different.
```

Resource Utilization

Tukey Pairwise Comparisons

```
Grouping Information Using the Tukey Method and 95% Confidence

Input
time
rate    N    Mean  Grouping
1       8  0.7461  A
2       8  0.6302  A

Means that do not share a letter are significantly different.
```

Cost

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Input time rate	N	Mean	Grouping
2	8	0.5025	A
1	8	0.4950	A

Means that do not share a letter are significantly different.

Process Rate

Cycle Time

Fisher Pairwise Comparisons

Grouping Information Using the Fisher LSD Method and 95% Confidence

Process time rate	N	Mean	Grouping
2	8	96.2	A
1	8	65.9	A

Means that do not share a letter are significantly different.

Resource Utilization

Fisher Pairwise Comparisons

Grouping Information Using the Fisher LSD Method and 95% Confidence

Process time rate	N	Mean	Grouping
2	8	0.7465	A
1	8	0.6299	A

Means that do not share a letter are significantly different.

Cost

Fisher Pairwise Comparisons

Grouping Information Using the Fisher LSD Method and 95% Confidence

Process time rate	N	Mean	Grouping
2	8	0.6525	A
1	8	0.3450	B

Means that do not share a letter are significantly different.

QC Rate

Cycle Time

Fisher Pairwise Comparisons

Grouping Information Using the Fisher LSD Method and 95% Confidence

QC time rate	N	Mean	Grouping
2	8	107.2	A
1	8	54.9	A

Means that do not share a letter are significantly different.

Resource Utilization

Fisher Pairwise Comparisons

Grouping Information Using the Fisher LSD Method and 95% Confidence

QC time rate	N	Mean	Grouping
2	8	0.6916	A
1	8	0.6848	A

Means that do not share a letter are significantly different.

Cost

Fisher Pairwise Comparisons

Grouping Information Using the Fisher LSD Method and 95% Confidence

QC time rate	N	Mean	Grouping
2	8	0.5100	A
1	8	0.4875	A

Means that do not share a letter are significantly different.

Rework Rate

Cycle Time

Fisher Pairwise Comparisons

Grouping Information Using the Fisher LSD Method and 95% Confidence

Rework time rate	N	Mean	Grouping
1	8	86.4	A
2	8	75.7	A

Means that do not share a letter are significantly different.

Resource Utilization

Fisher Pairwise Comparisons

Grouping Information Using the Fisher LSD Method and 95% Confidence

Rework time rate	N	Mean	Grouping
2	8	0.7272	A
1	8	0.6492	A

Means that do not share a letter are significantly different.

Cost

Fisher Pairwise Comparisons

Grouping Information Using the Fisher LSD Method and 95% Confidence

Rework time rate	N	Mean	Grouping
2	8	0.7272	A
1	8	0.6492	A

Means that do not share a letter are significantly different.

Rework Stations

Cycle Time

Fisher Pairwise Comparisons

Grouping Information Using the Fisher LSD Method and 95% Confidence

No. Rework stations	N	Mean	Grouping
6	8	85.2	A
1	8	76.9	A

Means that do not share a letter are significantly different.

Resource Utilization

Fisher Pairwise Comparisons

Grouping Information Using the Fisher LSD Method and 95% Confidence

No. Rework stations	N	Mean	Grouping
1	8	0.7725	A
6	8	0.6039	B

Means that do not share a letter are significantly different.

Cost

Fisher Pairwise Comparisons

Grouping Information Using the Fisher LSD Method and 95% Confidence

No. Rework stations	N	Mean	Grouping
1	8	0.5475	A
6	8	0.4500	A

Means that do not share a letter are significantly different.

Sigma Level

Cycle Time

Fisher Pairwise Comparisons

Grouping Information Using the Fisher LSD Method and 95% Confidence

Quality Sigma level	N	Mean	Grouping
2	8	103.3	A
5	8	58.7	A

Means that do not share a letter are significantly different.

Resource Utilization

Fisher Pairwise Comparisons

Grouping Information Using the Fisher LSD Method and 95% Confidence

Quality Sigma level	N	Mean	Grouping
2	8	0.7525	A
5	8	0.6239	A

Means that do not share a letter are significantly different.

Cost

Fisher Pairwise Comparisons

Grouping Information Using the Fisher LSD Method and 95% Confidence

Quality Sigma level	N	Mean	Grouping
2	8	0.5100	A
5	8	0.4875	A

Means that do not share a letter are significantly different.

Appendix 3

GA Programming

Appendix 3 has the program used for the optimization through the GA.

```
Sub first_gen()
'
' first_gen Macro
'
'
    Range("A2").Select
    ActiveCell.FormulaR1C1 = "=RANDBETWEEN(0,1)"
    Range("A2").Select
    Selection.Copy
    Range("A3:A21").Select
    ActiveSheet.Paste
    Range("A2:A21").Select
    Application.CutCopyMode = False
    Selection.Copy
    Range("B2:T21").Select
    ActiveSheet.Paste
    Range("A22").Select
    Application.CutCopyMode = False
    ActiveCell.FormulaR1C1 = "a"
    Range("A22").Select
    ActiveCell.FormulaR1C1 = ""
    Range("A2:T21").Select
    Selection.Copy
```

```
    Range("A25").Select
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False
    Range("U21").Select
    Application.CutCopyMode = False
    Range("A23").Select
    ActiveCell.FormulaR1C1 = "a"
    Range("A23").Select
    ActiveCell.FormulaR1C1 = ""
    Range("A23").Select
End Sub
Sub first_to_eval()
'
' first_to_eval Macro
'

'
    Range("A25:T44").Select
    Selection.Copy
    Sheets("Evaluation").Select
    Range("A2").Select
    ActiveSheet.Paste
    Range("A23").Select
    Application.CutCopyMode = False
    ActiveCell.FormulaR1C1 = "a"
    Range("A23").Select
    ActiveCell.FormulaR1C1 = ""
```

```
    Range("A23").Select
End Sub



Sub first_gen()
'
' first_gen Macro
'

'
    Range("A2").Select
    ActiveCell.FormulaR1C1 = "=RANDBETWEEN(0,1)"
    Range("A2").Select
    Selection.Copy
    Range("A3:A21").Select
    ActiveSheet.Paste
    Range("A2:A21").Select
    Application.CutCopyMode = False
    Selection.Copy
    Range("B2:T21").Select
    ActiveSheet.Paste
    Range("A22").Select
    Application.CutCopyMode = False
    ActiveCell.FormulaR1C1 = "a"
    Range("A22").Select
    ActiveCell.FormulaR1C1 = ""
    Range("A2:T21").Select
```

```
    Selection.Copy
    Range("A25").Select
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False
    Range("U21").Select
    Application.CutCopyMode = False
    Range("A23").Select
    ActiveCell.FormulaR1C1 = "a"
    Range("A23").Select
    ActiveCell.FormulaR1C1 = ""
    Range("A23").Select
End Sub
Sub first_to_eval()
'
' first_to_eval Macro
'

'
    Range("A25:T44").Select
    Selection.Copy
    Sheets("Evaluation").Select
    Range("A2").Select
    ActiveSheet.Paste
    Range("A23").Select
    Application.CutCopyMode = False
    ActiveCell.FormulaR1C1 = "a"
    Range("A23").Select
```

```
    ActiveCell.FormulaR1C1 = ""
    Range("A23").Select
End Sub


Sub Select_best()
'
' Select_best Macro
'

'
    Columns("Z:Z").Select
    ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
    ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range("Z1") _
        , SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:=xlSortNormal
    With ActiveWorkbook.Worksheets("Evaluation").Sort
        .SetRange Range("A2:Z28")
        .Header = xlGuess
        .MatchCase = False
        .Orientation = xlTopToBottom
        .SortMethod = xlPinYin
        .Apply
    End With
    ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
    ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range("Z1") _
        , SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:=xlSortNormal
    With ActiveWorkbook.Worksheets("Evaluation").Sort
```

```
    .SetRange Range("A2:Z28")
    .Header = xlGuess
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range("Z1") _
    , SortOn:=xlSortOnValues, Order:=xlDescending, DataOption:=xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
    .SetRange Range("A2:Z28")
    .Header = xlGuess
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
Range("A2:T10").Select
Selection.Copy
Range("A29").Select
ActiveSheet.Paste
Range("A27").Select
Application.CutCopyMode = False
ActiveCell.FormulaR1C1 = "q"
Range("A27").Select
ActiveCell.FormulaR1C1 = ""
```

```
    Range("A27").Select
End Sub
Sub Cross_over()
'
' Cross_over Macro
'

'
    Range("K29:T37").Select
    Selection.Copy
    Range("A38").Select
    ActiveSheet.Paste
    Range("A29:J37").Select
    Application.CutCopyMode = False
    Selection.Copy
    Range("K38").Select
    ActiveSheet.Paste
    ActiveWindow.SmallScroll Down:=11
    Range("A29:T30").Select
    Application.CutCopyMode = False
    Selection.Copy
    Range("A47").Select
    ActiveSheet.Paste
    Range("A47").Select
    Application.CutCopyMode = False
    ActiveCell.FormulaR1C1 = "0"
    Range("J47").Select
```

```
    ActiveCell.FormulaR1C1 = "1"
    Range("T47").Select
    ActiveCell.FormulaR1C1 = "0"
    Range("R48").Select
    ActiveCell.FormulaR1C1 = "1"
    Range("M48").Select
    ActiveCell.FormulaR1C1 = "1"
    Range("F48").Select
    ActiveCell.FormulaR1C1 = "0"
    Range("A48").Select
    ActiveCell.FormulaR1C1 = "1"
    Range("A26").Select
    ActiveCell.FormulaR1C1 = "a"
    Range("A26").Select
    ActiveCell.FormulaR1C1 = ""
    Range("A26").Select
End Sub
Sub new_gen()
'
' new_gen Macro
'

'
    Range("A29:T48").Select
    Selection.Copy
    ActiveWindow.SmallScroll Down:=-221
    Range("A2").Select
```

```
    ActiveSheet.Paste
    Range("U2:Y21").Select
    Application.CutCopyMode = False
    Selection.ClearContents
    Range("A29:T48").Select
    Selection.ClearContents
    ActiveWindow.SmallScroll Down:=-73
    Range("A26").Select
    ActiveCell.FormulaR1C1 = "a"
    Range("A26").Select
    ActiveCell.FormulaR1C1 = ""
    Range("A26").Select
End Sub
Sub Evaluation_rev2()
'
' Evaluation_rev2 Macro
'

'
    Range("AB2:AB21").Select
    Selection.Copy
    Range("U2").Select
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False
    Range("A1:U21").Select
    Application.CutCopyMode = False
    ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
```

```
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range( _
    "U2:U21"), SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:= _
    xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
    .SetRange Range("A1:U21")
    .Header = xlYes
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
Range("V2").Select
ActiveCell.FormulaR1C1 = "20"
Range("V3").Select
ActiveCell.FormulaR1C1 = "19"
Range("V4").Select
ActiveCell.FormulaR1C1 = "18"
Range("V5").Select
ActiveCell.FormulaR1C1 = "17"
Range("V6").Select
ActiveCell.FormulaR1C1 = "16"
Range("V7").Select
ActiveCell.FormulaR1C1 = "15"
Range("V8").Select
ActiveCell.FormulaR1C1 = "14"
Range("V9").Select
ActiveCell.FormulaR1C1 = "13"
```

```
Range("V10").Select
ActiveCell.FormulaR1C1 = "12"
Range("V11").Select
ActiveCell.FormulaR1C1 = "11"
Range("V12").Select
ActiveCell.FormulaR1C1 = "10"
Range("V13").Select
ActiveCell.FormulaR1C1 = "9"
Range("V14").Select
ActiveCell.FormulaR1C1 = "8"
Range("V15").Select
ActiveCell.FormulaR1C1 = "7"
Range("V16").Select
ActiveCell.FormulaR1C1 = "6"
Range("V17").Select
ActiveCell.FormulaR1C1 = "5"
Range("V18").Select
ActiveCell.FormulaR1C1 = "4"
Range("V19").Select
ActiveCell.FormulaR1C1 = "3"
Range("V20").Select
ActiveCell.FormulaR1C1 = "2"
Range("V21").Select
ActiveCell.FormulaR1C1 = "1"
Range("AC2:AC21").Select
Selection.Copy
Range("U2").Select
```

```
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
Range("A1:V21").Select
Application.CutCopyMode = False
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range( _
    "U2:U21"), SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:= _
    xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
    .SetRange Range("A1:V21")
    .Header = xlYes
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
Range("W2").Select
ActiveCell.FormulaR1C1 = "20"
Range("W3").Select
ActiveCell.FormulaR1C1 = "19"
Range("W4").Select
ActiveCell.FormulaR1C1 = "18"
Range("W5").Select
ActiveCell.FormulaR1C1 = "17"
Range("W6").Select
ActiveCell.FormulaR1C1 = "16"
Range("W7").Select
```

```
ActiveCell.FormulaR1C1 = "15"
Range("W8").Select
ActiveCell.FormulaR1C1 = "14"
Range("W9").Select
ActiveCell.FormulaR1C1 = "13"
Range("W10").Select
ActiveCell.FormulaR1C1 = "12"
Range("W11").Select
ActiveCell.FormulaR1C1 = "11"
Range("W12").Select
ActiveCell.FormulaR1C1 = "10"
Range("W13").Select
ActiveCell.FormulaR1C1 = "9"
Range("W14").Select
ActiveCell.FormulaR1C1 = "8"
Range("W15").Select
ActiveCell.FormulaR1C1 = "7"
Range("W16").Select
ActiveCell.FormulaR1C1 = "6"
Range("W17").Select
ActiveCell.FormulaR1C1 = "5"
Range("W18").Select
ActiveCell.FormulaR1C1 = "4"
Range("W19").Select
ActiveCell.FormulaR1C1 = "3"
Range("W20").Select
ActiveCell.FormulaR1C1 = "2"
```

```
Range("W21").Select
ActiveCell.FormulaR1C1 = "1"
Range("AD2:AD21").Select
Selection.Copy
Range("U2").Select
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
Range("A1:W21").Select
Application.CutCopyMode = False
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range( _
    "U2:U21"), SortOn:=xlSortOnValues, Order:=xlDescending, DataOption:= _
    xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
    .SetRange Range("A1:W21")
    .Header = xlYes
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
Range("X2").Select
ActiveCell.FormulaR1C1 = "20"
Range("X3").Select
ActiveCell.FormulaR1C1 = "19"
Range("X4").Select
ActiveCell.FormulaR1C1 = "18"
```

```
Range("X5").Select
ActiveCell.FormulaR1C1 = "17"
Range("X6").Select
ActiveCell.FormulaR1C1 = "16"
Range("X7").Select
ActiveCell.FormulaR1C1 = "15"
Range("X8").Select
ActiveCell.FormulaR1C1 = "14"
Range("X9").Select
ActiveCell.FormulaR1C1 = "13"
Range("X10").Select
ActiveCell.FormulaR1C1 = "12"
Range("X11").Select
ActiveCell.FormulaR1C1 = "11"
Range("X12").Select
ActiveCell.FormulaR1C1 = "10"
Range("X13").Select
ActiveCell.FormulaR1C1 = "9"
Range("X14").Select
ActiveCell.FormulaR1C1 = "8"
Range("X15").Select
ActiveCell.FormulaR1C1 = "7"
Range("X16").Select
ActiveCell.FormulaR1C1 = "6"
Range("X17").Select
ActiveCell.FormulaR1C1 = "5"
Range("X18").Select
```

```
ActiveCell.FormulaR1C1 = "4"
Range("X19").Select
ActiveCell.FormulaR1C1 = "3"
Range("X20").Select
ActiveCell.FormulaR1C1 = "2"
Range("X21").Select
ActiveCell.FormulaR1C1 = "1"
Range("AE2:AE21").Select
Selection.Copy
Range("U2").Select
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
Range("A1:X21").Select
Application.CutCopyMode = False
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range( _
    "U2:U21"), SortOn:=xlSortOnValues, Order:=xlDescending, DataOption:= _
    xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
    .SetRange Range("A1:X21")
    .Header = xlYes
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
Range("Y2").Select
```

```
ActiveCell.FormulaR1C1 = "20"
Range("Y3").Select
ActiveCell.FormulaR1C1 = "19"
Range("Y4").Select
ActiveCell.FormulaR1C1 = "18"
Range("Y5").Select
ActiveCell.FormulaR1C1 = "17"
Range("Y6").Select
ActiveCell.FormulaR1C1 = "16"
Range("Y7").Select
ActiveCell.FormulaR1C1 = "15"
Range("Y8").Select
ActiveCell.FormulaR1C1 = "14"
Range("Y9").Select
ActiveCell.FormulaR1C1 = "13"
Range("Y10").Select
ActiveCell.FormulaR1C1 = "12"
Range("Y11").Select
ActiveCell.FormulaR1C1 = "11"
Range("Y12").Select
ActiveCell.FormulaR1C1 = "10"
Range("Y13").Select
ActiveCell.FormulaR1C1 = "9"
Range("Y14").Select
ActiveCell.FormulaR1C1 = "8"
Range("Y15").Select
ActiveCell.FormulaR1C1 = "7"
```

```
    Range("Y16").Select
    ActiveCell.FormulaR1C1 = "6"
    Range("Y17").Select
    ActiveCell.FormulaR1C1 = "5"
    Range("Y18").Select
    ActiveCell.FormulaR1C1 = "4"
    Range("Y19").Select
    ActiveCell.FormulaR1C1 = "3"
    Range("Y20").Select
    ActiveCell.FormulaR1C1 = "2"
    Range("Y21").Select
    ActiveCell.FormulaR1C1 = "1"
    Range("Y22").Select
    ActiveCell.FormulaR1C1 = "q"
    Range("Y22").Select
    ActiveCell.FormulaR1C1 = ""
    Range("X22").Select
End Sub


Sub Select_best()
'
' Select_best Macro
'

'
    Columns("Z:Z").Select
```

```
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range("Z1") _
    , SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:=xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
    .SetRange Range("A2:Z28")
    .Header = xlGuess
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range("Z1") _
    , SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:=xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
    .SetRange Range("A2:Z28")
    .Header = xlGuess
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range("Z1") _
    , SortOn:=xlSortOnValues, Order:=xlDescending, DataOption:=xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
    .SetRange Range("A2:Z28")
```

```
        .Header = xlGuess
        .MatchCase = False
        .Orientation = xlTopToBottom
        .SortMethod = xlPinYin
        .Apply
    End With
    Range("A2:T10").Select
    Selection.Copy
    Range("A29").Select
    ActiveSheet.Paste
    Range("A27").Select
    Application.CutCopyMode = False
    ActiveCell.FormulaR1C1 = "q"
    Range("A27").Select
    ActiveCell.FormulaR1C1 = ""
    Range("A27").Select
End Sub
Sub Cross_over()
'
' Cross_over Macro
'

'
    Range("K29:T37").Select
    Selection.Copy
    Range("A38").Select
    ActiveSheet.Paste
```

```
Range("A29:J37").Select
Application.CutCopyMode = False
Selection.Copy
Range("K38").Select
ActiveSheet.Paste
ActiveWindow.SmallScroll Down:=11
Range("A29:T30").Select
Application.CutCopyMode = False
Selection.Copy
Range("A47").Select
ActiveSheet.Paste
Range("A47").Select
Application.CutCopyMode = False
ActiveCell.FormulaR1C1 = "0"
Range("J47").Select
ActiveCell.FormulaR1C1 = "1"
Range("T47").Select
ActiveCell.FormulaR1C1 = "0"
Range("R48").Select
ActiveCell.FormulaR1C1 = "1"
Range("M48").Select
ActiveCell.FormulaR1C1 = "1"
Range("F48").Select
ActiveCell.FormulaR1C1 = "0"
Range("A48").Select
ActiveCell.FormulaR1C1 = "1"
Range("A26").Select
```

```
    ActiveCell.FormulaR1C1 = "a"
    Range("A26").Select
    ActiveCell.FormulaR1C1 = ""
    Range("A26").Select
End Sub
Sub new_gen()
'
' new_gen Macro
'

'
    Range("A29:T48").Select
    Selection.Copy
    ActiveWindow.SmallScroll Down:=-221
    Range("A2").Select
    ActiveSheet.Paste
    Range("U2:Y21").Select
    Application.CutCopyMode = False
    Selection.ClearContents
    Range("A29:T48").Select
    Selection.ClearContents
    ActiveWindow.SmallScroll Down:=-73
    Range("A26").Select
    ActiveCell.FormulaR1C1 = "a"
    Range("A26").Select
    ActiveCell.FormulaR1C1 = ""
    Range("A26").Select
```

```
End Sub
Sub Evaluation_rev2()
'
' Evaluation_rev2 Macro
'

'
    Range("AB2:AB21").Select
    Selection.Copy
    Range("U2").Select
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False
    Range("A1:U21").Select
    Application.CutCopyMode = False
    ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
    ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range( _
        "U2:U21"), SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:= _
        xlSortNormal
    With ActiveWorkbook.Worksheets("Evaluation").Sort
        .SetRange Range("A1:U21")
        .Header = xlYes
        .MatchCase = False
        .Orientation = xlTopToBottom
        .SortMethod = xlPinYin
        .Apply
    End With
    Range("V2").Select
```

```
ActiveCell.FormulaR1C1 = "20"
Range("V3").Select
ActiveCell.FormulaR1C1 = "19"
Range("V4").Select
ActiveCell.FormulaR1C1 = "18"
Range("V5").Select
ActiveCell.FormulaR1C1 = "17"
Range("V6").Select
ActiveCell.FormulaR1C1 = "16"
Range("V7").Select
ActiveCell.FormulaR1C1 = "15"
Range("V8").Select
ActiveCell.FormulaR1C1 = "14"
Range("V9").Select
ActiveCell.FormulaR1C1 = "13"
Range("V10").Select
ActiveCell.FormulaR1C1 = "12"
Range("V11").Select
ActiveCell.FormulaR1C1 = "11"
Range("V12").Select
ActiveCell.FormulaR1C1 = "10"
Range("V13").Select
ActiveCell.FormulaR1C1 = "9"
Range("V14").Select
ActiveCell.FormulaR1C1 = "8"
Range("V15").Select
ActiveCell.FormulaR1C1 = "7"
```

```
Range("V16").Select
ActiveCell.FormulaR1C1 = "6"
Range("V17").Select
ActiveCell.FormulaR1C1 = "5"
Range("V18").Select
ActiveCell.FormulaR1C1 = "4"
Range("V19").Select
ActiveCell.FormulaR1C1 = "3"
Range("V20").Select
ActiveCell.FormulaR1C1 = "2"
Range("V21").Select
ActiveCell.FormulaR1C1 = "1"
Range("AC2:AC21").Select
Selection.Copy
Range("U2").Select
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
   False, Transpose:=False
Range("A1:V21").Select
Application.CutCopyMode = False
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range( _
   "U2:U21"), SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:= _
   xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
   .SetRange Range("A1:V21")
   .Header = xlYes
   .MatchCase = False
```

```
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
Range("W2").Select
ActiveCell.FormulaR1C1 = "20"
Range("W3").Select
ActiveCell.FormulaR1C1 = "19"
Range("W4").Select
ActiveCell.FormulaR1C1 = "18"
Range("W5").Select
ActiveCell.FormulaR1C1 = "17"
Range("W6").Select
ActiveCell.FormulaR1C1 = "16"
Range("W7").Select
ActiveCell.FormulaR1C1 = "15"
Range("W8").Select
ActiveCell.FormulaR1C1 = "14"
Range("W9").Select
ActiveCell.FormulaR1C1 = "13"
Range("W10").Select
ActiveCell.FormulaR1C1 = "12"
Range("W11").Select
ActiveCell.FormulaR1C1 = "11"
Range("W12").Select
ActiveCell.FormulaR1C1 = "10"
Range("W13").Select
```

```
ActiveCell.FormulaR1C1 = "9"
Range("W14").Select
ActiveCell.FormulaR1C1 = "8"
Range("W15").Select
ActiveCell.FormulaR1C1 = "7"
Range("W16").Select
ActiveCell.FormulaR1C1 = "6"
Range("W17").Select
ActiveCell.FormulaR1C1 = "5"
Range("W18").Select
ActiveCell.FormulaR1C1 = "4"
Range("W19").Select
ActiveCell.FormulaR1C1 = "3"
Range("W20").Select
ActiveCell.FormulaR1C1 = "2"
Range("W21").Select
ActiveCell.FormulaR1C1 = "1"
Range("AD2:AD21").Select
Selection.Copy
Range("U2").Select
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
   False, Transpose:=False
Range("A1:W21").Select
Application.CutCopyMode = False
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range( _
   "U2:U21"), SortOn:=xlSortOnValues, Order:=xlDescending, DataOption:= _
```

```
    xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
    .SetRange Range("A1:W21")
    .Header = xlYes
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
Range("X2").Select
ActiveCell.FormulaR1C1 = "20"
Range("X3").Select
ActiveCell.FormulaR1C1 = "19"
Range("X4").Select
ActiveCell.FormulaR1C1 = "18"
Range("X5").Select
ActiveCell.FormulaR1C1 = "17"
Range("X6").Select
ActiveCell.FormulaR1C1 = "16"
Range("X7").Select
ActiveCell.FormulaR1C1 = "15"
Range("X8").Select
ActiveCell.FormulaR1C1 = "14"
Range("X9").Select
ActiveCell.FormulaR1C1 = "13"
Range("X10").Select
ActiveCell.FormulaR1C1 = "12"
```

```
Range("X11").Select
ActiveCell.FormulaR1C1 = "11"
Range("X12").Select
ActiveCell.FormulaR1C1 = "10"
Range("X13").Select
ActiveCell.FormulaR1C1 = "9"
Range("X14").Select
ActiveCell.FormulaR1C1 = "8"
Range("X15").Select
ActiveCell.FormulaR1C1 = "7"
Range("X16").Select
ActiveCell.FormulaR1C1 = "6"
Range("X17").Select
ActiveCell.FormulaR1C1 = "5"
Range("X18").Select
ActiveCell.FormulaR1C1 = "4"
Range("X19").Select
ActiveCell.FormulaR1C1 = "3"
Range("X20").Select
ActiveCell.FormulaR1C1 = "2"
Range("X21").Select
ActiveCell.FormulaR1C1 = "1"
Range("AE2:AE21").Select
Selection.Copy
Range("U2").Select
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
```

```
Range("A1:X21").Select
Application.CutCopyMode = False
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range( _
    "U2:U21"), SortOn:=xlSortOnValues, Order:=xlDescending, DataOption:= _
    xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
    .SetRange Range("A1:X21")
    .Header = xlYes
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
Range("Y2").Select
ActiveCell.FormulaR1C1 = "20"
Range("Y3").Select
ActiveCell.FormulaR1C1 = "19"
Range("Y4").Select
ActiveCell.FormulaR1C1 = "18"
Range("Y5").Select
ActiveCell.FormulaR1C1 = "17"
Range("Y6").Select
ActiveCell.FormulaR1C1 = "16"
Range("Y7").Select
ActiveCell.FormulaR1C1 = "15"
Range("Y8").Select
```

```
ActiveCell.FormulaR1C1 = "14"
Range("Y9").Select
ActiveCell.FormulaR1C1 = "13"
Range("Y10").Select
ActiveCell.FormulaR1C1 = "12"
Range("Y11").Select
ActiveCell.FormulaR1C1 = "11"
Range("Y12").Select
ActiveCell.FormulaR1C1 = "10"
Range("Y13").Select
ActiveCell.FormulaR1C1 = "9"
Range("Y14").Select
ActiveCell.FormulaR1C1 = "8"
Range("Y15").Select
ActiveCell.FormulaR1C1 = "7"
Range("Y16").Select
ActiveCell.FormulaR1C1 = "6"
Range("Y17").Select
ActiveCell.FormulaR1C1 = "5"
Range("Y18").Select
ActiveCell.FormulaR1C1 = "4"
Range("Y19").Select
ActiveCell.FormulaR1C1 = "3"
Range("Y20").Select
ActiveCell.FormulaR1C1 = "2"
Range("Y21").Select
ActiveCell.FormulaR1C1 = "1"
```

```
    Range("Y22").Select
    ActiveCell.FormulaR1C1 = "q"
    Range("Y22").Select
    ActiveCell.FormulaR1C1 = ""
    Range("X22").Select
End Sub


Sub Select_best()
'
' Select_best Macro
'

'
    Columns("Z:Z").Select
    ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
    ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range("Z1") _
        , SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:=xlSortNormal
    With ActiveWorkbook.Worksheets("Evaluation").Sort
        .SetRange Range("A2:Z28")
        .Header = xlGuess
        .MatchCase = False
        .Orientation = xlTopToBottom
        .SortMethod = xlPinYin
        .Apply
    End With
    ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
```

```
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range("Z1") _
    , SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:=xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
    .SetRange Range("A2:Z28")
    .Header = xlGuess
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range("Z1") _
    , SortOn:=xlSortOnValues, Order:=xlDescending, DataOption:=xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
    .SetRange Range("A2:Z28")
    .Header = xlGuess
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
Range("A2:T10").Select
Selection.Copy
Range("A29").Select
ActiveSheet.Paste
Range("A27").Select
Application.CutCopyMode = False
```

```
    ActiveCell.FormulaR1C1 = "q"
    Range("A27").Select
    ActiveCell.FormulaR1C1 = ""
    Range("A27").Select
End Sub
Sub Cross_over()
'
' Cross_over Macro
'

'
    Range("K29:T37").Select
    Selection.Copy
    Range("A38").Select
    ActiveSheet.Paste
    Range("A29:J37").Select
    Application.CutCopyMode = False
    Selection.Copy
    Range("K38").Select
    ActiveSheet.Paste
    ActiveWindow.SmallScroll Down:=11
    Range("A29:T30").Select
    Application.CutCopyMode = False
    Selection.Copy
    Range("A47").Select
    ActiveSheet.Paste
    Range("A47").Select
```

```
    Application.CutCopyMode = False
    ActiveCell.FormulaR1C1 = "0"
    Range("J47").Select
    ActiveCell.FormulaR1C1 = "1"
    Range("T47").Select
    ActiveCell.FormulaR1C1 = "0"
    Range("R48").Select
    ActiveCell.FormulaR1C1 = "1"
    Range("M48").Select
    ActiveCell.FormulaR1C1 = "1"
    Range("F48").Select
    ActiveCell.FormulaR1C1 = "0"
    Range("A48").Select
    ActiveCell.FormulaR1C1 = "1"
    Range("A26").Select
    ActiveCell.FormulaR1C1 = "a"
    Range("A26").Select
    ActiveCell.FormulaR1C1 = ""
    Range("A26").Select
End Sub
Sub new_gen()
'
' new_gen Macro
'


'
    Range("A29:T48").Select
```

```
    Selection.Copy
    ActiveWindow.SmallScroll Down:=-221
    Range("A2").Select
    ActiveSheet.Paste
    Range("U2:Y21").Select
    Application.CutCopyMode = False
    Selection.ClearContents
    Range("A29:T48").Select
    Selection.ClearContents
    ActiveWindow.SmallScroll Down:=-73
    Range("A26").Select
    ActiveCell.FormulaR1C1 = "a"
    Range("A26").Select
    ActiveCell.FormulaR1C1 = ""
    Range("A26").Select
End Sub
Sub Evaluation_rev2()
'
' Evaluation_rev2 Macro
'

'
    Range("AB2:AB21").Select
    Selection.Copy
    Range("U2").Select
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False
```

```
Range("A1:U21").Select
Application.CutCopyMode = False
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range( _
    "U2:U21"), SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:= _
    xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
    .SetRange Range("A1:U21")
    .Header = xlYes
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
Range("V2").Select
ActiveCell.FormulaR1C1 = "20"
Range("V3").Select
ActiveCell.FormulaR1C1 = "19"
Range("V4").Select
ActiveCell.FormulaR1C1 = "18"
Range("V5").Select
ActiveCell.FormulaR1C1 = "17"
Range("V6").Select
ActiveCell.FormulaR1C1 = "16"
Range("V7").Select
ActiveCell.FormulaR1C1 = "15"
Range("V8").Select
```

```
ActiveCell.FormulaR1C1 = "14"
Range("V9").Select
ActiveCell.FormulaR1C1 = "13"
Range("V10").Select
ActiveCell.FormulaR1C1 = "12"
Range("V11").Select
ActiveCell.FormulaR1C1 = "11"
Range("V12").Select
ActiveCell.FormulaR1C1 = "10"
Range("V13").Select
ActiveCell.FormulaR1C1 = "9"
Range("V14").Select
ActiveCell.FormulaR1C1 = "8"
Range("V15").Select
ActiveCell.FormulaR1C1 = "7"
Range("V16").Select
ActiveCell.FormulaR1C1 = "6"
Range("V17").Select
ActiveCell.FormulaR1C1 = "5"
Range("V18").Select
ActiveCell.FormulaR1C1 = "4"
Range("V19").Select
ActiveCell.FormulaR1C1 = "3"
Range("V20").Select
ActiveCell.FormulaR1C1 = "2"
Range("V21").Select
ActiveCell.FormulaR1C1 = "1"
```

```
Range("AC2:AC21").Select
Selection.Copy
Range("U2").Select
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
Range("A1:V21").Select
Application.CutCopyMode = False
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range( _
    "U2:U21"), SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:= _
    xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
    .SetRange Range("A1:V21")
    .Header = xlYes
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
Range("W2").Select
ActiveCell.FormulaR1C1 = "20"
Range("W3").Select
ActiveCell.FormulaR1C1 = "19"
Range("W4").Select
ActiveCell.FormulaR1C1 = "18"
Range("W5").Select
ActiveCell.FormulaR1C1 = "17"
```

```
Range("W6").Select
ActiveCell.FormulaR1C1 = "16"
Range("W7").Select
ActiveCell.FormulaR1C1 = "15"
Range("W8").Select
ActiveCell.FormulaR1C1 = "14"
Range("W9").Select
ActiveCell.FormulaR1C1 = "13"
Range("W10").Select
ActiveCell.FormulaR1C1 = "12"
Range("W11").Select
ActiveCell.FormulaR1C1 = "11"
Range("W12").Select
ActiveCell.FormulaR1C1 = "10"
Range("W13").Select
ActiveCell.FormulaR1C1 = "9"
Range("W14").Select
ActiveCell.FormulaR1C1 = "8"
Range("W15").Select
ActiveCell.FormulaR1C1 = "7"
Range("W16").Select
ActiveCell.FormulaR1C1 = "6"
Range("W17").Select
ActiveCell.FormulaR1C1 = "5"
Range("W18").Select
ActiveCell.FormulaR1C1 = "4"
Range("W19").Select
```

```
ActiveCell.FormulaR1C1 = "3"
Range("W20").Select
ActiveCell.FormulaR1C1 = "2"
Range("W21").Select
ActiveCell.FormulaR1C1 = "1"
Range("AD2:AD21").Select
Selection.Copy
Range("U2").Select
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
Range("A1:W21").Select
Application.CutCopyMode = False
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range( _
    "U2:U21"), SortOn:=xlSortOnValues, Order:=xlDescending, DataOption:= _
    xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
    .SetRange Range("A1:W21")
    .Header = xlYes
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
Range("X2").Select
ActiveCell.FormulaR1C1 = "20"
Range("X3").Select
```

```
ActiveCell.FormulaR1C1 = "19"
Range("X4").Select
ActiveCell.FormulaR1C1 = "18"
Range("X5").Select
ActiveCell.FormulaR1C1 = "17"
Range("X6").Select
ActiveCell.FormulaR1C1 = "16"
Range("X7").Select
ActiveCell.FormulaR1C1 = "15"
Range("X8").Select
ActiveCell.FormulaR1C1 = "14"
Range("X9").Select
ActiveCell.FormulaR1C1 = "13"
Range("X10").Select
ActiveCell.FormulaR1C1 = "12"
Range("X11").Select
ActiveCell.FormulaR1C1 = "11"
Range("X12").Select
ActiveCell.FormulaR1C1 = "10"
Range("X13").Select
ActiveCell.FormulaR1C1 = "9"
Range("X14").Select
ActiveCell.FormulaR1C1 = "8"
Range("X15").Select
ActiveCell.FormulaR1C1 = "7"
Range("X16").Select
ActiveCell.FormulaR1C1 = "6"
```

```
Range("X17").Select
ActiveCell.FormulaR1C1 = "5"
Range("X18").Select
ActiveCell.FormulaR1C1 = "4"
Range("X19").Select
ActiveCell.FormulaR1C1 = "3"
Range("X20").Select
ActiveCell.FormulaR1C1 = "2"
Range("X21").Select
ActiveCell.FormulaR1C1 = "1"
Range("AE2:AE21").Select
Selection.Copy
Range("U2").Select
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
Range("A1:X21").Select
Application.CutCopyMode = False
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range( _
    "U2:U21"), SortOn:=xlSortOnValues, Order:=xlDescending, DataOption:= _
    xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
    .SetRange Range("A1:X21")
    .Header = xlYes
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
```

```
    .Apply
End With
Range("Y2").Select
ActiveCell.FormulaR1C1 = "20"
Range("Y3").Select
ActiveCell.FormulaR1C1 = "19"
Range("Y4").Select
ActiveCell.FormulaR1C1 = "18"
Range("Y5").Select
ActiveCell.FormulaR1C1 = "17"
Range("Y6").Select
ActiveCell.FormulaR1C1 = "16"
Range("Y7").Select
ActiveCell.FormulaR1C1 = "15"
Range("Y8").Select
ActiveCell.FormulaR1C1 = "14"
Range("Y9").Select
ActiveCell.FormulaR1C1 = "13"
Range("Y10").Select
ActiveCell.FormulaR1C1 = "12"
Range("Y11").Select
ActiveCell.FormulaR1C1 = "11"
Range("Y12").Select
ActiveCell.FormulaR1C1 = "10"
Range("Y13").Select
ActiveCell.FormulaR1C1 = "9"
Range("Y14").Select
```

```
    ActiveCell.FormulaR1C1 = "8"
    Range("Y15").Select
    ActiveCell.FormulaR1C1 = "7"
    Range("Y16").Select
    ActiveCell.FormulaR1C1 = "6"
    Range("Y17").Select
    ActiveCell.FormulaR1C1 = "5"
    Range("Y18").Select
    ActiveCell.FormulaR1C1 = "4"
    Range("Y19").Select
    ActiveCell.FormulaR1C1 = "3"
    Range("Y20").Select
    ActiveCell.FormulaR1C1 = "2"
    Range("Y21").Select
    ActiveCell.FormulaR1C1 = "1"
    Range("Y22").Select
    ActiveCell.FormulaR1C1 = "q"
    Range("Y22").Select
    ActiveCell.FormulaR1C1 = ""
    Range("X22").Select
End Sub


Sub Select_best()
'
' Select_best Macro
'
```

```
'

    Columns("Z:Z").Select
    ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
    ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range("Z1") _
        , SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:=xlSortNormal
    With ActiveWorkbook.Worksheets("Evaluation").Sort
        .SetRange Range("A2:Z28")
        .Header = xlGuess
        .MatchCase = False
        .Orientation = xlTopToBottom
        .SortMethod = xlPinYin
        .Apply
    End With
    ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
    ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range("Z1") _
        , SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:=xlSortNormal
    With ActiveWorkbook.Worksheets("Evaluation").Sort
        .SetRange Range("A2:Z28")
        .Header = xlGuess
        .MatchCase = False
        .Orientation = xlTopToBottom
        .SortMethod = xlPinYin
        .Apply
    End With
    ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
    ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range("Z1") _
```

```
        , SortOn:=xlSortOnValues, Order:=xlDescending, DataOption:=xlSortNormal
    With ActiveWorkbook.Worksheets("Evaluation").Sort
        .SetRange Range("A2:Z28")
        .Header = xlGuess
        .MatchCase = False
        .Orientation = xlTopToBottom
        .SortMethod = xlPinYin
        .Apply
    End With
    Range("A2:T10").Select
    Selection.Copy
    Range("A29").Select
    ActiveSheet.Paste
    Range("A27").Select
    Application.CutCopyMode = False
    ActiveCell.FormulaR1C1 = "q"
    Range("A27").Select
    ActiveCell.FormulaR1C1 = ""
    Range("A27").Select
End Sub
Sub Cross_over()
'
' Cross_over Macro
'


'
    Range("K29:T37").Select
```

```
Selection.Copy
Range("A38").Select
ActiveSheet.Paste
Range("A29:J37").Select
Application.CutCopyMode = False
Selection.Copy
Range("K38").Select
ActiveSheet.Paste
ActiveWindow.SmallScroll Down:=11
Range("A29:T30").Select
Application.CutCopyMode = False
Selection.Copy
Range("A47").Select
ActiveSheet.Paste
Range("A47").Select
Application.CutCopyMode = False
ActiveCell.FormulaR1C1 = "0"
Range("J47").Select
ActiveCell.FormulaR1C1 = "1"
Range("T47").Select
ActiveCell.FormulaR1C1 = "0"
Range("R48").Select
ActiveCell.FormulaR1C1 = "1"
Range("M48").Select
ActiveCell.FormulaR1C1 = "1"
Range("F48").Select
ActiveCell.FormulaR1C1 = "0"
```

```
    Range("A48").Select
    ActiveCell.FormulaR1C1 = "1"
    Range("A26").Select
    ActiveCell.FormulaR1C1 = "a"
    Range("A26").Select
    ActiveCell.FormulaR1C1 = ""
    Range("A26").Select
End Sub
Sub new_gen()
'
' new_gen Macro
'

'
    Range("A29:T48").Select
    Selection.Copy
    ActiveWindow.SmallScroll Down:=-221
    Range("A2").Select
    ActiveSheet.Paste
    Range("U2:Y21").Select
    Application.CutCopyMode = False
    Selection.ClearContents
    Range("A29:T48").Select
    Selection.ClearContents
    ActiveWindow.SmallScroll Down:=-73
    Range("A26").Select
    ActiveCell.FormulaR1C1 = "a"
```

```
    Range("A26").Select
    ActiveCell.FormulaR1C1 = ""
    Range("A26").Select
End Sub
Sub Evaluation_rev2()
'
' Evaluation_rev2 Macro
'

'
    Range("AB2:AB21").Select
    Selection.Copy
    Range("U2").Select
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False
    Range("A1:U21").Select
    Application.CutCopyMode = False
    ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
    ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range( _
        "U2:U21"), SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:= _
        xlSortNormal
    With ActiveWorkbook.Worksheets("Evaluation").Sort
        .SetRange Range("A1:U21")
        .Header = xlYes
        .MatchCase = False
        .Orientation = xlTopToBottom
        .SortMethod = xlPinYin
```

```
    .Apply
End With
Range("V2").Select
ActiveCell.FormulaR1C1 = "20"
Range("V3").Select
ActiveCell.FormulaR1C1 = "19"
Range("V4").Select
ActiveCell.FormulaR1C1 = "18"
Range("V5").Select
ActiveCell.FormulaR1C1 = "17"
Range("V6").Select
ActiveCell.FormulaR1C1 = "16"
Range("V7").Select
ActiveCell.FormulaR1C1 = "15"
Range("V8").Select
ActiveCell.FormulaR1C1 = "14"
Range("V9").Select
ActiveCell.FormulaR1C1 = "13"
Range("V10").Select
ActiveCell.FormulaR1C1 = "12"
Range("V11").Select
ActiveCell.FormulaR1C1 = "11"
Range("V12").Select
ActiveCell.FormulaR1C1 = "10"
Range("V13").Select
ActiveCell.FormulaR1C1 = "9"
Range("V14").Select
```

```
ActiveCell.FormulaR1C1 = "8"
Range("V15").Select
ActiveCell.FormulaR1C1 = "7"
Range("V16").Select
ActiveCell.FormulaR1C1 = "6"
Range("V17").Select
ActiveCell.FormulaR1C1 = "5"
Range("V18").Select
ActiveCell.FormulaR1C1 = "4"
Range("V19").Select
ActiveCell.FormulaR1C1 = "3"
Range("V20").Select
ActiveCell.FormulaR1C1 = "2"
Range("V21").Select
ActiveCell.FormulaR1C1 = "1"
Range("AC2:AC21").Select
Selection.Copy
Range("U2").Select
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
   False, Transpose:=False
Range("A1:V21").Select
Application.CutCopyMode = False
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range( _
   "U2:U21"), SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:= _
   xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
```

```
    .SetRange Range("A1:V21")
    .Header = xlYes
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
Range("W2").Select
ActiveCell.FormulaR1C1 = "20"
Range("W3").Select
ActiveCell.FormulaR1C1 = "19"
Range("W4").Select
ActiveCell.FormulaR1C1 = "18"
Range("W5").Select
ActiveCell.FormulaR1C1 = "17"
Range("W6").Select
ActiveCell.FormulaR1C1 = "16"
Range("W7").Select
ActiveCell.FormulaR1C1 = "15"
Range("W8").Select
ActiveCell.FormulaR1C1 = "14"
Range("W9").Select
ActiveCell.FormulaR1C1 = "13"
Range("W10").Select
ActiveCell.FormulaR1C1 = "12"
Range("W11").Select
ActiveCell.FormulaR1C1 = "11"
```

```
Range("W12").Select
ActiveCell.FormulaR1C1 = "10"
Range("W13").Select
ActiveCell.FormulaR1C1 = "9"
Range("W14").Select
ActiveCell.FormulaR1C1 = "8"
Range("W15").Select
ActiveCell.FormulaR1C1 = "7"
Range("W16").Select
ActiveCell.FormulaR1C1 = "6"
Range("W17").Select
ActiveCell.FormulaR1C1 = "5"
Range("W18").Select
ActiveCell.FormulaR1C1 = "4"
Range("W19").Select
ActiveCell.FormulaR1C1 = "3"
Range("W20").Select
ActiveCell.FormulaR1C1 = "2"
Range("W21").Select
ActiveCell.FormulaR1C1 = "1"
Range("AD2:AD21").Select
Selection.Copy
Range("U2").Select
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
   False, Transpose:=False
Range("A1:W21").Select
Application.CutCopyMode = False
```

```
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range( _
    "U2:U21"), SortOn:=xlSortOnValues, Order:=xlDescending, DataOption:= _
    xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
    .SetRange Range("A1:W21")
    .Header = xlYes
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
Range("X2").Select
ActiveCell.FormulaR1C1 = "20"
Range("X3").Select
ActiveCell.FormulaR1C1 = "19"
Range("X4").Select
ActiveCell.FormulaR1C1 = "18"
Range("X5").Select
ActiveCell.FormulaR1C1 = "17"
Range("X6").Select
ActiveCell.FormulaR1C1 = "16"
Range("X7").Select
ActiveCell.FormulaR1C1 = "15"
Range("X8").Select
ActiveCell.FormulaR1C1 = "14"
Range("X9").Select
```

```
ActiveCell.FormulaR1C1 = "13"
Range("X10").Select
ActiveCell.FormulaR1C1 = "12"
Range("X11").Select
ActiveCell.FormulaR1C1 = "11"
Range("X12").Select
ActiveCell.FormulaR1C1 = "10"
Range("X13").Select
ActiveCell.FormulaR1C1 = "9"
Range("X14").Select
ActiveCell.FormulaR1C1 = "8"
Range("X15").Select
ActiveCell.FormulaR1C1 = "7"
Range("X16").Select
ActiveCell.FormulaR1C1 = "6"
Range("X17").Select
ActiveCell.FormulaR1C1 = "5"
Range("X18").Select
ActiveCell.FormulaR1C1 = "4"
Range("X19").Select
ActiveCell.FormulaR1C1 = "3"
Range("X20").Select
ActiveCell.FormulaR1C1 = "2"
Range("X21").Select
ActiveCell.FormulaR1C1 = "1"
Range("AE2:AE21").Select
Selection.Copy
```

```
Range("U2").Select
Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False
Range("A1:X21").Select
Application.CutCopyMode = False
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Clear
ActiveWorkbook.Worksheets("Evaluation").Sort.SortFields.Add Key:=Range( _
    "U2:U21"), SortOn:=xlSortOnValues, Order:=xlDescending, DataOption:= _
    xlSortNormal
With ActiveWorkbook.Worksheets("Evaluation").Sort
    .SetRange Range("A1:X21")
    .Header = xlYes
    .MatchCase = False
    .Orientation = xlTopToBottom
    .SortMethod = xlPinYin
    .Apply
End With
Range("Y2").Select
ActiveCell.FormulaR1C1 = "20"
Range("Y3").Select
ActiveCell.FormulaR1C1 = "19"
Range("Y4").Select
ActiveCell.FormulaR1C1 = "18"
Range("Y5").Select
ActiveCell.FormulaR1C1 = "17"
Range("Y6").Select
ActiveCell.FormulaR1C1 = "16"
```

```
Range("Y7").Select
ActiveCell.FormulaR1C1 = "15"
Range("Y8").Select
ActiveCell.FormulaR1C1 = "14"
Range("Y9").Select
ActiveCell.FormulaR1C1 = "13"
Range("Y10").Select
ActiveCell.FormulaR1C1 = "12"
Range("Y11").Select
ActiveCell.FormulaR1C1 = "11"
Range("Y12").Select
ActiveCell.FormulaR1C1 = "10"
Range("Y13").Select
ActiveCell.FormulaR1C1 = "9"
Range("Y14").Select
ActiveCell.FormulaR1C1 = "8"
Range("Y15").Select
ActiveCell.FormulaR1C1 = "7"
Range("Y16").Select
ActiveCell.FormulaR1C1 = "6"
Range("Y17").Select
ActiveCell.FormulaR1C1 = "5"
Range("Y18").Select
ActiveCell.FormulaR1C1 = "4"
Range("Y19").Select
ActiveCell.FormulaR1C1 = "3"
Range("Y20").Select
```

```
    ActiveCell.FormulaR1C1 = "2"
    Range("Y21").Select
    ActiveCell.FormulaR1C1 = "1"
    Range("Y22").Select
    ActiveCell.FormulaR1C1 = "q"
    Range("Y22").Select
    ActiveCell.FormulaR1C1 = ""
    Range("X22").Select
End Sub
```

Appendix 4

List of Abbreviations

AI: Artificial Inteligence

ANOVA: Analysis of Variances

CART: Classification and regression trees

DOE: Design of Experiments

Dpmo: defects per million opportunities

EPA: Environmental Protection Agency

FMEA: Failure Mode and Effect Analysis

GHG: Green House Gases

GA: Genetic Algorithm

HPANN: Hollis-Paulos Artificial Neural Network

LCA: Life Cycle Assessment

MAE: Mean absolute error

MAPE: Mean Absolute percentage error

NVA: Non-Value Added

PDF: Probability Density Function

PV: Photovoltaic

QA: Quality Assurance

QC: Quality Control

RAM: Responsibility Assignment Matrix

RMSE: Root Mean Square Deviation

SCC: Social Cost of Carbon

SVSM: Sustainable Value Stream Mapping

VA: Value Added

WBS: Work Breakdown Structure

WIP: Work In Process

Vita

Juan Saavedra was born in Texcoco, Estado de Mexico, Mexico. He completed his B.S. and M.S. degrees from the University of Texas at El Paso in Industrial Engineering and Manufacturing Engineering in 2010 and 2012, respectively. During his undergraduate study, he was the president of the Institute of Industrial Engineers (IIE) UTEP chapter. He graduated the B.S. degree with honors and was a recipient of the "Best Manufacturing Engineer" awarded by the Department of Industrial, Manufacturing and Systems Engineering (IMSE) in 2012. Furthermore, he expanded his skills into publishing research papers in international conferences.

In 2010, he started working with Johnson and Johnson in the Medical Devices and Diagnostic sector in three different areas: Quality, Manufacturing and Supply Chain. In 2012, he worked at General Labels and Printing in El Paso, TX as Quality Engineer where he was responsible for the entire supply chain quality of the organization. In 2015, he was an intern at Care Fusion as a Manufacturing Engineer. He is currently working with Bard Medical as a Quality Engineer.

List of publications

<u>Conference Papers</u>

[1] B. Tseng, J. Saavedra, and A. Akundi, Comparative study of teaching lean manufacturing via hands on and computer aided simulation, in *Proc. of the 2016 ASEE Annual Conference and Exposition,* New Orleans, LA, 2016.

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[3] B. Tseng, A. Akundi, J. Saavedra, and E. Smith, Augmenting high school students' interest in STEM education using advanced manufacturing technology, in *Proc. of the 2015 ASEE Annual Conference and Exposition*, Seattle, WA, 2015.

[4] B. Tseng, F. Jiang, C. C. Huang, R. Chiou, P. Mandal, M. Gonzalez, K. V. Koppella, and J. Saavedra, "Quality control of bio scaffold using intelligent data mining," in *Proc. of the Industrial Systems Engineering Research*, 2012, Orlando, FL, May 19-23, 2012.

[5] B. Tseng, N. Vargas-Hernandez, R. Chiou, P. Mandal, M. Gonzalez, J. V. Mendez, and J. Saavedra, "Cyber based layer manufacturing with virtual facility," in *Proc. of the 2012 ASEE Gulf-Southwest Annual Conference*, University of Texas, El Paso, TX, April 4-6, 2012.

M.S. Thesis

[6] J. Saavedra, "Identification of rework station location to enhance reworkability using design for disassembly" (January 1, 2012). *ETD Collection for University of Texas*, El Paso. Paper AAI1518231.

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