2012-01-01

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Dedication

I would like to dedicate this thesis first of all to my family that has always supported me. My wife Nadia Carrillo and my little baby Valentina Saavedra who knows how much work I have done and the time I haven't been with them in order to finish this project. I am really thankful for the support and love that they have showed me at all times. I do not think I would be able to finish this project without their support.

I also dedicate this thesis to my mom Sara Saavedra, dad Angel Saavedra and brother Angel Saavedra which have been my support since I was little. They have shown me what effort really means and that there is a lot of work to do so you can get to wherever you want to. My dad and brother are both PhD graduates and are the ones who motivate me continuously to continue with the research track and hopefully one day become also a PhD as they are.

IDENTIFICATION OF REWORK STATION LOCATION TO ENHANCE REWORKABILITY USING DESIGN FOR DISASSEMBLY

by

JUAN ALEJANDRO SAAVEDRA, B.S.

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Industrial, Manufacturing and Systems Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

August 2012

Acknowledgements

I would like to thank Dr. Bill Tseng for helping me out during the whole research of this thesis. He was my mentor and guide in understanding how research work and what we can do with it. He allowed me to research the topic that I really was interested instead of just guiding me towards one topic. I remember starting out with a list of ideas of different topics and not knowing exactly what to research on. Understanding and support was given by Dr. Tseng in order to identify the topics I was interested in. I always received full support from him the entire way. Understanding that research is about giving back to society something that will benefit it is another lesson I understood from him. The support from my thesis committee members, Dr. Eric Smith and Dr. Paras Mandal, has to be also acknowledged. Without both of their comments, I believe that this thesis would have not been able to achieve an excellent quality level. Their support, time, concern and willingness to provide suggestions, comments and corrections are greatly appreciated. Thanks to this mentoring and support from my advisor and committee members, is why my research is something that I believe can be applicable for a manufacturing setting.

I also acknowledge Dr. Heidi Taboada and Dr. Jose Espiritu. I had the opportunity to work with them as an undergrad and understand what research meant. I received the motivation to get into research thanks to them. Because of this is that I am doing a thesis and hopefully continue on to get my PhD. Last but not least I acknowledge EES (Ethicon Endo Surgery), part of the Johnson & Johnson family of companies. Real life problems were found thanks to the extraordinary support received for this thesis. Thanks to this support is that I am sure that this thesis is helpful and can be applied in a real manufacturing setting and it is not just theoretical research.

Abstract

Rework stations are commonly established as part of each assembly stations causing the material flow of the process to be constantly interrupted. Another option is to place the rework station at the end of the production, but this is not cost effective. This breakeven point between reworkability and cost methodology has been proposed in this thesis to identify the location of a single rework station in an assembly line in order to enhance reworkability using the Design for Disassembly (DfD) principles. The methodology uses the 17 guidelines of DfD in a manufacturing scenario in order to propose a reworkability index of a product. This index is compared to cost index in order to find their breakeven point. This breakeven point allows the methodology to identify a location in the assembly process for the rework station in order to find a balance between these two factors. The methodology proposed is a series of simple step that can allow a company to reduce extra work and improve material flow by establishing one rework station in any production line.

Table of Contents

List of Tables

List of Figures

List of Illustrations

Chapter 1: Introduction

In many cases the assembly line or production line uses may rework stations thru out of the process. This approach may be very expensive and may not be the optimal option for a company. The Design for Disassembly (DfD) tools allows a product to be disassembled in an easier way [1]. Most of the time, disassembly is used for the end of the products life cycle; referring mostly to recycling products or reusing parts [2]. In this study this approach is used to identify at which point of the assembly line the product can be easily disassemble being cost effective. After a certain point in any manufacturing process it is convenient to think about having a disassembly line or a process established and not just a rework station.

Having only one rework station throughout the entire assembly line will decrease the rework cost of a product and will allow a better material flow. Reworking products is very important and most of the time always needed in order to recuperate parts of the product being manufactured. Once products or parts have been recuperated the manufacturer can reuse them in the assembly of the product and reduce its total scrap in order to reduce the total cost [3]. The main focus of this study is to be able to identify the location for a rework station in a production line in order to breakeven the cost of reworking a product or system and it reworkability.

Locating a rework station in a production line is not as simple as it might be thought. Commonly rework stations are placed at the end of production lines after a quality inspection is made. This is effective in order to prevent defective products to be shipped to the customer; the issue is that many times this is not cost effective. Finding a balance between the desire of having no quality defects for a finish good, reworking the product and using rework stations in a cost effective way is not a simple task. This is where the term “reworkability” of a product plays an important role. By calculating reworkability and cost of the production of a product the issue of where to place a rework station can be solved with the proposed methodology of this work.

Reworkability is not always considered in industry. The trend is to consider Design for Disassembly with a more sustainable objective for the product of system. This means that the DfD principles are considered mostly for products at the end of their life cycle and not during their

manufacturing process [4]. If the DfD principles are considered during design and reworkability is considered during the manufacturing process, it is sure that products will be easily reworked, material flow less interrupted and money saved in the industry by recovering and reworking products easily.

1.1 Problem statement and rationale

In industry it is common to use rework for products in order to recuperate the most possible of a defective product. The most frequent practice is to have a rework station after each step of the process. Rework stations do not have to be is a separate area from the ordinary work station; they just mean that the product is reworked right after the operation ends at that station if a defect is detected to the product. This generates a complication for the production process due to all the internal loops that are generated because of the reworks at each station. Fig. 1.1 illustrates an IDEF0 functional modeling of a process where rework is performed at every station during the manufacturing process [5]. After each rework during the process, parts are recovered and some are used at the same station but others are sent to previous stations in the process. All of these loops can easily interrupt material flow and create bottle necks during the process. The dotted line in Fig. 1.1 represents that an infinity number of intermediate stations might exist in the assembly process. Fig. 1.2 illustrates an IDEF0 functional modeling of a process after the proposed methodology is applied. There is only one rework station in the process which allows a better material flow, which is one of the specific objectives that the proposed methodology achieves.

1.2 Objective of the study

The main objective of the study is to identify the location of one single rework station in an assembly line in order to find a balance between reworkability and cost. Specific objectives that are achieved when a single rework station is placed in an assembly line are that material flow is improved, parts that are too costly to rework are not reworked and parts that can be reworked in the same production line are recuperated and used during the assembly process.

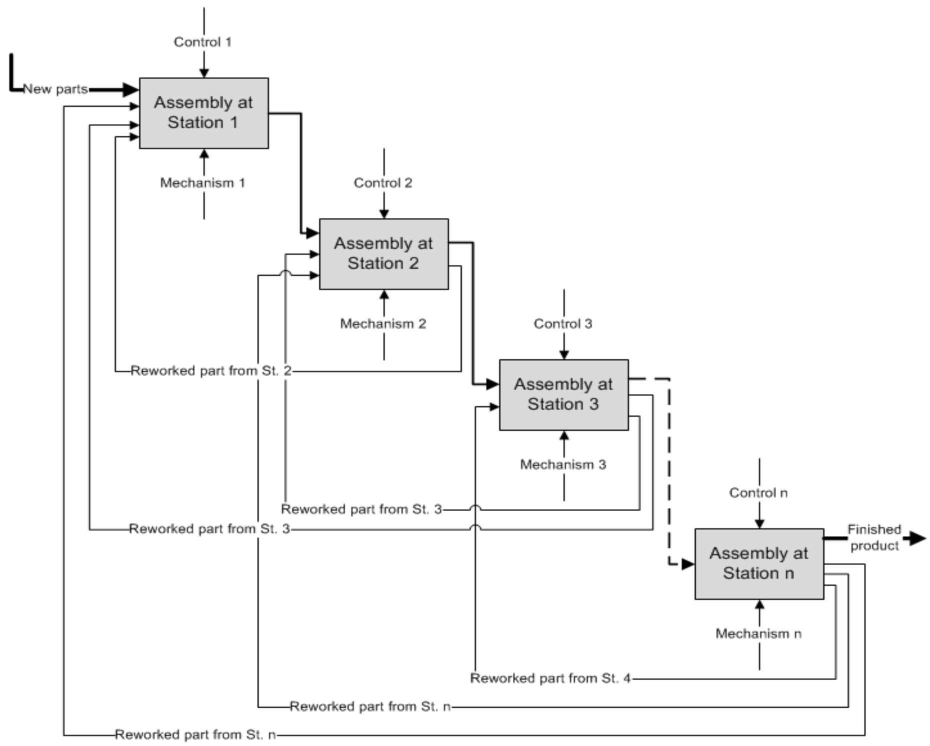


Figure 1.1: IDEF0 model of parts flow when rework is performed at each station.

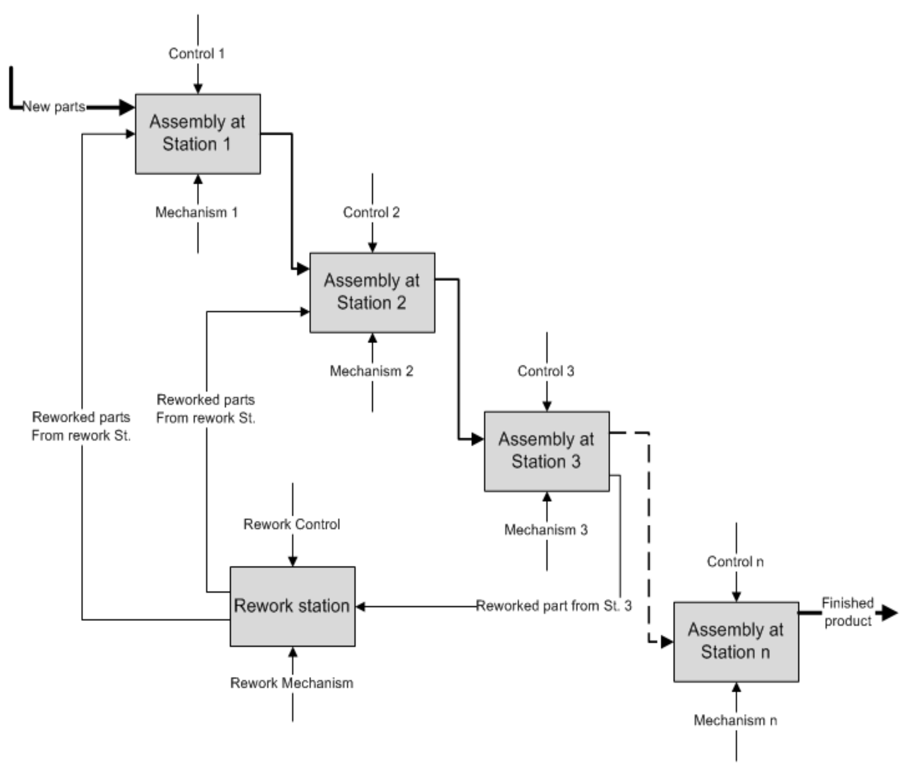


Figure 1.2: IDEF0 model of parts flow when only one rework station exists.

1.3 Scope and Limitations

The scope of the proposed methodology is:

1. Only a single manufacturing assembly line is considered.
2. Optimization of the amount of rework stations per production line will not be considered.
3. The methodology can be applied to any type of assembly line as long as it includes two or more process steps.
4. The assembly lines considered can be manual, automatic or semiautomatic.

The limitations of the methodology proposed are:

1. The methodology may be adapted for parallel lines or several manufacturing lines that assemble the same product; but in this study this will not be considered.
2. Find a location for the rework station in this line is the final objective.
3. The proposed methodology only works with one line and one rework station.

The general assumptions considered for this study are stated in Chapter 4.

1.4 Thesis outline

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

Chapter 2 "Theoretical background" talks about all the theoretical tools used in the methodology proposed. The chapter starts by explaining how the product design process takes place and the product/system process. This allows the reader to understand the basic concepts of design and product process in order to clear comprehend the section of DfD. Section 2.4 of this chapters start with a high level explanation of Sustainability and then it funnels down to the principles of design for the environment from where the principle of DfD is obtained and explained. Once the DfD concept has been explained a simple explanation of what rework stations is given. In section 2.6, the term "reworkability" is defined and tied together with the DfD concept. Disassembly is defined in section 2.7, and section 2.8 ties this concept into the part/product design. Finally sections 2.9 and 2.10 define

concepts used in the methodology such as the Integration Definition for Function Modeling (IDEF) and the breakeven point concept respectively.

Chapter 3 “Proposed methodology” will present the methodology that will be followed to solve this problem and how the solution is obtained. It is important to understand the problem in a theoretic manner, which is the intent of this chapter.

Chapter 4 “Applications of the methodology” will be given so that the methodology is clear. Two scenarios are reviewed in this chapter and in section 4.3 special scenarios that can happen using this methodology are presented and explained.

Finally Chapter 5 “Conclusions and recommendations” closes this study by clearly stating the conclusions of the proposed methodology based on the study results, the contribution that this methodology provides to the manufacturing field and finally, recommendations for future research that can be pursued.

Chapter 2: Theoretical Background

2.1 General

Design for Disassembly has received an important role when talking about sustainable design or eco-design. DfD focuses on the intent to design a product in order to separate it in different parts after its useful life has been concluded. The main intent of DfD principles is to design product that can be easily separated in order to reuse some of their parts or recycle them.

In order to understand the DfD principles of a design of a product, system or service, first there are two processes that need to be clearly understood. The first one is the details of the product design process and the second one is the product process by itself. The product design process is the process that all new systems or products must go thru in order to be transformed from an idea or a concept into a physical system or product. The product process is the process that the product goes thru in order to created, used and disposed. This process is very similar to a Life Cycle Assessment with the difference that LCA's take in considerations things such as procurement and transportation that is not considered in the process of the product.

Section 2.2 describes the product design process which is where the guidelines from DfD come from. Section 2.3 describes the product system process in order to understand how the design phase plays a role in the system. Section 2.4 provides an overview of sustainability and explains all the guidelines used to achieve a sustainable product. Section 2.5 defines what rework stations are. Section 2.6 ties together the concept of DfD and reworkability. Section 2.7 defines disassembly and section 2.8 relates the part/product design with the disassembly process. Finally sections 2.8 and 2.9 define what the IDEF model and the breakeven point respectively.

2.2 Product design process

The product design process must be understood because this were the actual changes to create a DfD product are achieved. In the book "Design basics, from ideas to product" written by Heufler [6], a simplified design process is presented. This process starts with an idea and ends with product ready for volume production. Fig. 2.1 illustrates this process and briefly describes each phase.

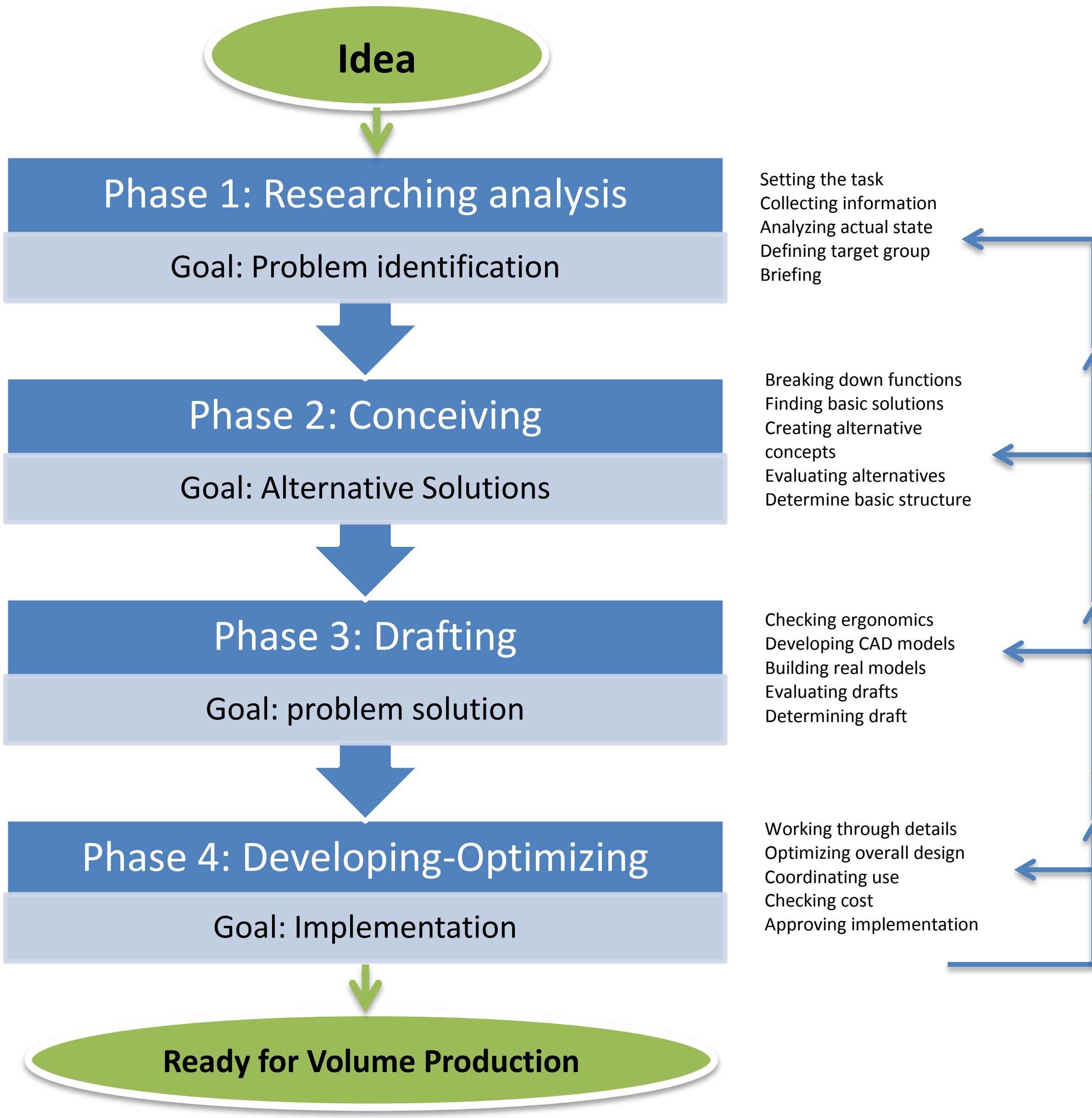


Figure 2.1: Design process with feedback loops.

These is a simplified design process that must consider DfD at phase 2, 3 and 4 in order to create a product that can be easily disassembled at the end of its life or at the manufacturing process. This process looks to be linear but it is really a process that goes back and forth for several iterations until the final desired product is developed.

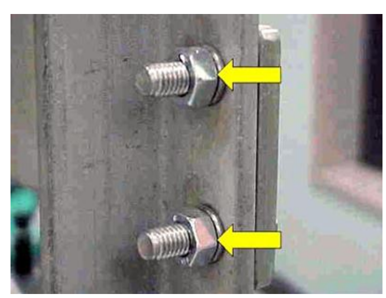
In the paper "A compilation of design for environment principles and guidelines" [2] the principle of Disassembly is divided into several guidelines. It is important to remember these guidelines

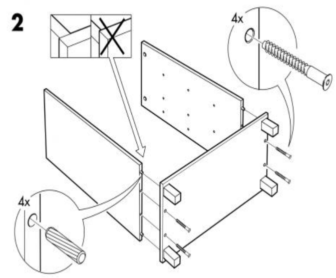
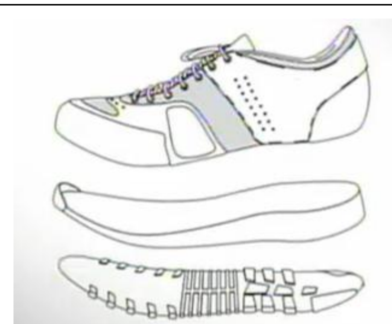
in order to design a product that is easily disassembled. This DfD applies for the end of life of the product and also for its manufacturing. The guidelines are explained in more detail in the following sections.

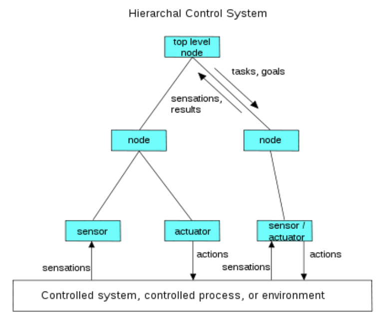
All of the 17 guidelines are applicable for any type of product and can make a product easy to disassemble. Some of the guidelines are more applicable when talking about rework in a manufacturing setting. An example is the guideline 14: Employing one disassembly direction without reorientation; if this guideline is followed the disassembly in the production line is easier, requires less time than if the product would have to be redirected, can be easily standardized and a fixture or gadget and implemented to improve the disassembly process. These guidelines are explained in table 2.1.

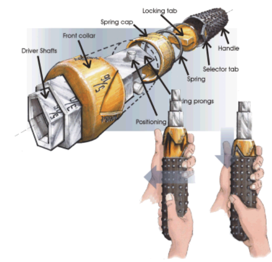
Once the product process, the design process and the DfD principles are understood, the application and combination of them will provide with a product uncomplicated to disassemble. Once this product has been created and a manufacturing process for it exists it is important to optimize its rework process. The following methodology presents a way to determine will an optimal rework station be in the production process.

Table 2.1: 17 Guidelines of DfD.

Guideline	Example	Picture
Indicating on the product how it should be opened and make access points obvious	Canon S520 inkjet printer. As it can be seen the cartridges are easily replaced and all of them have signals on how they should be placed and removed. Also the exits at this point is simply by lifting cover of the printer, making the access point obvious and easy.	
Ensuring that joints and fasteners are easily accessible	Structure used by DuPont that has all of the fasteners in an easy to reach position. This allows the operators of this structure to easily assembled or disassemble the structure as needed. When all the joints and fasteners are all hidden behind the structure, the disassembly becomes really complicated. The main goal is to have everything accessible in order to have an easy and simple disassembly.	

Maintaining stability and part placement during disassembly	Panasonic's Eco technology center located in Kato city, Japan. This is assembling is used for appliances that are all old or do not function as they should. It is said that once the parts have being separated the process allows a 90% of the full weight of the appliance to be recycled. In this recycling process some of the materials that are recuperated are copper and iron within 99.8% off purity [7].	
Minimizing the number and variety of joining elements	IKEA furniture is disassembled and the user has to assemble them. They try to use the less variety of joint elements as possible. This is the same guidelines can be used for a disassembly process. Using the less number of joint elements possible makes the disassembly easier because with one or two single tools the whole disassembly can be possible.	
Ensuring that destructive disassembly techniques do not harm people or reusable components	A bicycle wheel. Bicycle wheels had to be disassembled from the bicycle using a wrench; the person that was disassembling the bicycle wheel could be injured by turning the wrench and hitting on the bicycle. Nowadays bicycle wheels have their own part that allows the disassembly from the bicycle in an easy manner.	
Ensuring reusable parts can be cleaned easily and without damage	Reusable shopping bag. They are easily cleaned and follow this principle. The material of the bag makes the cleaning process simple and does not wear out the material easily making it durable and with the possibility of cleaning the bag many times and reusing it as many times as desired.	
Ensuring that incompatible materials are easily separated	Nike old shoes. What happens is that the show is broken down in three parts: Robber from the outside, fabric from the upper and foam from the mid part. This is done by simply tarring the shoe apart and separating it into the different parts [8].	

Making component interfaces simple and reversibly separable	Cables are designed to be easily connected and disconnected to different sources. All these cables can be easily connected or disconnected for whatever part in the system is required. Using this principle is what makes parts easily disassemble.	
Organizing a product or system into hierarchical modules by aesthetic, repair, and end-of-life protocol	Hierarchical control system. This control system is where a set of devices governing software is arranged in a hierarchical tree. The decomposition of the system is easily understood. The same occurs with parts that are arranged in this way.	
Implementing reusable/swappable platforms, modules, and components	Kontron XL-1000-Series. This platform allows the change of many different parts that may be required for computer use or as servers. When this product is to be disassembled it is easy to separate all of this part because of this characteristic.	
Condensing into a minimal number of parts	Computers. Remember what the first computers looked like. And it can be seeing it was really complex and there were many parts in order to make it function. As technology has evolved these parts have become a lot smaller and they have been reduced just too several parts and a computer.	
Specifying compatible adhesives, labels, surface coatings, pigments, etc. which do not interfere with cleaning	Appendix I show an incompatible material chart that allows identifying material groups that are incompatible to other material groups and what is their reaction if they are mixed. In this case is used to prevent safety hazards, but using this types of charts are also important for disassembly purposes. If two none compatible materials are used in the same product or system, the disassembly may become really complicated or sometimes even dangerous. This is why the use of compatible materials is always recommended for any design of a product.	
Employing one disassembly direction without reorientation	Cell Phones. This cell phone can be disassembling from the back part into all of the smaller parts. Using these principles allows the disassembly to be faster and more efficient.	

Specifying all joints so that they are separable by hand or only a few, simple tools	Bicycles. Even though it is very complex parts of that to be disassembled commonly have the principle that these joints are easily removed. Front and back tires are easily removed with what is called a quick release. The seat and handlebar can easily be removed with only one tool.	
Minimizing the number and length of operations for detachment	Screwdriver. This product is easily disassembled. It only requires one operation in order to remove the handle and with this, the other parts can be detached. Less operation means a faster disassembly.	
Marking materials in molds with types and reutilization protocols	Multi used water containers. This product has ability to be used over and over by the same user or even by different users. A protocol exists to use these water containers again and again once they have gone through a cleaning process.	
Using a shallow or open structure for easy access to subassemblies	2005 Skyline Gtr. This guideline is followed in almost all car designs. Having easy access to the motor is essential in order to do easy repairs or check for defects.	

2.3 Product/System process

The product process is part of the entire development of a product that starts with an idea (the design) and finishes with the disposal of the product once it has been used. When talking about environmental design this product development can be easily explained with the process that the Life Cycle Analysis (LCA) uses to evaluate how environmentally friendly a product is. Ciambrone, in his book "Environmental Life Cycle Analysis" [4] presents the life cycle of a product that is shown in Fig. 2.2 with the following steps:

1. Raw Material.
2. Bulk Material Processing.

3. Manufacturing.

4. Transportation.

5. Distribution.

6. End User.

7. Recycle.

8. Disposal.

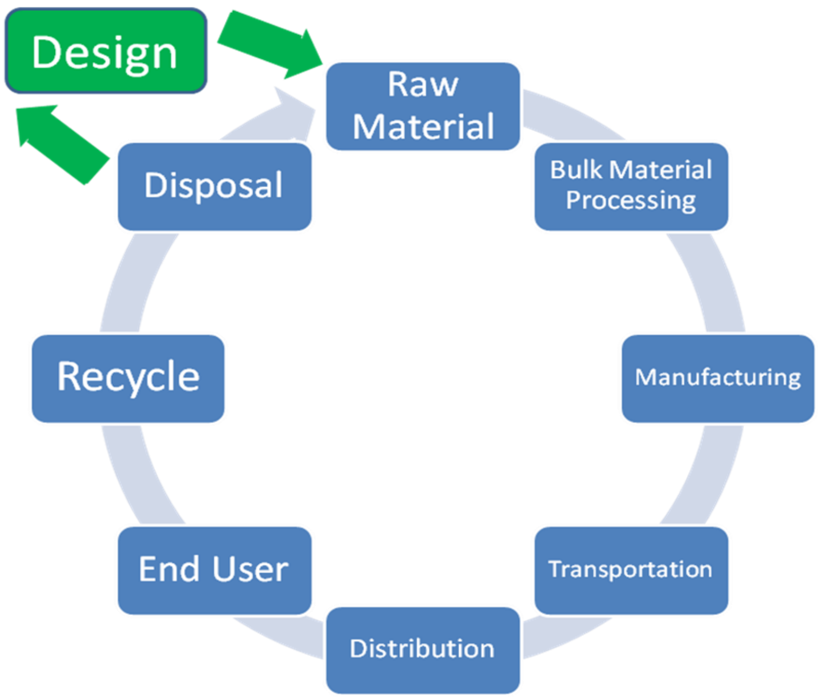


Figure 2.2: Environmental life cycle analysis stages including design stage.

These are the most commonly used steps when evaluating the LCA of any product. For the purposes of this study the design phase also plays a step at the beginning of this cycle. Fig. 2.2 illustrates this concept. The design stage is included as a small cycle before the raw materials enters and after the disposal. This is because the design is the one the starts the products and also can have an effect on what and how the product is disposed. The design stage in this process is only done once. Once the product is on its normal product cycle it is not included again as a stage. Due to this most of

the environmental beneficial impacts to a product are tried to do during its development phase which in this case represents the design stage.

2.4 Sustainability

The concept of sustainability comes from the ability or capacity to endure a certain situation. This is commonly used to talk about sustainable development. Sustainable development refers to the ability to create or develop something that will be able to endure many situations. In this case sustainability and sustainable development are referring to different ideas. Sustainability by itself is referring to the ability to conserve the environment, and sustainable development refers to the ability of conserving any system developed.

Sustainability has been already recognized as a big area of opportunity for the humanity. It is easily said that if sustainability is not considered in the future development of systems there will be an impact to our eco-system and our way of life. This concept of sustainability can be dated backwards to at least 30 years. Since then, there has been research going on how to improve different systems and products in order to make them more sustainable and more eco-friendly.

Now a day's sustainability is one of the factors that must be considered for any system development around the world. There are still some critiques that have three main points in order defend the idea that sustainability might not be the best option for systems [9]. The first of these critiques is it is not clear what sustainable development really means. As mentioned before this is true because sustainability and sustainable development referred to different terms and they are not easily identify one from the other. The second critique is at the trade-offs are not valuable enough to focus on sustainability instead of other factors such as cost and reliability. In many cases this might be true but if sustainability is not considered we will be killing our ecosystem and we wouldn't have, at the end, another option but to consider it. The third and last critique is the problem of existing metrics. This is referred to the ability of not being able to define clear metrics to know what is sustainable and what is not. In this particular point there has been a lot of research done in order to improve this using lifecycle analysis.

In order to clearly understand the whole concept of sustainability there are many terms that must be considered and understood. Table 2.2 shows many of these terms and their definitions in order to understand them as clearly as possible [10].

Table 2.2: Sustainability definitions of terms.

Principle	Terminology	Definition
Environmental principles	Renewable resources	Are resources available in a continually renewing manner, supplying materials and energy in more or less continues way [10].
	Minimization of resource usage	It is understood as the conservation of natural resources at its maximum capacity.
	Source reduction (dematerialization)	It is the practice that reduces the quantity of material entering a waste stream from a specific source by redesigning products or patterns of production and consumption [11].
	Recycling	Resource recovery method involving the collection and treatment of waste products for use as raw material in the manufacture of the same or a similar product [10].
	Reuse	Using waste as a raw material in a different process without any structural change [10].
	Repair	Means and improvement or complement of a product, in order to increase quality and usefulness before it being reuse or recycled.
	Regeneration	It is an activity of material renewal to return it in its primary form for usage in the same o a different process.
	Recovery	It is an activity applicable to materials, energy and waste. It is a process of restoring material found in the waste stream to a beneficial use which may be for purposes other than the

		original use [11].
	Remanufacturing	Substantial rebuilding or refurbishment of machines, mechanical devices, or other objects to bring them to a reusable or almost new state [12].
	Purification	It is the removal of unwanted mechanical particles, organic compounds and other impurities.
	End-of-Pipe	A practice of treating polluting substances at the end of the production process when all products and waste products have been made and the waste products are being released (through a pipe, smokestack or other release point) [13].
	Degradation	Understood as a biological, chemical or physical process, which results in the loss of productive potential [10].
Ecological principles	Competition	Influences the species in a negative way and none of the species benefit; the main objective is the elimination of the other species.
	Predatory	One species “eats” the pray.
	Amensalism	One species is impaired and the other is neither positively nor negatively affected.
	Parasitism	One species benefits and the other is impaired
	Neutralism	A hypothetical category where one species does not harm or benefit the other species.
	Commensalism	One species receives benefits and the other is not impaired.
	Protocooperation	Both interrelated species receive conditional benefits, but they can survive separately.
	Mutualism	Both species receive benefit.

Economic principles	Environmental accounting	Is designed to bring environmental cost to attention of the corporate stakeholders who may be able and motivated to identify ways of reducing or avoiding those costs while at the same time improving environmental quality and profitability of the organization [13].
	Eco-efficiency	It is the delivery of competitively priced goods and services that satisfy human needs and bring quality life, while progressively reducing ecological impacts and resource intensity throughout the life cycle, to a level at least in line with the earth's estimated carrying capacity [13, 14].
	Factor X	A direct way of utilizing metrics in various activities that can reduce the throughput of resources and energy in a given process [3].
	Factor 4	A fourfold increase in resources productivity [15].
	Factor 10	Tenfold increase in productivity [15].
	Ethical investment	They are financial instruments favoring environmentally responsible corporate practices and those, supporting workforce diversity as well as increasing product safety and quality [16].
Societal principles	Social responsibility	It refers to safe, respectful, liberal, equitable and equal human development, contributing to humanity and the environment.
	Polluter pays principle	A principle that those causing pollution should pay the cost it causes [10].
	Reporting to the stakeholders	It is about sharing the progress, results and planning with the general public [17].

2.4.1 Design for the Environment

Design for the Environment refers to taking into consideration factors that will affect the environment during the design face of a product. Design for the Environment is also commonly used as a synonym of eco-design, sustainable design, green design or clean design [18]. All of these terms refer to what have been mentioned previously.

Designing for the Environment (DfE) is not as simple as it sounds. There are many principles of must be understood and follow in order to create a green design or an equal to sign [2]. These principles will be discussed in the following sections. The main objective in her to create a sustainable design of product is to consider its effect on the environment. In order to do this, a lifecycle assessment (LCA) must be done for the entire life of the product. This type of assessment is what we call a cradle to cradle assessment. This means that not only is it taking into consideration the beginning of the product until it's final use but it is also considering the recycle process or any other process that might help the product go back to a production step.

Lifecycle assessment aims to assess the overall impact to the environment through the life of a product or service with the objective of comparing different sources, materials, manufacturing process etc [19]. These lifecycle assessments have been trying to improve day to day. There are many aspects that might not be considered in a normal lifecycle assessment of a product. One of these examples is that lifecycle assessment excludes the impact of possible accidents, such as fire or pollution accidents. But there are many efforts en route to include as many aspects as possible such as the ones mentioned previously [20].

It can be said then that design for the environment is the process of integrating the environmental aspects of the development of a product into consideration during the design face [21]. If during the design phase the impact of the product is considered, it is safe to say that the product will be eco-friendly and will be able to perform its objective for which it was designed for fully and also have a minimum impact to the environment. Having good products that have a minimum impact on the environment is the main objective of design for the environment.

2.4.1.1 Principle A: Ensure sustainability of resources

This principle refers to the ability of using resources for a product of service that are sustainable. This can be addressed by many ways such as the reuse of the resources that can be materials components or even energy. Another way to ensure sustainable resources can be by altering at least as possible environment. An easy example of this is eco-tourism that has been done in many different parts of the world and that every day it is becoming more popular [22]. These guidelines to ensure sustainable resource usage are applied to every aspect of the product or service.

The guidelines used to fulfill the principle of insuring sustainability of resources are listed following [1, 23]:

1. Specifying renewable and abundant resources.
2. Specifying recyclable, or recycled materials, especially those within the company or for which a market exists or needs to be stimulated.
3. Layering recycled and virgin material where virgin material is necessary.
4. Exploiting unique properties of recycled materials.
5. Employing common and remanufactured components across models.
6. Specifying mutually compatible materials and fasteners for recycling.
7. Specifying one type of material for the product and its subassemblies.
8. Specifying one type of material for the product and its subassemblies.
9. Specifying renewable forms of energy.

One of the guidelines refers to exploring unique properties of recycled materials. Illustration 2.1 shows an example of this principle. In this is specific case, scrap that was created from producing plastic flip-flops was used in order to make original key-chains [24]. This key chains, that not only have the original colors on the flip-flop scraps balls, but also have special characteristics that make them unique. One of this unique characteristics is this key chains is that they have really bright colors and float in water, making them really useful for a hotel that has pools or that is in the ocean shore. Using these key chains the hotel will not be only helping the environment by using Scrap from sandals but would also have the ability to locate easily lost keys in the pools or ocean.

Illustration 2.1: Floating key chains.

2.4.1.2 Principle B: Ensure healthy input and output

This principle refers and applies to every aspect of a product or service including packaging and consumables. It refers to having input to the product or service that do not affect human health adversely or have a negative impact to the ecosystem. When designing the inputs of the product this must be taken into consideration; and the same applies to all the outputs of the product [25]. The inputs of the product refer to everything that must be used to create this product or service. The outputs referred to everything that is produced when using or creating this service or product.

The following is the list of principles that must be used in order to ensure healthy inputs and outputs meaning that there is a use of cleaner resources for the product [26, 27]:

1. Installing protection against release of pollutants and hazardous substances.
2. Specifying non-hazardous and otherwise environmentally "clean" substances, especially in regards to user health.
3. Ensuring that wastes are water-based or biodegradable.
4. Specifying the cleanest source of energy.
5. Including labels and instructions for safe handling of toxic materials.
6. Specifying clean production processes for the product and in selection of components.
7. Concentrating toxic elements for easy removal and treatment.

An example of the guideline that states to specify the cleanest source of energy is Seiko kinetic watches [28]. There are many different types' forms and shapes of these watches but what makes them unique is that they use kinetic energy in order to function. These watches do not require any battery to function and are not using any external chargers. They use a clean energy source which is movement. With the site to site movement the watch is charged and it operates by an automatic power generator. If the watch is not moved after a total of 72 hours, an additional power saving feature is turned on in order to keep the correct time. This watch can maintain the correct timing for up to four years, and after that it can be shaken and it will return to the correct time. Illustration 2.2 shows the Kinetic GMT watch that uses this technology.

Illustration 2.2: Kinetic GMT watch.

2.4.1.3 Principle C: Ensure minimal use of resources in production and transportation phases

Ensure minimal use of resources in production and transportation phases. This guideline refers to the use of material and the optimum way. This use of material must be considered, not only for production of the product but also for its transportation. When designing a product the main goal is to use as less material as possible creating a minimum scrap due to the design during this process. In this is specific principal packaging please a very important role. If the designing of the packaging is done correctly and follows these principles, the transportation for phase will be effective. When referring that transportation will be effective, this means that not only will the cost of transportation be reduced but also it will reduce the impact to the environment such as carbon dioxide emissions [29].

The following are the principles used to ensure minimal use of resource in protection and transportation phase [30, 31]:

1. Replacing the functions and appeals of packaging through the product's design.
2. Employing folding, nesting or disassembly to distribute products in a compact state.
3. Applying structural techniques and materials to minimize the total volume of material.
4. Specifying lightweight materials and components.
5. Specifying materials that do not require additional surface treatment or inks.
6. Structuring the product to avoid rejects and minimize material waste in production.
7. Minimizing the number of components.
8. Specifying materials with low-intensity production and agriculture.
9. Specifying clean, high-efficiency production processes.
10. Employing as few manufacturing steps as possible.

Illustration 2.3: iPhone packaging reduction of 42%.

One of the guidelines of this principle is to apply structural techniques and materials to minimize the total volume of materials. This guideline is commonly applied to packaging processes. There are

many examples where the packaging has a lot more volume or material itself than the actual product. This is to protect the products of being damaged during transportation and something just required. An example of this guideline is what Apple did. Design engineers from Apple were able to develop packaging for the iPhone that was slimmer, lighter and yet gave the same protection to the product. Illustration 2.3 shows how the packaging was reduced and this allows less material, less waste and also how reduces the admissions during transportation. The example demonstrates that the packaging of the iPhone 4 is 42% smaller than the original iPhone shipped in 2007. This means that 80% more iPhone4 boxes fit on the shipment. If more boxes fit in one shipment, this allows the reduction of the total carbon dioxide emissions due to transportation [32].

2.4.1.4 Principle D: Ensure minimal use of resources during use

This principle leans towards the ability of the product or system to be efficient in the use and consumption of energy and material during the usage of its lifecycle. This pushes the designer to be more conscious of how the product will be you or miss use. The use and miss use of the product must be considered to eliminate any type of excessive resources that the product may need to function as it was designed for or as it can be used for.

The following list shows all the guidelines that can help with the design in order to create a system that ensures a minimal use of resources during its useful life [33, 34]:

1. Implementing reusable supplies or ensuring the maximum usefulness of consumables.
2. Implementing fail safes against heat and material loss.
3. Minimizing the volume, area and weight of parts and materials to which energy is transferred.
4. Specifying best-in-class, energy efficient components.
5. Implementing default power down for subsystems that are not in use.
6. Ensuring rapid warm up and power down.
7. Maximizing system efficiency for an entire range of usage conditions.
8. Interconnecting available flows of energy and materials within the product and between the product and its environment.

9. Incorporating partial operation and permitting users to turn off systems partially or completely.
10. Using feedback mechanisms to indicate how much energy or water is being consumed.
11. Incorporating intuitive controls for resource-saving features.
12. Incorporating features that prevent waste of materials by the user.
13. Defaulting mechanisms to automatically reset the product to its most efficient setting.

One of the guidelines is to incorporate features that prevent waste of material by the user. In easy way to use this guideline is by using calibration marks so that the user of the product can measure the correct amount of water or any substance that is required to place into the system. This guideline also refers to the design of products that incorporate different functions so that the user utilizes fewer resources during the use. An example of this is the Eco kettle that provides already insulation and direction of heat through the use of an enclosed heating coil. The internal reservoir hold a full capacity of water ready for use, and the ECO control knob allows any quantity to be released into the separate chamber for boiling [35]. With this only the exact right amount of water is boiled every time the product is use. The ECO kettle uses on average 31% less energy than an ordinary kettle. An example of the ECO kettle is shown in illustration 2.4. Illustration 2.5 shows how the separate boiling chamber is used in the road to reduce the energy required to boil the water needed.

Illustration 2.4: ECO kettle example.

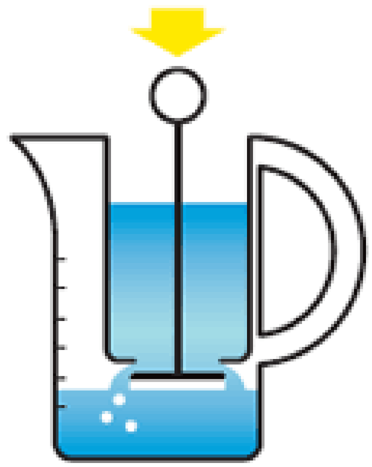


Illustration 2.5: Separate boiling chamber.

2.4.1.5 Principle E: Ensure appropriate durability of the product and components

If the product is able to last for many months or years this will allow a slower it back to the environment. A product that is able to have a long life avoids extra transportation and processing steps and also postpones waste, recycling and manufacturing steps. This principle has to take into consideration two aspects that have to be tight together carefully. These are the durability for long life of the product and also the ability to update the product is great best practices. If this is taken into consideration, the use of inefficient or old technologies will not become a problem.

In order to comply with this principle the following guidelines must be followed for any product or system [35, 36]:

1. Reutilizing high-embedded energy components.
2. Planning for on-going efficiency improvements.
3. Improving aesthetics and functionality to ensure the aesthetic life is equal to the technical life.
4. Ensuring minimal maintenance and minimizing failure modes in the product and its components.
5. Specifying better materials, surface treatments, or structural arrangements to protect products from dirt, corrosion, and wear.
6. Indicating on the product which parts are to be cleaned/maintained in a specific way.

7. Making wear detectable.
8. Allowing easy repair and upgrading, especially for components that experience rapid change.
9. Requiring few service and inspection tools.
10. Facilitating testing of components.
11. Allowing for repetitive dis- and re- assembly.

One of the guidelines of this principle is that the product should be easy to repair and upgrade, especially for component that experience rapid change. One of the best examples for the use of this principle is desktop computers. The rapid pace of advancement in technology for computers is extremely high. This rapid pace makes the computer easily to be obsolete if the parts do not change or cannot be changed. The difference between laptop computers and desktop computers is that laptops computers do not have the facility of changing its parts in an easy manner. The models that are our desktop computers have standard slots for DVD ROM, CD ROMs and video cards. Also motherboards and memory cards have standard slots that have the option to be upgraded or change at any moment easily. These interchangeable parts of the product allow the product to be easily modified so that it does not become obsolete. If these computers were to become obsolete like it happens to laptops, they would have to be disposed entirely and not just a few parts. Illustration 2.6 shows a desktop tower computer that has these properties.

Illustration 2.6: Desktop tower computer.

2.4.1.6 Principle F: Enable disassembly, separation, and purification

One of the main principles in the entire design for the environment approach is idea of designing for disassembly. What this principle is trying to promote is that the design of products and systems can be easily decompose so that all of the parts can be either reused, recycled or remanufactured and be used again in similar products or at least have the minimum impact to the environment once they are disposed.

The following list is the guidelines in order to achieve a product that can be disassembled separated or purify [37, 38]:

1. Indicating on the product how it should be opened and make access points obvious.
2. Ensuring that joints and fasteners are easily accessible.
3. Maintaining stability and part placement during disassembly.
4. Minimizing the number and variety of joining elements.
5. Ensuring that destructive disassembly techniques do not harm people or reusable components.
6. Ensuring reusable parts can be cleaned easily and without damage.
7. Ensuring that incompatible materials are easily separated.
8. Making component interfaces simple and reversibly separable.
9. Organizing a product or system into hierarchical modules by aesthetic, repair, and end-of-life protocol.
10. Implementing reusable/swappable platforms, modules, and components.
11. Condensing into a minimal number of parts.
12. Specifying compatible adhesives, labels, surface coatings, pigments, etc. which do not interfere with cleaning.
13. Employing one disassembly direction without reorientation.
14. Specifying all joints so that they are separable by hand or only a few, simple tools.
15. Minimizing the number and length of operations for detachment.
16. Marking materials in molds with types and reutilization protocols.
17. Using a shallow or open structure for easy access to subassemblies.

One of the principles that say to enable disassembly, separation and purification is easily exemplify with the Ford model U concept car. This concept car is equipped with a vast number of upgradable technologies and a multi-function tailgate that allows the user to adapt the car to their needs as life changes. Some of the key features of this car are that it has a reconfigurable interior and exterior, a hydrogen ICE plus hybrid electric power-train, a conversational speech interface, improved driver visibility and awareness thru active safety, and green materials and processes [41]. Illustration 2.7 shows the concept of the Ford model U car.

Illustration 2.7: Ford U concept car.

2.5 Rework stations

Rework is commonly defined as a process of just repeating a work again. In the manufacturing setting rework refers to recovering not an accepted product in order to use its components to assembly a new and conforming to qualities specifications product. Rework stations can be defined as a station that is able to recover nonconforming products in order to decompose them and convert them into conforming products.

Rework stations commonly are used to decompose nonconforming product and separate the parts in order to identify the ones that can be recovered. Once these parts have been recovered they are sent back to the assembly line so they can be reused in the normal assembly process. These stations perform the disassembly of the product in one single physical station. If a product must go thru several stations

in order to be disassembled it is no longer considered a rework station, and it becomes a disassembly line.

2.6 Design for Disassembly (DfD) vs Reworkability

Rework-ability is a very new concept that refers to the ability of a product or system to be reworked. In other words it means how simple it is to rework a product. There is not an easy way to evaluate the simplicity but it is certain that some products are easier to disassemble than others. Almost any type of rework done to a product in a manufacturing facility requires some disassembly process. And depending on the simplicity of the rework is that the manufacturer decides to disassemble and rework the product or scrap it. When the product has high rework-ability, it is certain that the manufacturer will decide to rework this product at one or several steps in the assembly process. This is because reworking the product or recovering some of its parts is more cost-effective than scrapping it entirely.

Design for disassembly has been discussed in detail previously. This concept and work-ability are closely linked together. If a product uses the principles of DfD, it will almost certainly have high rework-ability. The design stage of the product is critical in order to have systems that have the ability to be reworked. Using the principles for disassembly will allow the product to be reworked not only at the final stage of its life but also during the assembly process.

The design must take into consideration all of the disassembly principles not only for the product but also for the assembly line itself. The main goal for the assembly line is to have the highest rework-ability during the entire process. This can be achieved in many different ways, if the design phase considered the disassembly principles, the assembly process will be able to identify the process that it should follow in order to keep the rework-ability to its maximum possible point.

In the assembly process of any product or system, parts are put together in order to form a final product that will be shipped to the customer. When considering the disassembly principles the assembly process should become simpler. At this point, in order to create the assembly line, this design will make the line simpler and the steps that must be followed easy to identify. An example of keeping rework-ability to the highest level in a production line could be any product that uses a welding process. At any

point of the assembly line once the welding process has been done the rework-ability of the product will follow considerable. This is because now the product would have to be torn apart in order to rework. In cases like this is when rework-ability has to be considered in order to keep these processes at the end of the assembly line if possible. Any process that decreases reworkability in a high level must be tried to do at the end of the assembly. If this is achieved all of the parts of the product will be recuperated causing less cost and scrap for the manufacturer.

2.7 Disassembly

Disassembly is defined as the methodical extraction of valuable parts/subassemblies and materials from discarded products through a series of operations [40]. Disassembly allows the product breakdown into its many single components or subsystems. As mentioned in this definition, disassembling is commonly used for discarded products, meaning that these are products that have ended their lifecycle. In the case of this study the disassembly will be focused on products that have not left the manufacturing facility.

Some of the objectives of disassembly is to able to recuperate valuable components in order to use them again, remove broken or non-usable parts, the reusability of several parts, the reduction of amount of leftover, the possibility of contaminating less the environment, recycling plastic or metal parts that are not functional any more, etc [41]. All of these objectives are imbedded into the Design of Disassembly principles that will be discussed further on.

2.2.1 Modeling Disassembly processes

Modeling disassembly processes is important to create a disassembly sequence for a disassembly process [42]. Modeling refers to representing in depth the process of disassembly in order to understand the steps that should be followed for the disassembly of the product. There are many modeling strategies but they can be categorized into four types: connection graph/component-mating graph [43], direct graph [44], AND/OR graph [46] and disassembly Petri Nets [47]. The connection graph/component-mating graph and the direct graph are the most simple and commonly used disassembly modeling process and will be explained and exemplified in sections 1.3.1 and 1.3.2. AND/ OR graphs use nodes and hyper-arcs. Nodes are used to represent parts of a product or subsistence,

while hyper-arcs represent a set of feasibility disassembly tasks. Petri Nets represent in a single representation, process and system resources required for the full disassembly. One of the advantages of this modeling representation is that it has a dynamic behavior. The dynamic behavior of this modeling process allows the identification of systems resources and requirements for the disassembly.

2.2.1.1 Connection graph/component-mating graph

This modeling process is created by drawing the product or system and identifying its vertices and edges. This representation allows the identification of the constraints for the disassembly of the product alone a feasibility analysis. Fig. 2.3 illustrates an example of a connection graph for a light bulb.

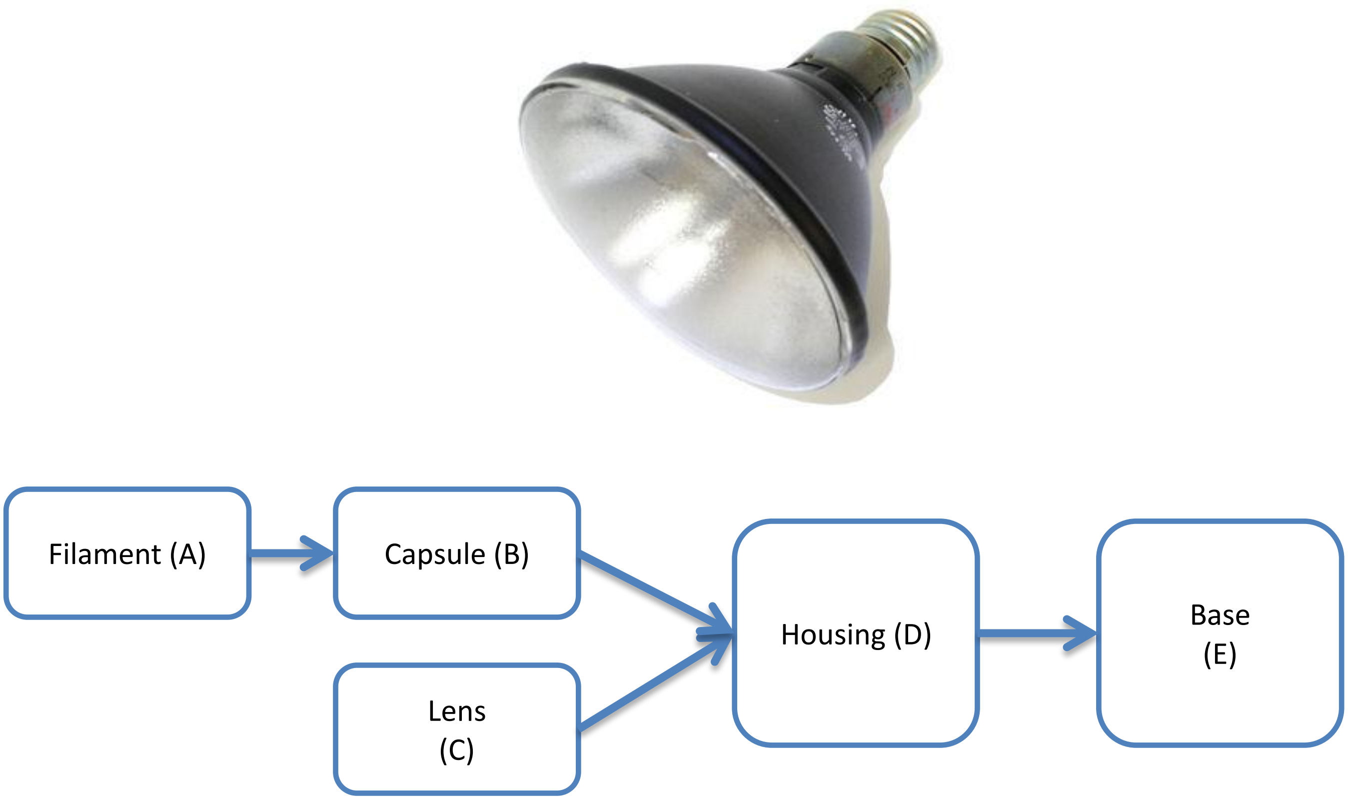


Figure 2.3: Light bulb connection graph.

2.2.1.2 Direct graph

This modeling process is used to identify the disassembly sequence of the product. This process can easily done using a connection graph of the system. The disassembly sequence also allows a feasibility analysis allowing a visual identification of parts and how it is that they are connected to every

other part is. All of these connections can make the disassembly extremely complicated. Fig. 2.2 represents a direct graph for the disassembly of the light bulb and its feasibility. This direct graph has five different disassembly levels. The top one is the first level and following a top-bottom approach the fifth is the last level. The first level represents the product entirely assembled; and the fifth and last level represents the product separated completely in all of it different component. In Fig. 2.4, the letters represent the parts of the light bulb that are mentioned in Fig. 2.3.

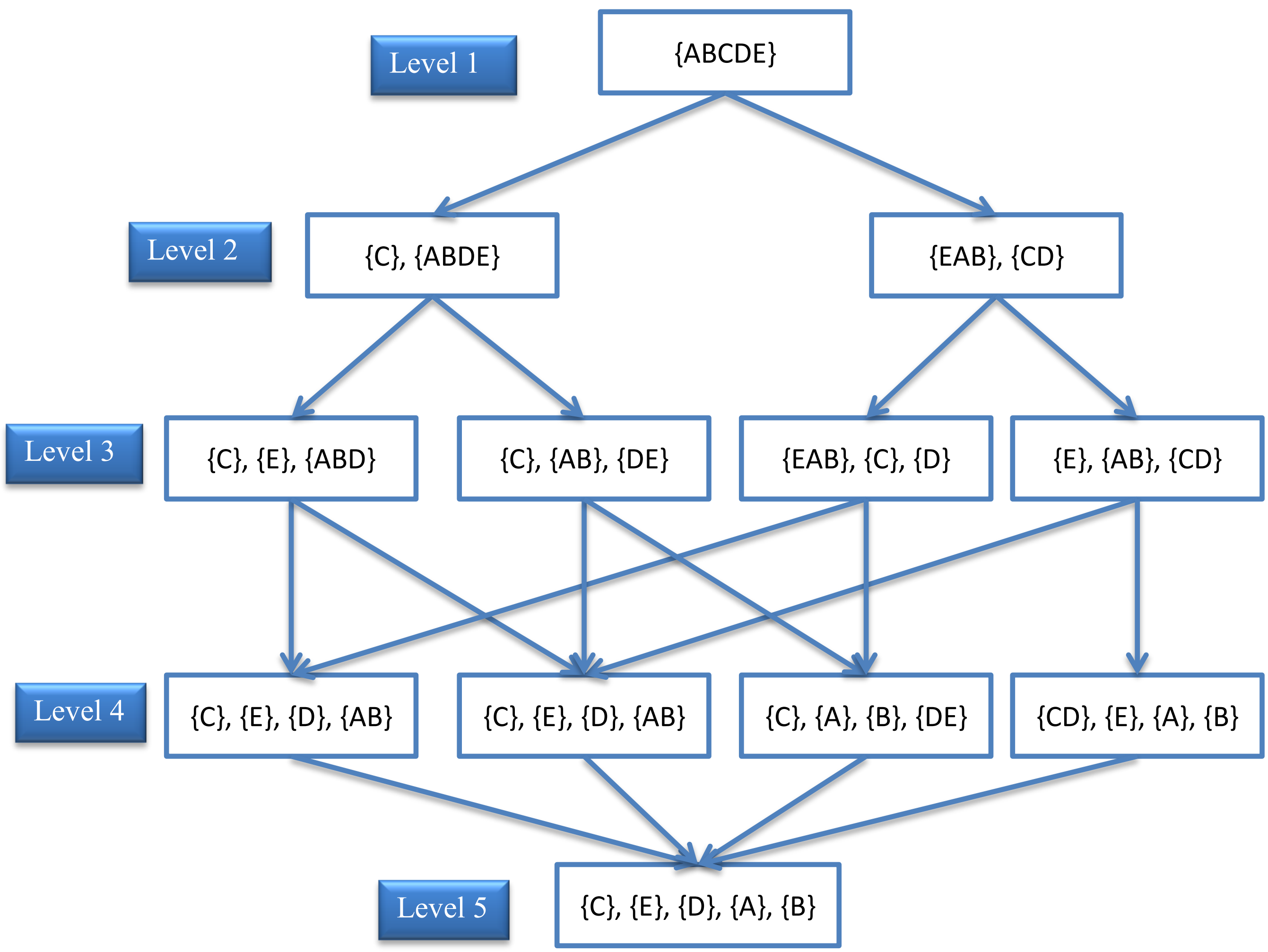


Figure 2.4: Direct graph of light bulb disassembly.

2.2.2 Disassembly process breakdown

In order to use the modeling processes for disassembly, the breakdown process of a system product must be understood. There are four main concepts that need to be defined in order to create an

efficient breakdown of the product. The first one is a component; this refers to all the physical parts that together form the product. The second one is fasteners; these are physical independent entities which have as objective to hold together two or more components. The third concept is initial assembly; this is the original or first set up, of the components and fasteners in order to form subassemblies. The fourth and last concept that must be understood is Product; it refers to the final assembly of one or more subsistence in order to create physical usable system [48].

During a process breakdown it is important to understand all the parts or components of the product and also all the fasteners that whole these parts together. The models for disassembly discussed previously helps in order to understand all of these relationships. For this disassembly processes it is important to obtain the required information of the model, define and describe the strategy used in order to disassemble the system, and finally, if possible simulate the disassembly process thru a computer or physical simulation.

There are several elements that must be taken into consideration in order to perform a disassembly process breakdown. One of them is to set the direction of the components of the system. This allows the system to be decomposed in an easier way than having to switch the direction of the system several ways in order to separate each component. Another element to consider is the direction of removal. This refers to the direction in which the components or subsystems are being removed from the entire system. If all components are being removed in the same direction, this allows an easier and faster disassembly. The final element that needs to be considered for this breakdown, is determining the sequence of movements for the disassembly. This process is very similar to determining the sequence of movements for assembly. It refers to the step-by-step process that a person or machine would have to do in order to disassemble entirely the product. With the consideration of all of the elements not only is the process breakdown easier to perform; but also a computer process simulation can be easily performed using computer software.

2.8 Part/product design vs the disassembly process

Product design has been previously discussed with all of the steps required in order to design a product or system. All of this process is done in order to create a product that satisfies a customer needs.

This need is what starts the process of forming an idea and then following for the steps in order to finally construct the product or system. During the design phase of research and analysis, conceiving, drafting and developing and optimizing the principles of design for the environment must be taken into consideration. In order to design products and can easily disassembled in the manufacturing facilities; the principle that must be taken into consideration the most is the one that enables disassembly, separation and purification of the product.

Once products are being manufactured it is very common that they must be reworked in some steps of the process. In order to rework the products once they have gone thru several steps the process of disassembly is required. This process can be very simple or very complicated depending on the product and on the step of the assembly process it is on. These reworked processes are normally not what are considered as a disassembly line. Disassembly lines are very similar to assembly lines but follow the process inversely then the assembly line. The main objective of the assembly line is to create or assemble the product from all of its parts. On the other hand, the disassembly lines are created in order to take the product and separated into all of its parts in order to use them in new products or recycle them.

It is important to understand that the product design is tightly link to the disassembly process in the manufacturing facility. If a product is designed without considering the disassembly principles, creating rework stations during the manufacturing process is extremely hard. If is a product uses several types of glues, fasteners, welding processes or any other process that makes a disassembly difficult the manufacturer might decide that it is better to throw away the entire product or scrap it instead of reworking it. This is why designing products that consider the disassembly principle is very important not only for the environment but also for the companies that manufacture this product. If the design does not help for the disassembly of the product, there is no point in trying to rework it because the rework might be more expensive than actually scrapping the product.

2.9 IDEF Model

Integration Definition for Function Modeling (IDEF) is a modeling methodology for many sorts of manufacturing and/or systems functions and process. The main objective of the methodology is to

graphically represent the decisions, actions, activities and flow of a process or system. The formal definition is “a set of activities that takes certain inputs and, by means of some mechanism, and subject to certain controls, transforms the inputs into outputs” [49]. The IDEF0 modeling will be used for the proposed methodology because it allows the user to identify the controls and mechanisms used during the assembly process. When special mechanisms are identified in this model a change of level of disassembly normally occurs. This allows the user to easily identify the changes in level and with this the changes in reworkability of the product or system. Fig. 2.5 provides an example of the IDEF model.

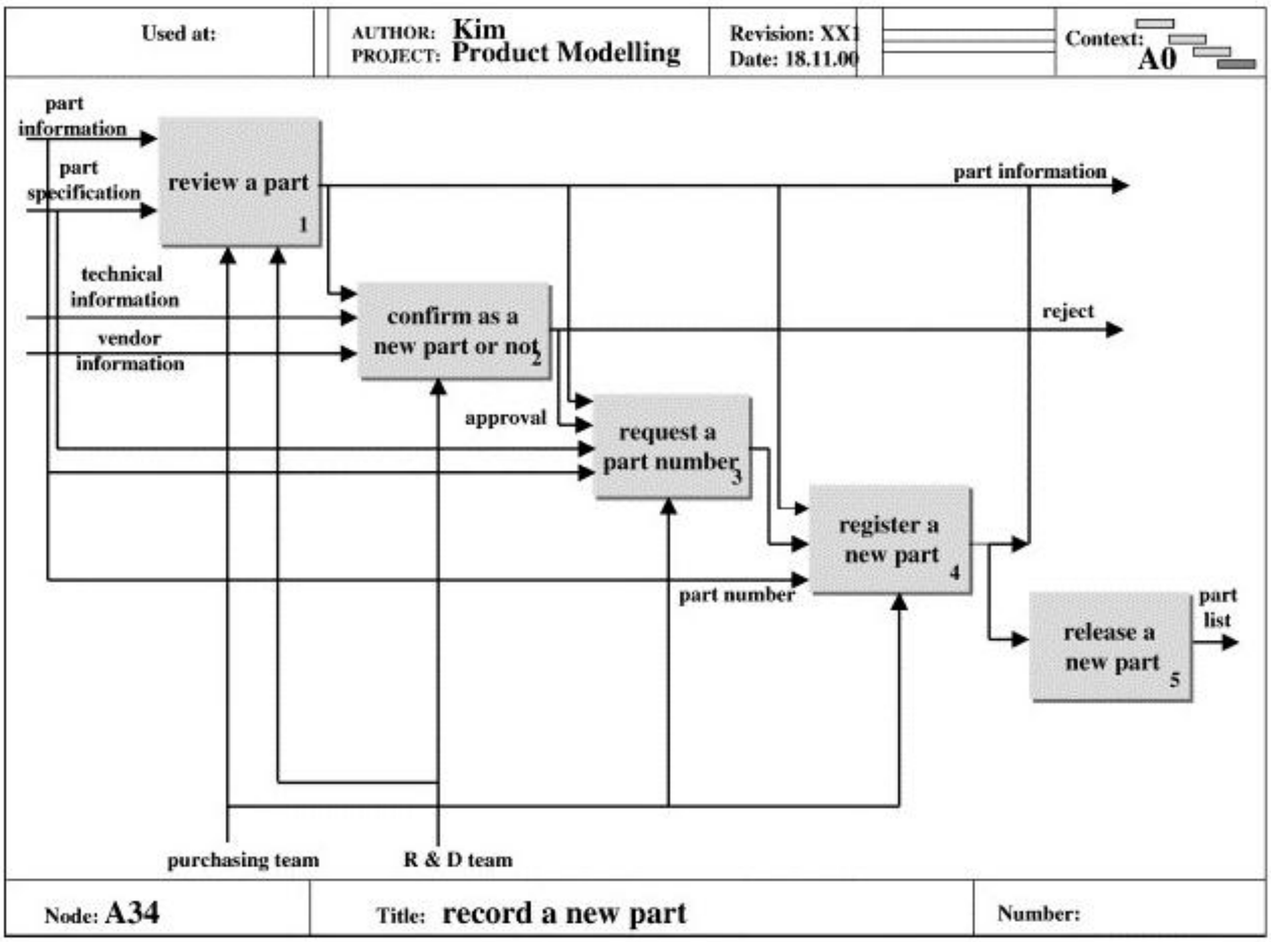


Figure 2.5: IDEF modeling example [5].

2.10 Breakeven point

The breakeven point methodology is used when a balance between two different, sometimes conflicting, factors is desired. For the proposed methodology this factors are the cost and the

reworkability. In general, breakeven points can be defined graphically as the point where two competing curves/traces intersect. Alternatively, a breakeven point can be calculated by utilizing the equations under evaluation and setting the equations equal to one another. Or, the equations can be solved for the independent variable that determines their intersection. The value obtained is the value of the independent variable where the breakeven point is found. Table 2.2 provides some examples of where this methodology is used.

Table 2.2: Disciplines and general applications for breakeven point analysis where a breakeven point is used.

Area Used	Description
Finance	The breakeven methodology is used as a feasibility analysis. Depending on the desired result, minimize or maximize, a result is selected. If minimization is desired the lower side (normally left side of a graph) of the independent variable axis is selected; if maximization is desired, the upper side (right side) is selected. At the breakeven point, both options are equal; and after the breakeven point the optimal solution changes [50].
Economics	One of the functionalities of the breakeven point in sales is to identify the point where income from sales equals the investment. At this point there is neither profit nor loss when comparing income against investment [51].
Materials management	The economic order quantity is used in Materials Management to identify how much of a material to buy. Most suppliers change prices after a certain amount of material is bought. At each of these changes of price, a breakeven point if found and used to calculate the optimum amount of material to buy [52].

Chapter 3: Proposed Methodology

3.1 General

This chapter describes in detail the methodology proposed in order to identify the breakeven point between reworkability and cost in order to locate the rework station. First the methodology is describes step by step with a process flow described by Fig. 3.1. Secondly general assumptions are identified and described in order for the methodology to work correctly. The third step is to present the graph of the cost index and reworkability is presented in order to understand the breakeven point. The fourth step is to present the formulas for the index used in the methodology. The fifth step is to show a disassembly modeling graph and how it impacts the methodology. The sixth step is to calculate demonstrate how both index (reworkability and cost) are calculated. The seventh and final step of this chapter shows how to obtain the result from the methodology.

3.2 Methodology description

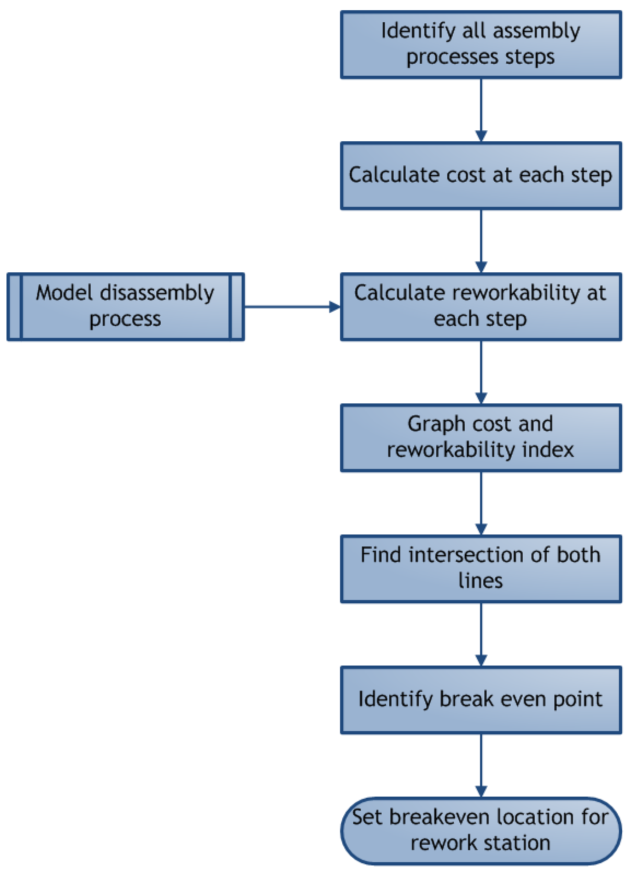


Figure 3.1: Methodology steps to find rework station location.

In order to solve the problem of where to put the rework station a methodology must be followed. This methodology will help find a breakeven point between the cost of reworking the product and the products reworkability (ability to easily rework the product or system). It also solves the conflicting objectives of minimizing rework cost (putting the rework station at step 1) and being able to rework all the defective products (putting the rework station at step N). In order to propose a methodology the cost and the reworkability must be considered and calculated at each step in the process. The proposed methodology has the steps as shown in Fig. 3.1:

The methodology presented in this section, presents an approach that will provide values in order to evaluate reworkability of the product. Reworkability is how easy it is to disassemble the product depending on the assembly stage it is in. The higher the reworkability of the product is it means it is easier to disassemble. There are similar approaches already used for disassembly lines. For mass production disassembly factors such as material handling and disassembly force [53] have higher importance than in rework stations that is what is being proposed. In order for the methodology to work, there are some general assumptions that must be taken into consideration:

1. Only one rework station for disassembled is considered.
2. Once parts are disassembled they return to normal flow depending on station were each part will be used.
3. Parts that are recuperated do not necessarily have to be built together again; they can be combined with new parts.
4. If the product passes the rework station and then becomes defective it will no longer be reworked; it will be entirely scrap.

Considering these assumptions, every manufacturing process has a sequence of steps that it must follow in order to have a finished product. Generally, as the process advances and time passes, the cost of the product increases but the reworkability (Ability to easily disassemble and rework the product) decreases. Fig. 3.2 shows a simple graph of how the three factors are related and seen graphically. The Y-axis is in a decimal basis that can be explained easily as percentage. When either line (Cost or reworkability) are at 1 (or 100%) this means that the product is at the point where it is most easy to

disassemble. This point is when all parts are separate and have not gone thru any type of assembly process. When the cost line is at 1, it means that the total cost of the assembly of the product has been completed and no more resources are needed in order to assemble the system.

The graph, as shown in Fig. 3.2 might not be the case for all manufacturing processes; but it is the most general and common one. The shape of the lines can vary depending on the manufacturing process and on the steps it most take but there are two rules that are always true:

1. At the beginning of the process, the reworkability of the product must be 100%.
   a. If this is not the case, the product must be divided into subsystems in order to perform this analysis.
2. At the end of the process, the cost index must be 1.0 (100%).
   a. All cost must be considered and there should not be any further costs related to assembly of the system.

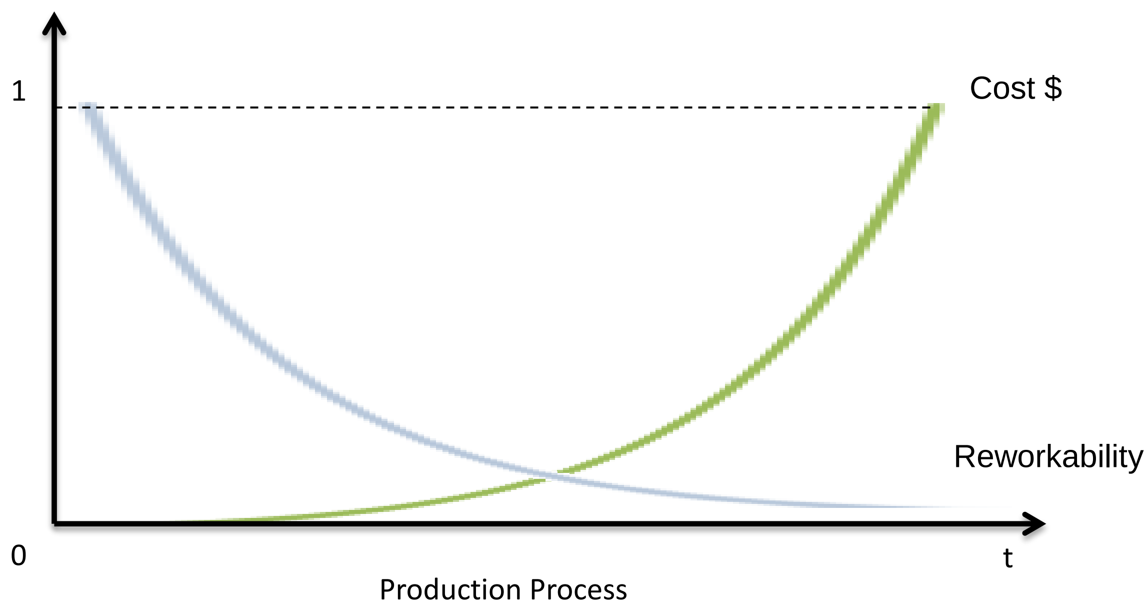


Figure 3.2: Relationship of Cost, Reworkability and time in a manufacturing process.

Once the production process starts, cost increases and reworkability decreases (not necessarily in the same rate). As shown in Fig. 3.2, an intersection point exists between the two graphs. This point will be considered as the optimal location or breakeven point for the rework station because it the

breakeven point between cost and reworkability. This optimal point will depend on the product assembly process and the cost of the process. In order to create a fair comparison between both graphs, Cost and Reworkability are expressed in indexes between zero and one. These indexes are easily calculated equation 1 and equation 2:

$$I_{Cj} = \frac{\sum_{i=1}^{j} C_i}{\sum_{i=1}^{N} C_i} \tag{1}$$

$$I_{Rj} = \frac{R_j}{\max[R_1, R_2, R_3, \dots, R_j]} \tag{2}$$

where

$I_{Cj} = Index\ of\ Cost\ at\ station\ 'j'$

$C_i = Cost\ of\ product\ at\ station\ 'i'$

$I_{Rj} = Index\ of\ Reworkability\ at\ station\ 'j'$

$R_j = Reworkability\ score\ at\ station\ 'j'$

$N = Total\ number\ of\ stations\ in\ the\ production\ process$

In order to obtain the graph that represents the Index of cost (equation 1), the cost of the product at each station must be identified. This process is not at all simple because several production cost must be included in the product cost. This cost must include direct material, direct labor, overhead and any other cost that needs to be incurred in order to manufacture the product at that specific stage. This will make the cost index as objective as possible. All of the direct charges of production at each stage can be simply added and the indirect cost of the production can be evenly distributed in order to simplify the calculation of the cost of at each stage of the production process.

This work proposes a methodology in order to establish the reworkability index thru reworkability scores at each stage of the product production. The reworkability scores are subjective and depend on the user's knowledge. The methodology does not include any proposed method to obtain

these factors. Some of the possible approaches for obtaining significant subjective values are: ranking methods, rating methods, questionnaire methods, interviews, checklist and more [54]. This methodology uses the rating method for the reworkability scores. This reworkability score will be given by adding points depending on how well the product follows the 17 guidelines to make a product easy to disassemble. As the manufacturing process advance, it is more difficult to disassemble the product because of many different factors depending on each product. Some examples of these factors are: more 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 weight might be included at each process to make this differentiation. If weights will be 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 in each station is critical in order to find the correct breakeven point between reworkability and cost. In order to this correctly the use of a disassembly modeling process is recommended. 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 from a top-bottom flow; and the assembly process from 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 decreases 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. Fig. 3.3 illustrates a direct graph with the different disassembly levels.

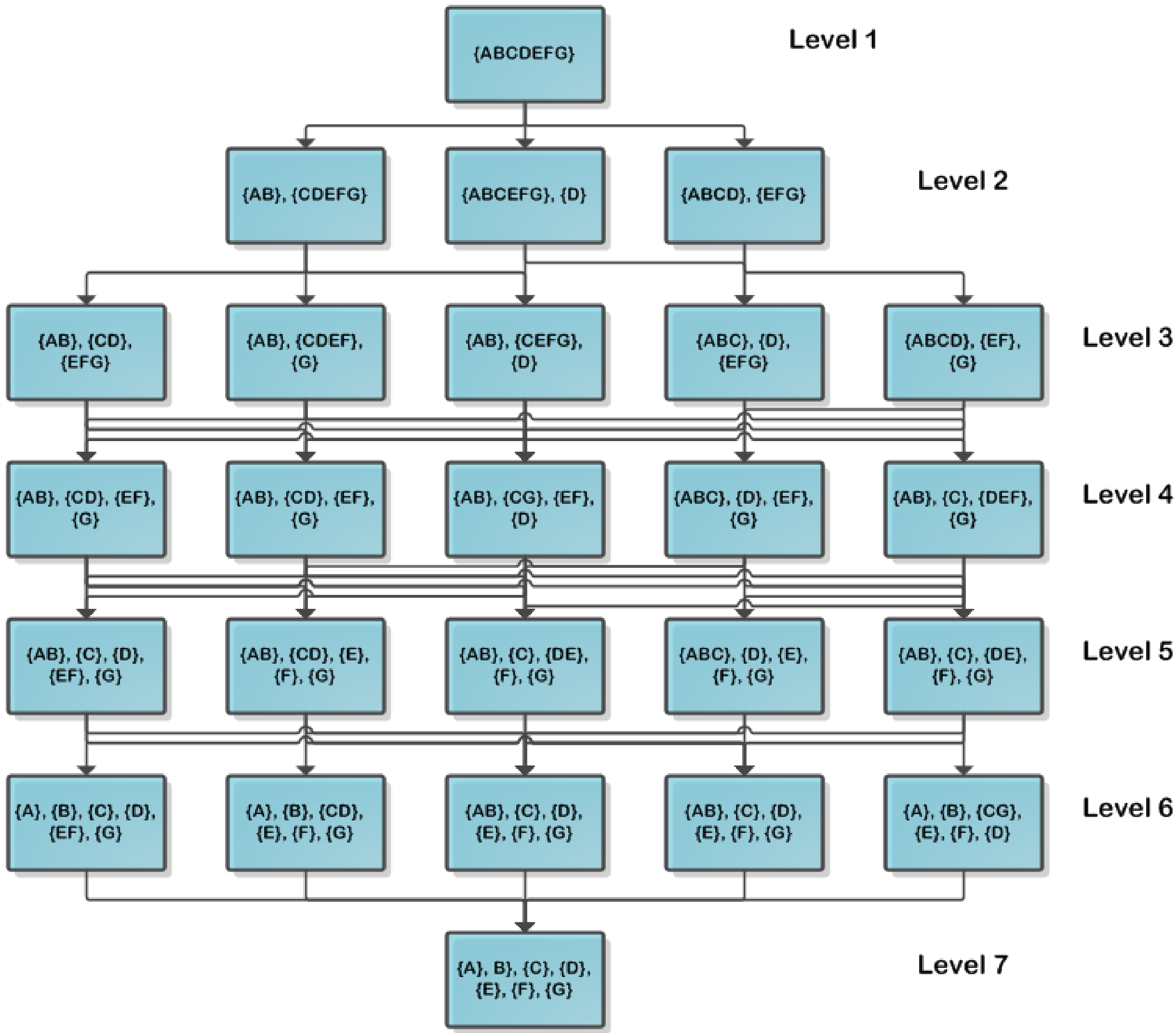


Figure 3.3: Direct graph of disassembly modeling.

In order to establish the reworkability score at each process, the scores of each of the 17 guidelines for disassembly must be evaluated. Each score assigned to each of the guidelines must use the same scale in order to have an accurate evaluation. It is recommended to use a score from 0 to 10 in order to keep the evaluation simple. Since each product is different some of the guidelines many not apply to all the products; in this case simply set that guideline to be ten and continue with the scoring assessment. Having the guidelines set to ten instead of zero is to assure that if guidelines do not apply it is easier to disassemble the product. One example of this would be that the criteria of "Specifying compatible adhesives, labels, surface coatings, pigments, etc." do not apply. If a value of zero is given,

it would mean that the product has many different adhesives, labels, surface coating, etc.; on the other hand a value of ten means that all of this is minimized to maximum expression which is that it does not exist, or in other words, it does not apply. The score assigned to each station is given product and manufacturer experts. All processes are different; and as so they must be treated his way. An expert opinion to define the score of each guideline is recommended.

In certain specific products some guidelines might be more important than others; if this is the case a weight can be added to give more important to the desired guideline. When weights are used it is important to keep the same weights during the evaluation of all the production stages. The summation of all the weights must be equal to one. Table 3.1 shows a table that illustrates how the scoring may be done. These scores are represented with letters for the theoretical explanation of this scoring methodology. The weights do not have to be evenly distributed in real life examples, but in some cases this might occur. The disassembly guidelines are presented as questions in order to make this evaluation more user-friendly for the user. Examples using this evaluation method are presented in chapter 4.

Table 3.1: Scoring process of reworkability.

	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'	$\sum_{i=0}^{i=n} \boldsymbol{W_i}$	$\sum_{i=0}^{i=n} \boldsymbol{S_i}$	$\sum_{i=0}^{i=n} \boldsymbol{R_i}$

Once the scoring of reworkability and cost at each manufacturing step has been established, there corresponding index are calculated. This index will provide the points in the graph that will be used to determine the location of the rework station in order to achieve the breakeven point with the cost graph. Once both graphs have been created a simple graphical method can be used in order to identify the breakeven point. This process is easily done by using tools such as Microsoft excel® or any other data graphing software. The break-even point can also be calculated by using mathematical methods such as the interpolation.

In every single case it is expected that the graph of reworkability will have a negative slope and the cost graph will have a positive slope. Table 3.2 demonstrates how the values of reworkability and

cost would be calculated. In this case the value of 'N' is set in the fifth station. This means that there are an infinite number of possible stations that the methodology can work with. It is important to remember, that the Index of the cost is calculated using the cumulative cost of each step of the process.

Table 3.2: Data Table of values.

				Index	
Station	Cost	Rework Score		Cost	Reworkability
1	C_1	R_1		$I_{C1} = \frac{C_1}{C_T}$	$I_{R1} = \frac{R_1}{R_{max}}$
2	C_2	R_2		$I_{C2} = \frac{\sum_{i=1}^{2} C_i}{C_T}$	$I_{R2} = \frac{R_2}{R_{max}}$
3	C_3	R_3		$I_{C3} = \frac{\sum_{i=1}^{3} C_i}{C_T}$	$I_{R3} = \frac{R_3}{R_{max}}$
4	C_4	R_4		$I_{C4} = \frac{\sum_{i=1}^{4} C_i}{C_T}$	$I_{R4} = \frac{R_4}{R_{max}}$
N	C_N	R_N		$I_{CN} = \frac{\sum_{i=1}^{N} C_i}{C_T}$	$I_{RN} = \frac{R_N}{R_{max}}$
Total/Max	$C_T = \sum_{i=0}^{N} C_i$	$R_{max} = Max(R_1, \dots, R_N)$			

Fig. 3.6 illustrates what an example of a graph would look like when graphing the stations (X-axis) against the index values (Y-axis). The X-axis is graphed as the stations of the process but can also be graphed as time. If it is graphed as time the identification of the location of the rework station calculation is a somehow more complex because it will provide the location of the rework station with respect to time. At this point, the rework station must be placed right after the process that is being performed at the time the methodology suggests the breakeven point. The breakeven point will most of the time not be exactly an integer number; rounding up the number is the most appropriate thing to do because the reworkability and the cost does not change in the station. If the breakeven point is calculated mathematically to be 3.1, rounding up should be done because during all station 3 (mathematical values between 3.0 and 4.0, excluding 4.0) the cost and the reworkability have the same value. This time must be from when the time the assembly process is being started assuming there are

no down times in the process. In this graph the breakeven point is easily identified as it should be between stations 3 and 4 of the production process.

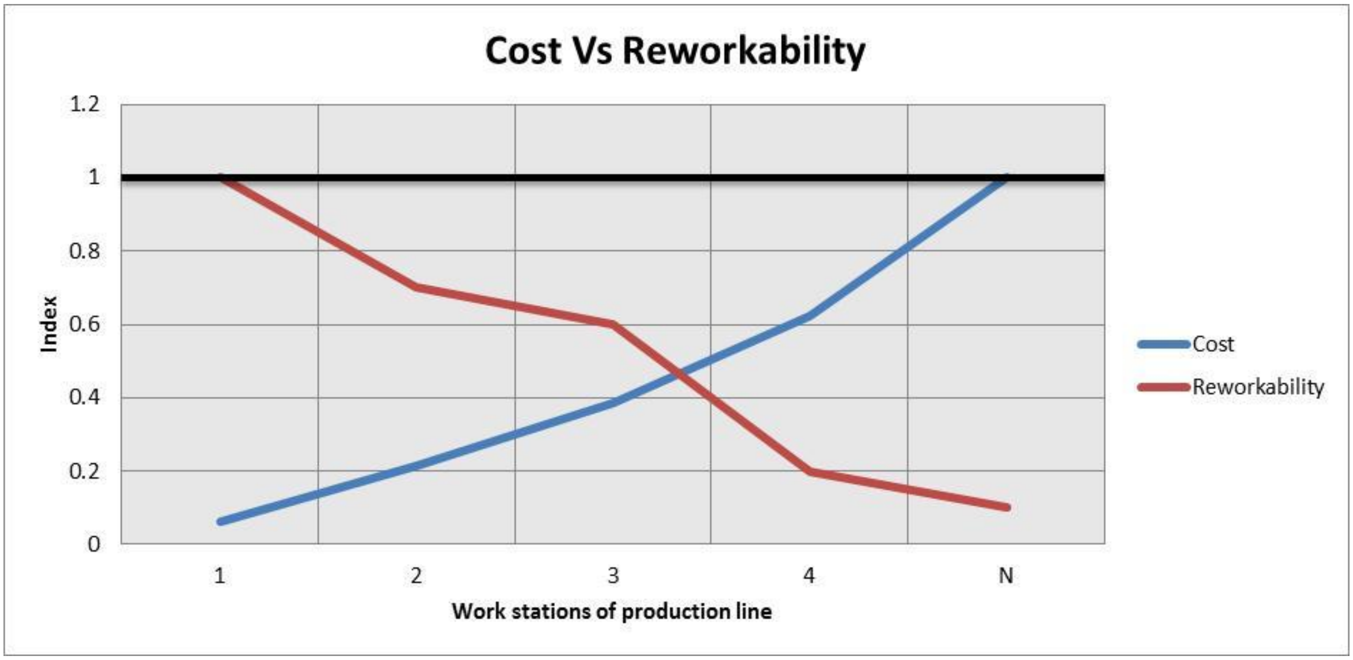


Figure 3.4: Graphical representation of breakeven point.

In order to identify the location of the rework station using this methodology the breakeven point must be identified. The breakeven point of Fig. 3.4 is where both lines intersect that is at stage 3 of the process (X-axis). This means that the best location to place the single rework station is between station 3 and 4. This will give a balance between the cost of the product and its reworkability. Fig. 3.4 demonstrates how the reworkability is decreasing after every step and cost is increasing. If reworkability would have decrease slower it would be possible that the breakeven point would be after station 4 or even station 5. On the contrary, if it would have decreased faster, the rework station would be placed after either station 1 or 2.

The solution of this process refers to the computational results of the problem. In this specific case, the solution was calculated using Microsoft Excel®. These calculations can be easily done with any software that has the ability to plot a set of numbers and either identify graphically or mathematically the intersection between the two lines. The core of the methodology proposed is not the use of technology or software's to create these calculations (because they can evenly be calculated by

hand). The core is to provide a standard and systematic methodology to identify the optimal location of 1 single rework station in order to find the breakeven point between cost and reworkability in any type of assembly process.

This methodology can be a predictive model if there is a similar process that already exists for the assembly of the product or the process is already established in a conceptual model. If the assembly process can be created in a conceptual module it is possible to create graphs, the cost and the reworkability ones, in order to find their intersection and estimate the possible optimal solution for the rework station. When trying to predict this optimal position a deep, clear understanding of the process is necessary because every calculation must be done with a mathematical or modeling process. The problem when doing this type of modeling is that there is no way to be 100% certain that the modeling is correct. The only possible manner to have this 100% certainty is to have the real life process created and verify all the data of the conceptual module. Creating a conceptual module following a structural process will allow the proposed methodology to have a predictive result very close to the optimal one of the real life assembly process.

Chapter 4: Applications of methodology

4.1 General

This chapter presents two examples using the proposed methodology to optimize the location of the rework station in an assembly line. The examples used will be from the medical industry using two different medical products. Both products are manufactured by Ethicon Endo Surgery, which is part of the family of companies of Johnson & Johnson [55]. Both devices that will be used as examples are used for laparoscopic and endoscopic surgeries. The first device that will be uses as an example are the ENDOPATH XCEL trocar in section 4.1 and the second one is called the ENSEAL energy device in section 4.2. Section 4.3 describes some special cases that are not covered in these two examples.

Using this product as examples is a great way to demonstrate the methodology because the first one has a simple assembly and the second one has an extremely complicated assembly. Most of the devices will be explained through their assembly process, and then the methodology will be applied to obtain the optimal location of the re-workstation and finally a conclusion on why this methodology works will help us understand the benefits of the methodology for these medical products.

4.2 Endopath XCEL study case

Trocars are medical instruments with a sharply pointed end used in laparoscopic surgeries to introduce ports into the body. These instruments are the gateway into the body for the other laparoscopic instruments used for the surgery. Through the Trocar is how the doctor can get access to the body and is able to inflate the body, introduce cameras and introduce the instruments required for the surgery.

EES has the Endopath XCEL Trocar portfolio that consists of five different trocars that provide the same final function but are different due to the surgery they are used on. Illustration 4.1 shows the portfolio and the five different trocars that are:

- Bladeless
- Dilating tip
- 5mm OPTIVIEW
- Bunt tip
- Universal Sleeve

Illustration 4.1: ENDOPATH XCEL Trocar Portfolio.

The definition of a trocar according to its United States patent number 6692467 is:

"A trocar assembly structured to regulate fluid flow as well as the introduction of predetermined medical instrumentation into and out of a body cavity of a patient during a surgical procedure such as, but not limited to laparoscopy, endoscopy, etc. The trocar assembly includes a housing having a hollow interior secured at one end to an elongated open ended sleeve through which fluid flow and medical instrumentation passes. A valve assembly includes a valve member disposed within the hollow interior and a valve structure including a valve seat rotatably connected to the housing such that the valve seat is selectively rotatable relative to the valve member and into and out of fluid sealing engagement therewith so as to respectively define a valve-closed position and a valve-open position. The valve assembly may be rotated between the aforementioned open and closed positions utilizing one hand of the person operating the trocar assembly, wherein the valve assembly will automatically remain either in an open or closed position, without continuous pressure being exerted thereon by the personnel operating the trocar assembly"[56].

In order to apply the proposed methodology the Bladeless trocar assembly will be used. Figure 4.1 and 4.2 shows an exploited view of the two main parts of the trocar which are the trocar body and the Obturator assembly respectively. The assembly process cannot be described in deep detail due to company information privacy policies but it will be generally explained.

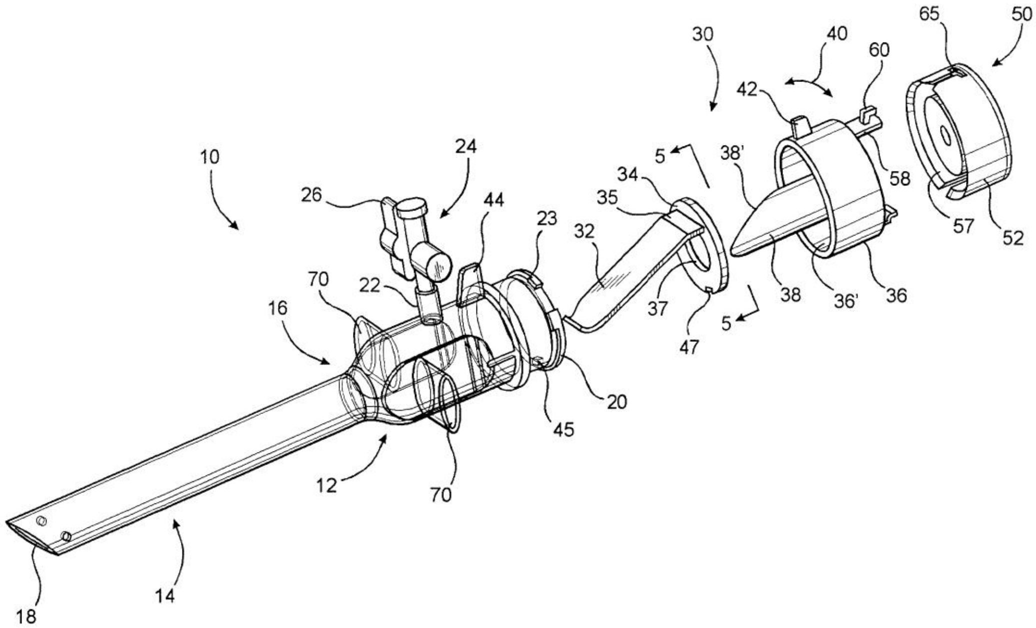


Figure 4.1: Exploited view of trocars body.

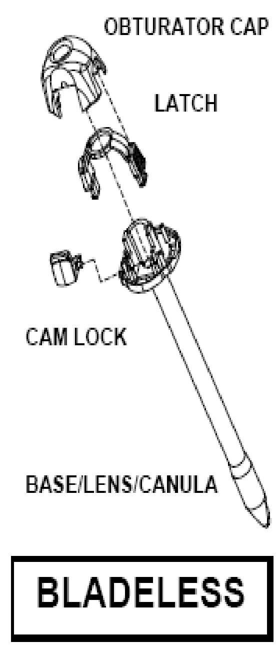


Figure 4.2: Exploited view of Obturator assembly.

The process of assembling a trocar is first divided into different manufacturing lines. The first line assembles the trocar body and in the second line assembles the obturator assembly. After both parts have been assembled they are put together and tested for final quality purposes. Once they have been assembled together, they are packaged and send to the sterilization process. After the product has been sterilized, it is sent finally to the customer. For the purposes of this example only the assembly stage and quality testing will be consider using the proposed methodology. Fig. 4.3 illustrates the IDEF0 model of the assembly process. This process does not show any rework station; the location of the rework station will be defined using the proposed methodology further on.

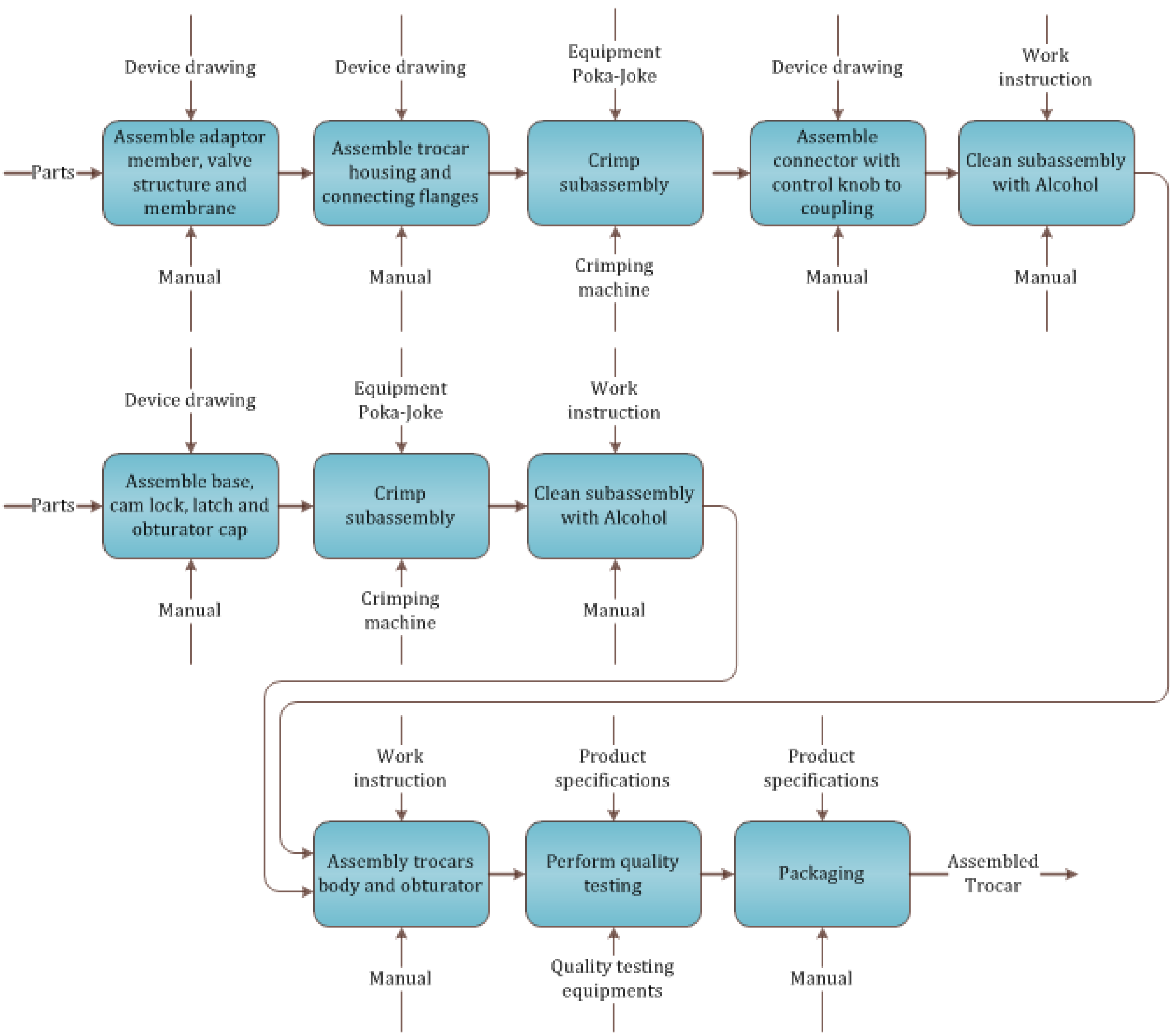


Figure 4.3: Trocars assembly process.

The first step is to place the adaptor member in the correct position with the valve structure and the valve membrane. Once this has been done, the subassembly must be placed on top of the trocars housing and the connecting flanges. After all this parts have been placed together, the next step is to crimp them using a specialized equipment to do this process. The third step is to manually place the connector that has the control knob into the coupling of the trocars housing. The final step is to clean the trocars body with alcohol.

Parallel to this process the operator is also being assembled. This subassembly has only three steps. The first one is to place the base with the cam lock, the latch and the obturator cap in the correct position. The second step is to crimp them using specialized equipment. The third and final step is to clean the subassembly with alcohol.

Once the two subassemblies have been complete, they are manually assembled together; a quality testing is done to the product and finally they are packaged in order to be shipped to be sterilized and finally be sent to the customer.

Now that the process has been defined the proposed methodology can be followed as shown in Fig. 3.1. The first step of the methodology is to identify all the process steps of the assembly process. This has been already done in Fig. 4.3. The second step is to calculate the cost of the product in each of these steps. The cost shown in table 4.1 are not the real costs of manufacturing this product, they are close estimates. Due to company policies the exact cost cannot be used.

Table 4.1: Assembly process steps cost of trocars.

Process step	Approximate cost USD
Assemble adaptor member, valve structure and membrane	$1.^{50}
Assemble trocar housing and connecting flanges	$0.^{75}
Crimp trocars body subassembly	$7.^{75}
Manually assembly connector with control knob to coupling	$2.^{00}
Clean with trocars body with alcohol	$0.^{50}
Assemble Base, cam lock, latch and obturator cap	$1.^{50}

Crimp obturator subassembly	\$5.25
Clean obturator with alcohol	\$0.50
Assemble trocars body and obturator	\$1.00
Perform final Quality testing	\$3.50
Packaging	\$0.75
Total Cost	**\$25.00**

Before the third step of calculating the reworkability score at each step of the process the disassembly modeling must be performed. This will give provide 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 work station. Fig. 4.4 shows the disassembly model using the direct graph methodology.

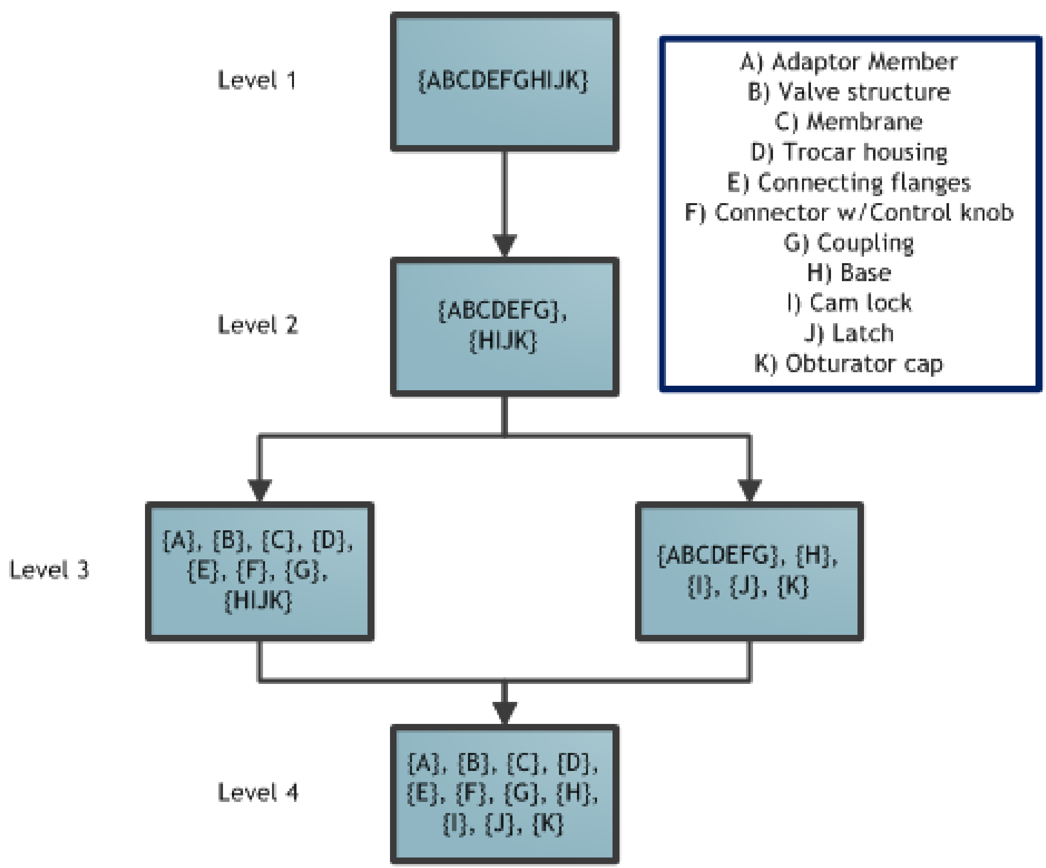


Figure 4.4: Trocar direct graph disassembly model.

The third step is to calculate the reworkability of each step of the process using the 14 guidelines of design for disassembly. Appendix II shows the table with all of the reworkability scores of the process. Remember that even though they are processes that are done in a parallel manner in real life; for this case study they are considered to be in series. If they would of have been considered as parallel, it must of have been necessary to perform the methodology as if they were two separate assembly lines in order to achieve an optimal rework station. Table 4.2 shows the calculation of the reworkability of the assemblies' stations 1 and 2. The scores are given by design and manufacturing experts.

Table 4.2: Reworkability of trocars 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	0.188679245	10	0.188679245
Are joints and fasteners easily accessible?	2	10	0.377358491	9	0.339622642
Is part able to disassemble maintaining product stability?	4	9	0.679245283	9	0.679245283
Are all joining elements of equal type?	4	9	0.679245283	9	0.679245283
Is destructive technique safe and will not harm people or affect reusable components?	5	10	0.943396226	10	0.943396226
Can reusable parts be cleaned easily and without damage?	5	10	0.943396226	9	0.849056604
Are incompatible materials easily separated?	5	10	0.943396226	9	0.849056604
Are all component interfaces simple and reversibly separable?	3	10	0.566037736	10	0.566037736
Is the product or system organized into hierarchical modules by aesthetic, repair, and end-of-life protocol?	3	10	0.566037736	10	0.566037736
Are reusable/swappable platforms, modules, and components implemented?	1	10	0.188679245	10	0.188679245
Does the product have only the minimal number of parts it requires?	5	10	0.943396226	9	0.849056604
Are compatible adhesives, labels, surface coatings, pigments, etc used?	4	10	0.754716981	10	0.754716981
Is only one disassembly direction without reorientation required?	2	10	0.377358491	10	0.377358491
Are all joints separable by hand or only a few, simple tools required?	3	9	0.509433962	9	0.509433962

Is the number and length of operations for detachment minimized?	4	10	0.754716981	10	0.754716981
Are materials marked in molds with types and reutilization protocols?	1	9	0.169811321	9	0.169811321
Is a shallow or open structure used for easy access to subassemblies?	1	10	0.188679245	10	0.188679245
Total Reworkability score at production station 'j'	53	166	9.773584906	162	9.452830189

The first 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 4.3 shows the summary of the coast and reworkability scores and the calculated index for both factors. Fig. 4.5 illustrates the data obtained from the table 4.3 in a graph. This graph allows easily identifying the intersection point of both factors in order to determine the optimal rework station location. As it can be seen in the graph, there are two significant decreases in reworkability. The first one is from station 2 to station 3 and the second one is from station 6 to station 7. The change in reworkability from station 2 to 3 is the change from level 4 to level 3 in the disassembly model shown in Fig. 4.4. The second drop in reworkability happens when the disassembly model changes from level 3 to level 2. There is no third drop in disassembly from level 2 to level 1 because this change is level is a manual assembly that does not require any special or complicated disassembly process. Since these drops in reworkability exist, it can be certain that the correct reworkability score was assigned to each step of the process. This is a simple way to verify if the methodology was done correctly.

All of these calculations were done using the Microsoft Excel® software. As the methodology implies the rework station must be placed after the 6th station of the process. Fig. 4.6 show the layout of the manufacturing line without the rework station and Fig. 4.7 shows the proposed layout including the rework station. The 6th station is "Assemble Base, cam lock, latch and obturator cap"; and after this station comes the crimping process. What this implies is that there is no point on reworking the assembly after it has been crimped. This is because the reworkability of the product is too low 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. Creating a process for recuperating the product would mean creating an entirely new disassembly process. A new analysis

must be created in order to decide if creating a disassembly process for the Trocar is cost effective because the use of only a rework station is not cost effective after station 6 of the process.

Table 4.3: Summary table of cost and reworkability for a Trocar.

				Index	
Station	Cost	Cum. Cost	Reworkability	Cost	Reworkability
1	$ 1.50	$ 1.50	9.774	0.06	1
2	$ 0.75	$ 2.25	9.453	0.09	0.967181467
3	$ 7.75	$ 10.00	6.170	0.4	0.631274131
4	$ 2.00	$ 12.00	5.887	0.48	0.602316602
5	$ 0.50	$ 12.50	5.887	0.5	0.602316602
6	$ 1.50	$ 14.00	5.245	0.56	0.536679537
7	$ 5.25	$ 19.25	3.623	0.77	0.370656371
8	$ 0.50	$ 19.75	3.623	0.79	0.370656371
9	$ 1.00	$ 20.75	3.396	0.83	0.347490347
10	$ 3.50	$ 24.25	3.396	0.97	0.347490347
11	$ 0.75	$ 25.00	3.057	1	0.312741313
Total/Max	$ 25.00		9.773584906		

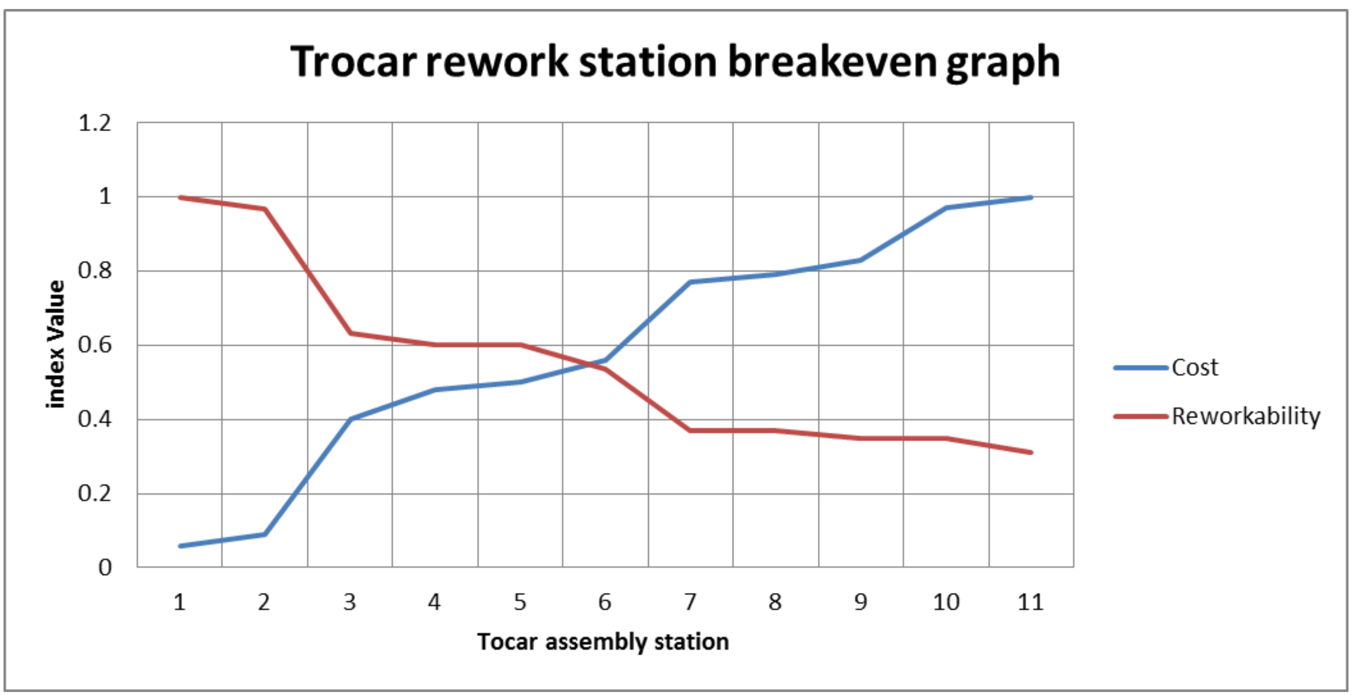


Figure 4.5: Graph of trocar rework station.

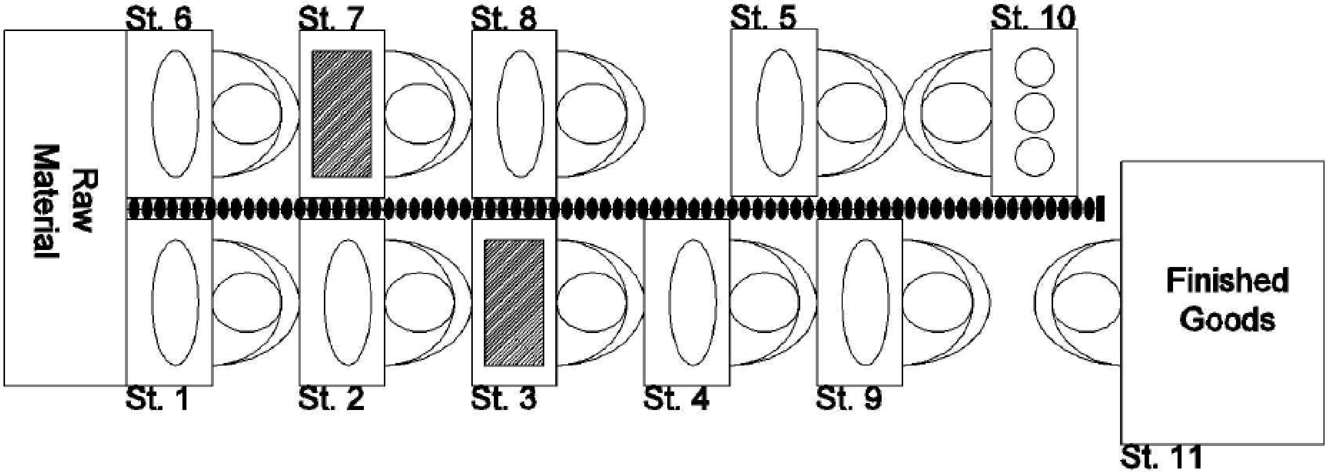


Figure 4.6: Manufacturing line layout without rework station.

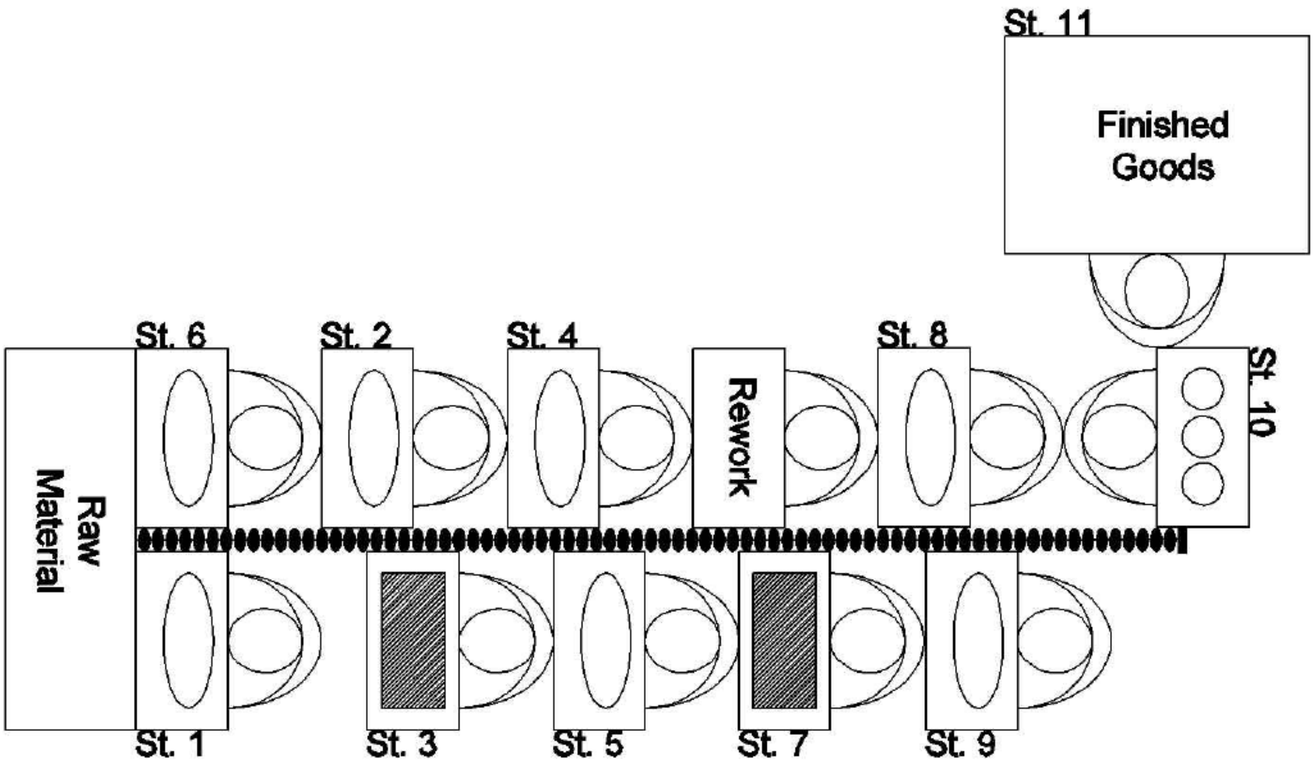


Figure 4.7: Manufacturing line layout including rework station.

4.3 ENSEAL study case

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 device has an ergonomic handle for better grip with the ability to rotate the jaws single handed. The length and diameter of the shaft varies depending on each instrument and the surgery it is intended for. This section of the instrument (the shaft) is the one that is introduced into the patient's body in order to carry out the surgery. The instrument ends with the jaws that are the ones that transmit the energy in order to seal the vessels; this section also includes the I-blade, which the part the cuts the vessels once they have been sealed. The instrument also has the ability to only cut without sealing, or to only grasp tissue without cutting or sealing. Illustration 4.2 shows the instrument with all its parts and some special characteristics.

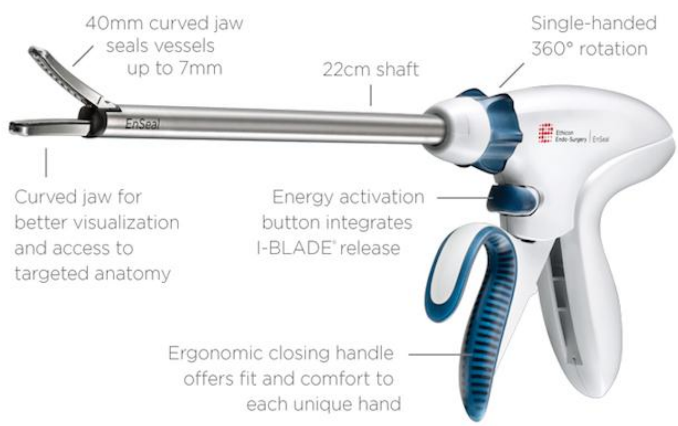


Illustration 4.2: EnSeal laparoscopic surgical device.

Other characteristics of the EnSeal laparoscopic surgical device are:

- Temperature Controlled: Temperature automatically regulated to approximately 100°C; thermal spread confined to approximately 1mm outside jaws.
- High Performing: Seals vessels up to 7mm with seal strength up to 7 times systolic pressure; patented I-BLADE™ Jaw offers strong, uniform compression along the entire seal line.
- Adaptable: Control speed of sealing and cutting based on tissue type.
- Efficient: One-step actuation for both cutting and sealing.

The manufacturing of the EnSeal device is extremely more complicated than the trocar explained previously. This device is manufactured in two steps. The first step is to assembly the shaft of the dives

and the second step is to assemble the entire device. Fig. 4.8 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.

Fig. 4.9 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.

Fig. 4.10 shows a layout of the entire production line and how it is that the two assembly lines are interconnected. As it can be seen in Fig. 4.10, 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. In the Fig. 4.10, 2 different manufacturing lines are shown (Line 108 and Line 109), for purpose of this methodology only one assembly line will be considered.

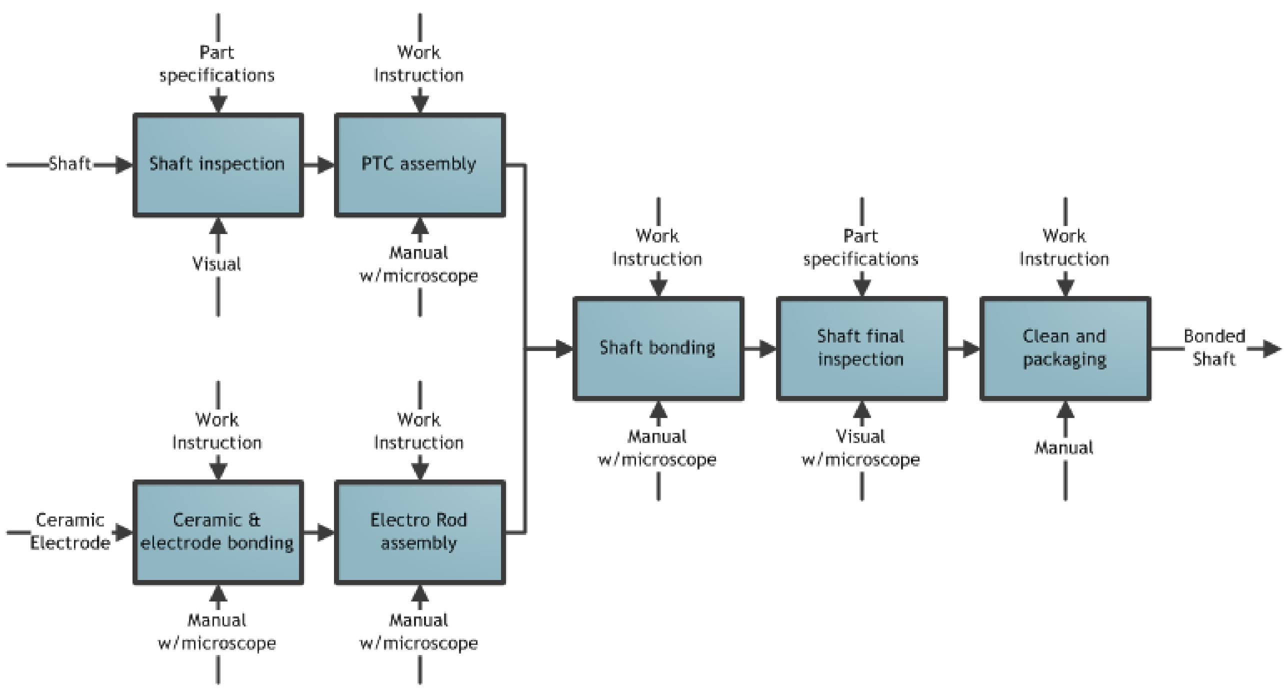


Figure 4.8: EnSeal shaft assembly process.

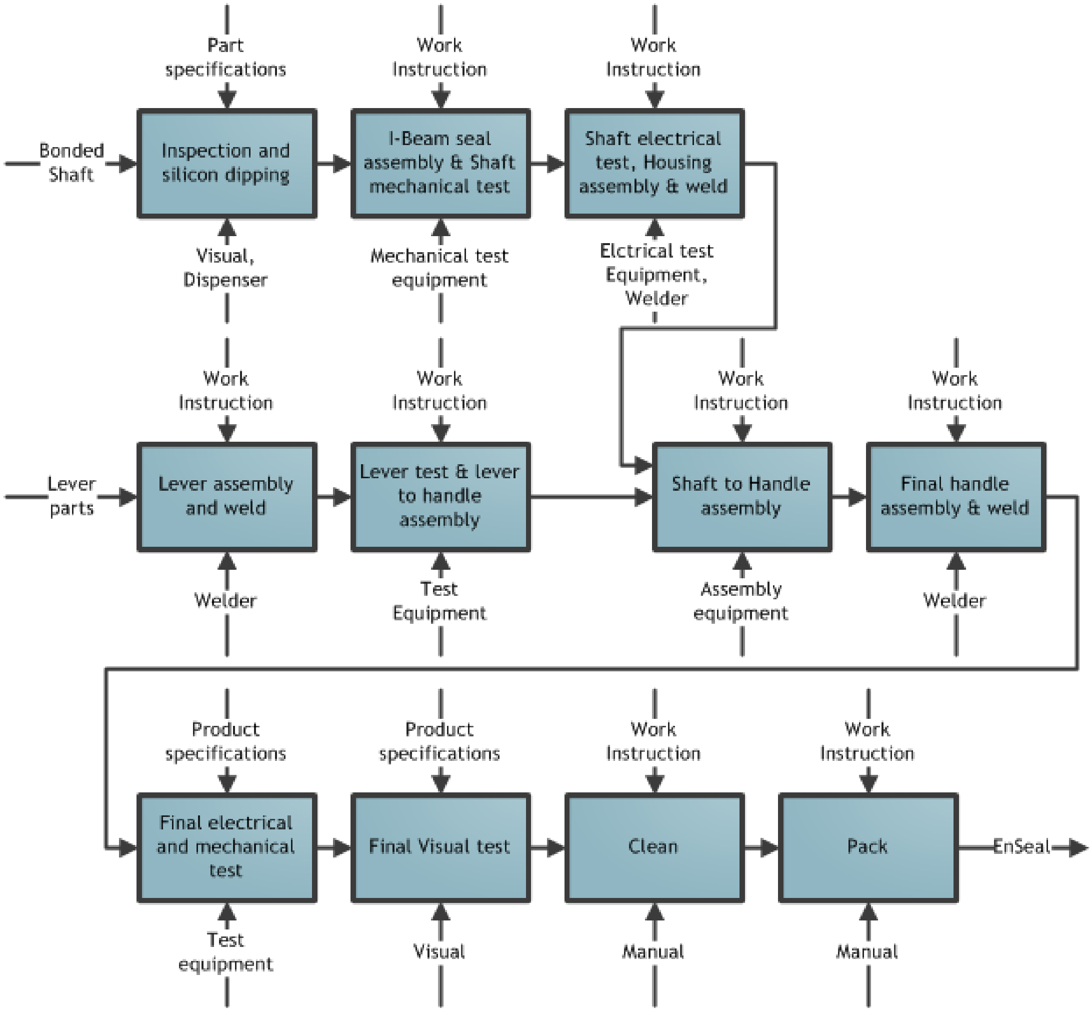


Figure 4.9: EnSeal instrument assembly process.

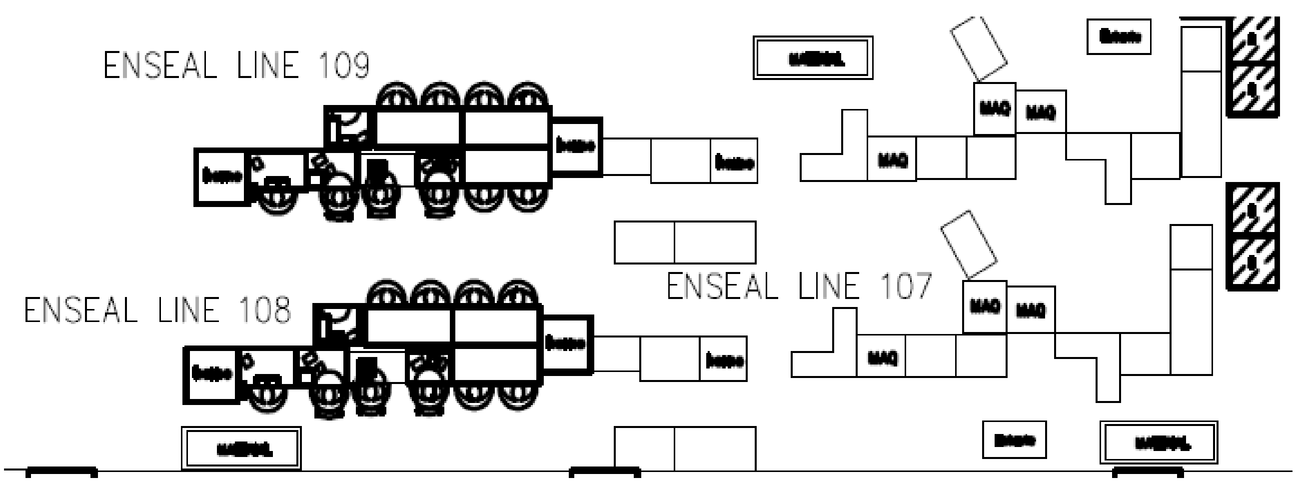


Figure 4.10: EnSeal assembly line layout.

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 work station. Fig. 4.11 shows the disassembly model using the direct graph methodology.

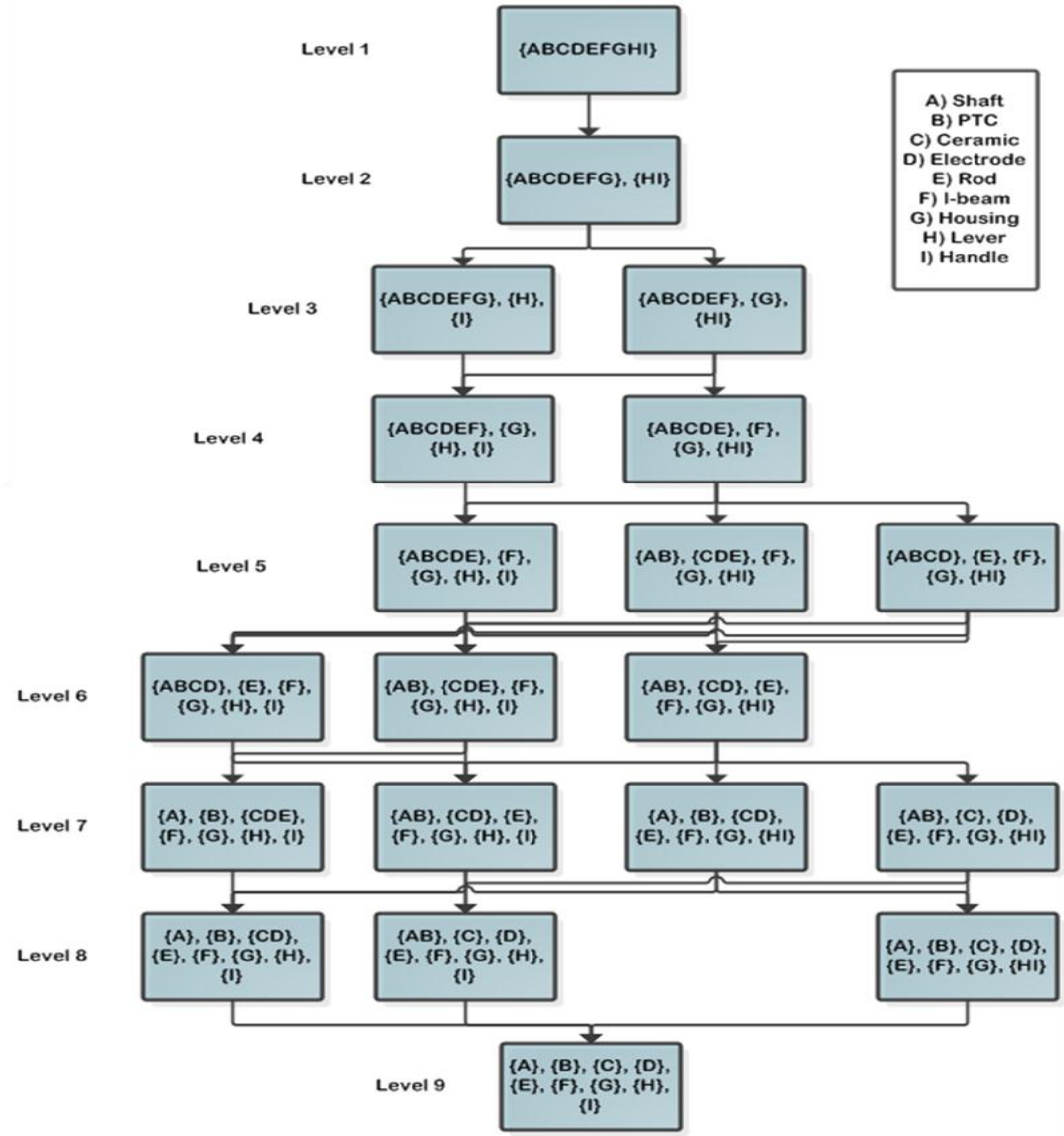


Figure 4.11: EnSeal direct graph disassembly model.

The step by step explanation of the process will not be discussed due to company privacy policies; but figures 4.8, 4.9 and 4.10 allow a good understanding of the process assembly. The proposed methodology will be followed as shown in Fig. 3.1 to obtain the optimal rework station location. The

first step of the methodology is to identify all the process steps of the assembly process. Figures 4.8 and 4.9 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.

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 rework-ability of the assemblies' stations 1 and 2. Appendix III shows the table with all of the reworkability scores of the process. 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: Rework-ability 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

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 4.6 shows the summary of the coast and rework-ability scores and the calculated index for both factors. Fig. 4.12 illustrates the data obtained from the table 4.6 in a graph. This graph allows easily identifying the intersection point of both factors in order to determine the optimal rework station location.

Table 4.6: 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		

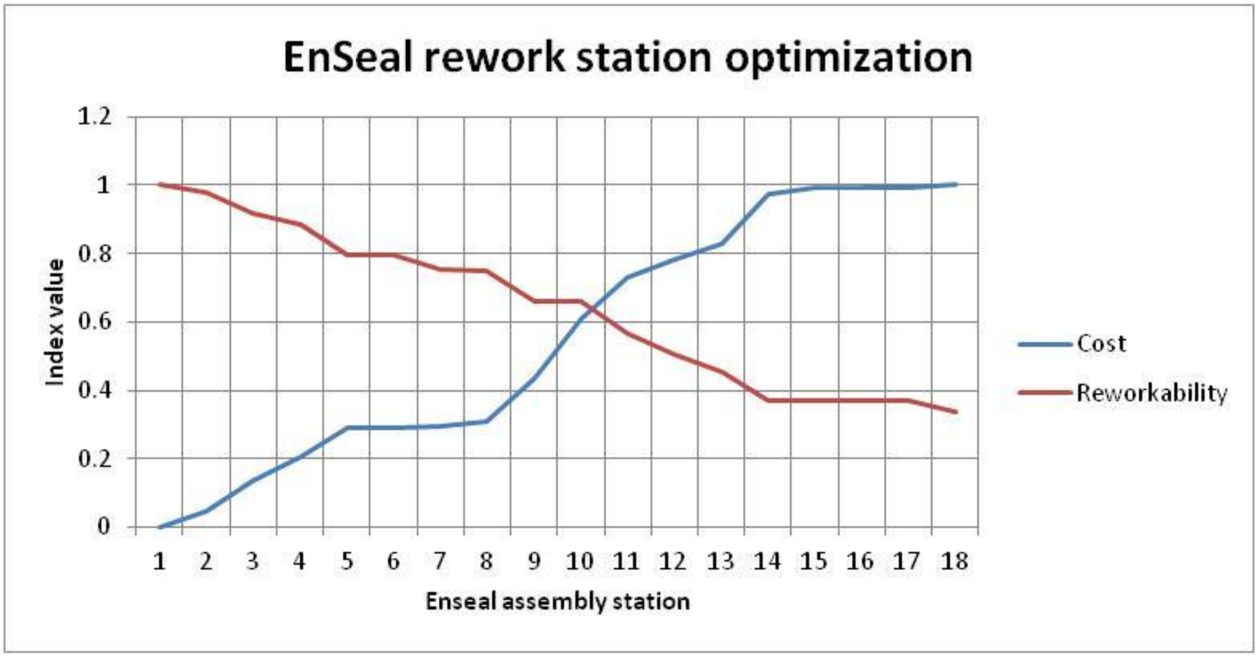


Figure 4.12: Graph of EnSeal rework station.

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.

4.4 Special scenarios

There are two special cases that must be understood when locating a rework station. This is when the analysis points to putting the rework station should be placed at:

1. The 1st station: This scenario can be caused because there is processes were chemical or physical properties of the material/product are being changed. One example of this is a process like plastic molding. In this scenario the product might change it color, or be

separated from other molded parts; but there is really no point of reworking the product further down the process if after the molding station it is not conforming.

2. The last station: Even though the rework is at the last station, it is not necessary the optimal condition. In this scenario the product goes thru all the manufacturing process and only at the end of the manufacturing line are the defective ones isolated and reworked. Examples of this scenario are rapid manufacturing lines such as consumer products. These lines can produce hundreds of products per minute and there is no point in separating the defective product at a certain station due to the velocity. The best option is to let the product follow all the process and just segregate the defective products at the end in order to rework them.

Chapter 5: Conclusions and Recommendations

This chapter will make a recapitulation of the intent of the study, the conclusion obtained by the methodology proposed, the contribution of this methodology to the field of manufacturing and recommendations for future research. Section 5.1describes the final conclusions of this study. Section 5.2 mentions the contribution of the proposed methodology to the field of manufacturing. Section 5.3 provides some possible ideas for future research related to the proposed methodology.

5.1 Conclusions

The proposed methodology based on reworkability and cost index, is a series of simple step that can allow a company to reduce extra work and improve material flow by establishing one rework station in any production line. The main challenge for this approach is that the common culture of manufacturing does not conceived right the idea of assembling the product without revising it for defects at every assembly stage. This methodology proves that this approach is not necessarily always the best option.

In both scenarios used to prove the proposed methodology in chapter 4, the rework stations where establish close to the middle of the assembly process. As designers continue to use the 14 guidelines for Design for Disassembly, the rework station is expected to move towards the end of the assembly line. If the rework station is able to be placed close to the end of the line, and hopefully after quality inspection, the material flow will improve significantly. Improvement in the material flow will transform the process to a more efficient and fast assembly, allowing a better throughput of the assembly line.

Establishing only one rework station at the assembly line will allow a faster throughput, a better detection of defects and a faster recuperation of components that can be recycled or reused. It is important to remember that because rework station is not placed at the end of the assembly line does not mean that the products that continue after this Station cannot be reworked. The proposed mythology says that after this rework station, products must be considered entering a different process external from the assembly line. These external process or considered disassembly line.

5.2 Contributions

The main contribution of this study to the manufacturing field is the methodology for identifying the location of one rework station in any production or assembly line. Including a rework station in the assembly line is not a common practice in the manufacturing science, with the methodology proposed numerical results supports the idea of including a rework station in the manufacturing line. The main challenge for this approach is that the common culture of manufacturing does not conceived right the idea of assembling the product without reworking it for defects at every assembly stage when possible.

5.3 Recommendations for future work

The methodology to establish a rework station location based on cost and reworkability works only for a single straight line manufacturing line. Future work can include the use one or several of the following scenarios.

1. Optimization of number of rework stations: In this scenario, an optimization method such as a genetic algorithms, neural network, integer programing, etc. can be used to establish the optimal number of rework stations in a production line.
2. Consideration of scrap factors to determine of rework station can work for several equal lines in a parallel layout: This scenario would consider the amount of idle time the rework station would have depending on scrap factors of the assembly line, in order to determine if it would be able to supply 2 assembly lines in parallel or just one.
3. Calculation of optimal location of rework station considering manufacturing cells: When manufacturing in production cells, a simple straight assembly process does not exist. In this scenario several more considerations must be included in order to determine the rework station location.
4. Consider several manufacturing lines: In the scenario, the consideration of several manufacturing lines that produce the same type of product is considered. Establishing the optimal number of rework stations for all assembly lines. In this scenario the possibility of using 1 rework station for 2 or more production lines must be considered.

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Appendix I – Incompatible Materials Chart

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Appendix 1, INCOMPATIBLE MATERIALS CHART

HMUG GROUP	MATERIAL GROUP	EXAMPLES	INCOMPATIBLE MATERIALS	EXAMPLES	REACTION IF MIXED
1	ACIDS	Battery Acids Paint Removers De-Rust Sprays	FLAMMABLE/COMBUSTABLES ALKALIES/BASES/CAUSTICS OXIDIZERS (GROUPS 2, 3, 4, 6, 7, 9, 10, 11, 12, 13, 14, 15, 17, 18, 19, 20, 22)	Degreasers, Carbon Removers Antifogging Compounds	HEAT GAS GENERATION VIOLENT REACTION
2	ADHESIVES	Epoxies Isocyanates Diethylenetriamine	ACIDS ALKALIES/BASES/CAUSTICS OXIDIZERS (HMUG GROUPS 1, 3, 18)		HEAT FIRE HAZARD
3	ALKALIES BASES/ CAUSTICS	Ammonia, Sodium Hydroxide Sodium Bicarbonate Cleaners/Detergents	ACIDS/OXIDIZERS FLAMMABLES/COMBUSTABLES (HMUG GROUPS 1, 2, 6, 8, 9, 10, 11, 12, 14, 15, 17, 18, 19, 20, 22)	Battery Acid, Paint Removers, De-Rust Sprays, Paint, Solvents	HEAT GAS GENERATION VIOLENT REACTION
4	CLEANING COMPOUNDS	Degreasers Carbon Removers Antifogging Compounds	DETERGENTS/SOAPS OXIDIZERS (HMUG GROUPS 7, 18)	Calcium Hydroclorite, Sodium Nitrate, Hydrogen Peroxide	HEAT FIRE HAZARD
5	COMPRESSED GASES	Acetylene, Helium Propane, Ammonia Oxygen	HEAT SOURCES CONSULT OPNAVIST 5100.19 (SERIES) AND NSTM 670 FOR SPECIFIC HANDLING AND STOWAGE GUIDANCE		FIRE HAZARD EXPLOSION HAZARD
6	CORROSION PREVENTIVE COMPOUNDS	Corrosion Inhibitors Chemical Conversion Compounds	ACIDS BASES OXIDIZERS IGNITION SOURCES (HMUG GROUPS 1, 3, 18)		FIRE HAZARD
7	DETERGENTS/ SOAPS	Detergents, Disinfectant, Scouring Powders, Sodium Hydroxide, Trisodium Phosphate, Potassium Hydroxide (Alkalies/Bases/Caustics)	ACID-CONTAINING COMPOUNDS (HMUG GROUPS 1, 4, 5)	Battery Acid, Paint Removers, De-Rust Sprays	VIOLENT REACTION HEAT
8	GREASES	Graphite Silicone Molybdenum	OXIDIZERS ALKALIES/BASES/ CAUSTICS (HMUG GROUPS 3, 18)		FIRE HAZARD
9	HYDRAULIC FLUIDS	Petroleum-Based Synthetic Fire-Resistant	CORROSIVES (HMUG GROUPS 1, 3) OXIDIZERS (HMUG GROUP 18)		HEAT VIOLENT REACTION
10	INSPECTION PENETRANTS	Petroleum-Based Dyes	CORROSIVES (HMUG GROUPS 1, 3) OXIDIZERS (HMUG GROUP 18)	Battery Acid Chlorine Laundry Bleach Calcium Hypochlorite Calcium Oxide	
11	LUBRICANTS/ OILS	Gen. Purpose, Turbine, Gear, Vacuum, Weapon	CORROSIVES (HMUG GROUPS 1, 3) OXIDIZERS (HMUG GROUP 18)	Hydrogen Peroxide OBA Canisters Lithium Hydroxide Ammonia Paint Removers	EXPLOSION HAZARD
12	PAINTS	Primers, Enamels, Laquers, Strippers	OXIDIZERS (HMUG GROUP 18) CORROSIVES (HMUG GROUPS 1, 3)		HEAT FIRE HAZARD
13	PHOTO CHEMICALS	Color and B/W, Toners Developers, Replenishers Bleaches/Stopbath	ACIDS HEAVY METALS (HMUG GROUPS 1, 20)		HEAT FIRE HAZARD
14	POLISH/WAX COMPOUNDS	Buffing Compound Metal Polish Gen. Purpose Wax	CORROSIVES OXIDIZERS (HMUG GROUPS 1, 3, 18)		HEAT, FIRE HAZARD VIOLENT REACTION
15	SOLVENTS (HYDROCARBONS)	Acetone, Methyl Ethyl Ketone (MEK), Tolulene, Xylene, Alcohols	CORROSIVES OXIDIZERS BATTERIES (HMUG GROUPS 1, 3, 18, 21)	Battery Acid Calcium Hypochlorite Sodium Nitrate Hydrogen Peroxide Sodium Hydroxide	HEAT FIRE HAZARD
16	THERMAL INSULATION	Asbestos, Fibrous Glass Man-Made Vitreous Fibers	MATERIAL IS NOT REACTIVE KEEP DRY		NO REACTION
17	WATER TREATMENT CHEMICALS	Tri-Sodium Phosphate Caustic Soda, Harness Buffer Citric Acid, Tirating Solutions	CORROSIVES OXIDIZERS HEAVY MEATALS (HMUG GROUPS 1, 3, 18, 20)		HEAT VIOLENT REACTION
18	OXIDIZERS	Chlorine Laundry Bleach Calcium Hypoclorite, Calcium Oxide Hydrogen Peroxide, OBA Canisters Lithium hydroxide	PETROLIUM BASED MATERIALS FUELS SOLVENTS, CORROSIVES, HEAT GROUPS 1, 2, 3, 4, 5, 8, 9, 10, 11,12, 14, 15, 17, 19, 20, 21, 22)		FIRE HAZARD TOXIC GAS GENERATION
19	FUELS	JP4, JP5, Gasoline	CORROSIVES OXIDIZERS (HMUG GROUPS 1, 3, 18)	Battery Acid Calcium Hypochlorite Sodium Nitrate Sodium Hydroxide	FIRE HAZARD TOXIC GAS GENERATION
20	HEAVY METALS	Beryllium, Chromium, Copper, Lead, Magnesium, Mercury, Nickel, Stronitum Chromate, Tin, Zinc	CORROSIVES OXIDIZERS WATER TREATMENT/ PHOTO CHEMICALS (HMUG GROUPS 1, 3, 6, 13, 17, 18, 21)		VIOLENT REACTION GENERATION OF TOXIC AND FLAMMABLE GAS
21	BATTERIES	Lead Acid, Alkaline Lithium, Dry Cell	SOLVENTS HEAVY METALS OXIDIZERS (HMUG GROUPS 15, 18, 20)	Xylene Toluene Alcohol Tin Zinc Chromium	HEAT VIOLENT REACTION TOXIC GAS GENERATION
22	PESTICIDES	Insecticides, Fungicides Rodenticides, Fumigants	CORROSIVES OXIDIZERS (HMUG GROUPS 1, 3, 18)		TOXIC GAS GENERATION

1. This Chart is to be used as a ***Guide Only!***
2. Compare the desired HMUG Group in the left column with the Incompatible Material(s) of that Group in the Center Column, on the same row.
3. Should the Material(s) in the Center Column be mixed with the desired Group in the Left Column, the Expected Reaction(s) can be seen in the right Column.
4. For ***specific information*** on storage of Hazardous Materials, consult the MSDS, HMUG, OPNAVINST 5100.19 (Series), NSTM 670, Ships Hazardous Material List (SHML), and NAVSUP PUB 573.

Produced for COMNAVSUPSYSCOM
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REV 1/JANUARY 1996

Navosh and environmental training center, http://www.public.navy.mil/navsafecen/Pages/training/generalinfo_trng.aspx

Appendix II – Reworkability score calculation for Trocars

		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	0.188679245	10	0.188679245
Are joints and fasteners easily accessible?	2	10	0.377358491	9	0.339622642
Is part able to disassemble maintaining product stability?	4	9	0.679245283	9	0.679245283
Are all joining elements of equal type?	4	9	0.679245283	9	0.679245283
Is destructive technique safe and will not harm people or affect reusable components?	5	10	0.943396226	10	0.943396226
Can reusable parts be cleaned easily and without damage?	5	10	0.943396226	9	0.849056604
Are incompatible materials easily separated?	5	10	0.943396226	9	0.849056604
Are all component interfaces simple and reversibly separable?	3	10	0.566037736	10	0.566037736
Is the product organized into hierarchical modules by aesthetic, repair, and end-of-life protocol?	3	10	0.566037736	10	0.566037736
Are reusable/swappable platforms, modules, and components implemented?	1	10	0.188679245	10	0.188679245
Does the product have only the minimal number of parts it requires?	5	10	0.943396226	9	0.849056604
Are compatible adhesives, labels, surface coatings, pigments, etc used?	4	10	0.754716981	10	0.754716981
Is only one disassembly direction without reorientation required?	2	10	0.377358491	10	0.377358491
Are all joints separable by hand or only a few, simple tools required?	3	9	0.509433962	9	0.509433962
Is the number and length of operations for detachment minimized?	4	10	0.754716981	10	0.754716981
Are materials marked in molds with types and reutilization protocols?	1	9	0.169811321	9	0.169811321
Is a shallow or open structure used for easy access to subassemblies?	1	10	0.188679245	10	0.188679245
Total Reworkability score at production station 'j'	53	166	9.773584906	162	9.452830189

		Station 3		Station 4	
17 disassembly guidelines	Weight	Score	Reworkability Score	Score	Reworkability Score
Are all access points obvious or indicated on the product?	1	6	0.113207547	5	0.094339623
Are joints and fasteners easily accessible?	2	5	0.188679245	4	0.150943396
Is part able to disassemble maintaining product stability?	4	7	0.528301887	7	0.528301887
Are all joining elements of equal type?	4	7	0.528301887	7	0.528301887
Is destructive technique safe and will not harm people or affect reusable components?	5	3	0.283018868	3	0.283018868
Can reusable parts be cleaned easily and without damage?	5	6	0.566037736	6	0.566037736
Are incompatible materials easily separated?	5	5	0.471698113	4	0.377358491
Are all component interfaces simple and reversibly separable?	3	8	0.452830189	8	0.452830189
Is the product organized into hierarchical modules by aesthetic, repair, and end-of-life protocol?	3	10	0.566037736	10	0.566037736
Are reusable/swappable platforms, modules, and components implemented?	1	10	0.188679245	10	0.188679245
Does the product have only the minimal number of parts it requires?	5	7	0.660377358	6	0.566037736
Are compatible adhesives, labels, surface coatings, pigments, etc used?	4	6	0.452830189	6	0.452830189
Is only one disassembly direction without reorientation required?	2	6	0.226415094	5	0.188679245
Are all joints separable by hand or only a few, simple tools required?	3	3	0.169811321	3	0.169811321
Is the number and length of operations for detachment minimized?	4	6	0.452830189	6	0.452830189
Are materials marked in molds with types and reutilization protocols?	1	7	0.132075472	7	0.132075472
Is a shallow or open structure used for easy access to subassemblies?	1	10	0.188679245	10	0.188679245
Total Reworkability score at production station 'j'	53	112	6.169811321	107	5.886792453

17 disassembly guidelines	Weight	Station 5 Score	Station 5 Reworkability Score	Station 6 Score	Station 6 Reworkability Score
Are all access points obvious or indicated on the product?	1	5	0.094339623	5	0.094339623
Are joints and fasteners easily accessible?	2	4	0.150943396	3	0.113207547
Is part able to disassemble maintaining product stability?	4	7	0.528301887	6	0.452830189
Are all joining elements of equal type?	4	7	0.528301887	5	0.377358491
Is destructive technique safe and will not harm people or affect reusable components?	5	3	0.283018868	3	0.283018868
Can reusable parts be cleaned easily and without damage?	5	6	0.566037736	6	0.566037736
Are incompatible materials easily separated?	5	4	0.377358491	4	0.377358491
Are all component interfaces simple and reversibly separable?	3	8	0.452830189	7	0.396226415
Is the product organized into hierarchical modules by aesthetic, repair, and end-of-life protocol?	3	10	0.566037736	9	0.509433962
Are reusable/swappable platforms, modules, and components implemented?	1	10	0.188679245	8	0.150943396
Does the product have only the minimal number of parts it requires?	5	6	0.566037736	5	0.471698113
Are compatible adhesives, labels, surface coatings, pigments, etc used?	4	6	0.452830189	6	0.452830189
Is only one disassembly direction without reorientation required?	2	5	0.188679245	4	0.150943396
Are all joints separable by hand or only a few, simple tools required?	3	3	0.169811321	3	0.169811321
Is the number and length of operations for detachment minimized?	4	6	0.452830189	5	0.377358491
Are materials marked in molds with types and reutilization protocols?	1	7	0.132075472	7	0.132075472
Is a shallow or open structure used for easy access to subassemblies?	1	10	0.188679245	9	0.169811321
Total Reworkability score at production station 'j'	53	107	5.886792453	95	5.245283019

17 disassembly guidelines	Weight	Station 7 Score	Station 7 Reworkability Score	Station 8 Score	Station 8 Reworkability Score
Are all access points obvious or indicated on the product?	1	4	0.075471698	4	0.075471698
Are joints and fasteners easily accessible?	2	2	0.075471698	2	0.075471698
Is part able to disassemble maintaining product stability?	4	4	0.301886792	4	0.301886792
Are all joining elements of equal type?	4	4	0.301886792	4	0.301886792
Is destructive technique safe and will not harm people or affect reusable components?	5	1	0.094339623	1	0.094339623
Can reusable parts be cleaned easily and without damage?	5	4	0.377358491	4	0.377358491
Are incompatible materials easily separated?	5	2	0.188679245	2	0.188679245
Are all component interfaces simple and reversibly separable?	3	5	0.283018868	5	0.283018868
Is the product organized into hierarchical modules by aesthetic, repair, and end-of-life protocol?	3	9	0.509433962	9	0.509433962
Are reusable/swappable platforms, modules, and components implemented?	1	7	0.132075472	7	0.132075472
Does the product have only the minimal number of parts it requires?	5	3	0.283018868	3	0.283018868
Are compatible adhesives, labels, surface coatings, pigments, etc used?	4	5	0.377358491	5	0.377358491
Is only one disassembly direction without reorientation required?	2	2	0.075471698	2	0.075471698
Are all joints separable by hand or only a few, simple tools required?	3	1	0.056603774	1	0.056603774
Is the number and length of operations for detachment minimized?	4	3	0.226415094	3	0.226415094
Are materials marked in molds with types and reutilization protocols?	1	6	0.113207547	6	0.113207547
Is a shallow or open structure used for easy access to subassemblies?	1	8	0.150943396	8	0.150943396
Total Reworkability score at production station 'j'	53	70	3.622641509	70	3.622641509

17 disassembly guidelines	Weight	Station 9 Score	Station 9 Reworkability Score	Station 10 Score	Station 10 Reworkability Score
Are all access points obvious or indicated on the product?	1	3	0.056603774	3	0.056603774
Are joints and fasteners easily accessible?	2	2	0.075471698	2	0.075471698
Is part able to disassemble maintaining product stability?	4	4	0.301886792	4	0.301886792
Are all joining elements of equal type?	4	3	0.226415094	3	0.226415094
Is destructive technique safe and will not harm people or affect reusable components?	5	1	0.094339623	1	0.094339623
Can reusable parts be cleaned easily and without damage?	5	4	0.377358491	4	0.377358491
Are incompatible materials easily separated?	5	2	0.188679245	2	0.188679245
Are all component interfaces simple and reversibly separable?	3	4	0.226415094	4	0.226415094
Is the product organized into hierarchical modules by aesthetic, repair, and end-of-life protocol?	3	9	0.509433962	9	0.509433962
Are reusable/swappable platforms, modules, and components implemented?	1	7	0.132075472	7	0.132075472
Does the product have only the minimal number of parts it requires?	5	3	0.283018868	3	0.283018868
Are compatible adhesives, labels, surface coatings, pigments, etc used?	4	5	0.377358491	5	0.377358491
Is only one disassembly direction without reorientation required?	2	2	0.075471698	2	0.075471698
Are all joints separable by hand or only a few, simple tools required?	3	1	0.056603774	1	0.056603774
Is the number and length of operations for detachment minimized?	4	2	0.150943396	2	0.150943396
Are materials marked in molds with types and reutilization protocols?	1	6	0.113207547	6	0.113207547
Is a shallow or open structure used for easy access to subassemblies?	1	8	0.150943396	8	0.150943396
Total Reworkability score at production station 'j'	53	66	3.396226415	66	3.396226415

		Station 11	
17 disassembly guidelines	Weight	Score	Reworkability Score
Are all access points obvious or indicated on the product?	1	3	0.056603774
Are joints and fasteners easily accessible?	2	2	0.075471698
Is part able to disassemble maintaining product stability?	4	4	0.301886792
Are all joining elements of equal type?	4	2	0.150943396
Is destructive technique safe and will not harm people or affect reusable components?	5	1	0.094339623
Can reusable parts be cleaned easily and without damage?	5	4	0.377358491
Are incompatible materials easily separated?	5	2	0.188679245
Are all component interfaces simple and reversibly separable?	3	4	0.226415094
Is the product organized into hierarchical modules by aesthetic, repair, and end-of-life protocol?	3	8	0.452830189
Are reusable/swappable platforms, modules, and components implemented?	1	7	0.132075472
Does the product have only the minimal number of parts it requires?	5	2	0.188679245
Are compatible adhesives, labels, surface coatings, pigments, etc used?	4	4	0.301886792
Is only one disassembly direction without reorientation required?	2	1	0.037735849
Are all joints separable by hand or only a few, simple tools required?	3	1	0.056603774
Is the number and length of operations for detachment minimized?	4	2	0.150943396
Are materials marked in molds with types and reutilization protocols?	1	6	0.113207547
Is a shallow or open structure used for easy access to subassemblies?	1	8	0.150943396
Total Reworkability score at production station 'j'	53	61	3.056603774

Appendix III – Reworkability score calculation for EnSeal

		Station 1		Station 2	
17 disassembly guidelines	Weight	Score	Reworkability Score	Score	Reworkability Score
Indicating on the product how it should be opened and make access points obvious	1	10	0.192307692	10	0.192307692
Ensuring that joints and fasteners are easily accessible	3	10	0.576923077	10	0.576923077
Maintaining stability and part placement during disassembly	5	10	0.961538462	10	0.961538462
Minimizing the number and variety of joining elements	4	10	0.769230769	9	0.692307692
Ensuring that destructive disassembly techniques do not harm people or reusable components	5	10	0.961538462	10	0.961538462
Ensuring reusable parts can be cleaned easily and without damage	5	10	0.961538462	10	0.961538462
Ensuring that incompatible materials are easily separated	4	10	0.769230769	9	0.692307692
Making component interfaces simple and reversibly separable	2	10	0.384615385	10	0.384615385
Organizing a product or system into hierarchical modules by aesthetic, repair, and end-of-life protocol	3	10	0.576923077	10	0.576923077
Implementing reusable/swappable platforms, modules, and components	5	10	0.961538462	10	0.961538462
Condensing into a minimal number of parts	3	10	0.576923077	10	0.576923077
Specifying compatible adhesives, labels, surface coatings, pigments, etc	4	10	0.769230769	9	0.692307692
Employing one disassembly direction without reorientation	2	10	0.384615385	10	0.384615385
Specifying all joints so that they are separable by hand or only a few, simple tools	1	10	0.192307692	10	0.192307692
Minimizing the number and length of operations for detachment	2	10	0.384615385	10	0.384615385
Marking materials in molds with types and reutilization protocols	1	10	0.192307692	10	0.192307692
Using a shallow or open structure 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

		Station 3		Station 4	
17 disassembly guidelines	Weight	Score	Reworkability Score	Score	Reworkability Score
Indicating on the product how it should be opened and make access points obvious	1	10	0.192307692	10	0.192307692
Ensuring that joints and fasteners are easily accessible	3	10	0.576923077	10	0.576923077
Maintaining stability and part placement during disassembly	5	9	0.865384615	9	0.865384615
Minimizing the number and variety of joining elements	4	8	0.615384615	7	0.538461538
Ensuring that destructive disassembly techniques do not harm people or reusable components	5	9	0.865384615	8	0.769230769
Ensuring reusable parts can be cleaned easily and without damage	5	10	0.961538462	10	0.961538462
Ensuring that incompatible materials are easily separated	4	8	0.615384615	7	0.538461538
Making component interfaces simple and reversibly separable	2	10	0.384615385	10	0.384615385
Organizing a product or system into hierarchical modules by aesthetic, repair, and end-of-life protocol	3	10	0.576923077	10	0.576923077
Implementing reusable/swappable platforms, modules, and components	5	10	0.961538462	10	0.961538462
Condensing into a minimal number of parts	3	9	0.519230769	9	0.519230769
Specifying compatible adhesives, labels, surface coatings, pigments, etc	4	8	0.615384615	7	0.538461538
Employing one disassembly direction without reorientation	2	9	0.346153846	9	0.346153846
Specifying all joints so that they are separable by hand or only a few, simple tools	1	9	0.173076923	9	0.173076923
Minimizing the number and length of operations for detachment	2	9	0.346153846	9	0.346153846
Marking materials in molds with types and reutilization protocols	1	10	0.192307692	10	0.192307692
Using a shallow or open structure for easy access to subassemblies	2	10	0.384615385	10	0.384615385
Total Reworkability score at production station 'j'	52	158	9.192307692	154	8.865384615

		Station 5		Station 6	
17 disassembly guidelines	Weight	Score	Reworkability Score	Score	Reworkability Score
Indicating on the product how it should be opened and make access points obvious	1	8	0.153846154	8	0.153846154
Ensuring that joints and fasteners are easily accessible	3	8	0.461538462	8	0.461538462
Maintaining stability and part placement during disassembly	5	8	0.769230769	8	0.769230769
Minimizing the number and variety of joining elements	4	6	0.461538462	6	0.461538462
Ensuring that destructive disassembly techniques do not harm people or reusable components	5	7	0.673076923	7	0.673076923
Ensuring reusable parts can be cleaned easily and without damage	5	10	0.961538462	10	0.961538462
Ensuring that incompatible materials are easily separated	4	6	0.461538462	6	0.461538462
Making component interfaces simple and reversibly separable	2	9	0.346153846	9	0.346153846
Organizing a product or system into hierarchical modules by aesthetic, repair, and end-of-life protocol	3	10	0.576923077	10	0.576923077
Implementing reusable/swappable platforms, modules, and components	5	9	0.865384615	9	0.865384615
Condensing into a minimal number of parts	3	8	0.461538462	8	0.461538462
Specifying compatible adhesives, labels, surface coatings, pigments, etc	4	6	0.461538462	6	0.461538462
Employing one disassembly direction without reorientation	2	8	0.307692308	8	0.307692308
Specifying all joints so that they are separable by hand or only a few, simple tools	1	8	0.153846154	8	0.153846154
Minimizing the number and length of operations for detachment	2	8	0.307692308	8	0.307692308
Marking materials in molds with types and reutilization protocols	1	9	0.173076923	9	0.173076923
Using a shallow or open structure for easy access to subassemblies	2	9	0.346153846	9	0.346153846
Total Reworkability score at production station 'j'	52	137	7.942307692	137	7.942307692

		Station 7		Station 8	
17 disassembly guidelines	Weight	Score	Reworkability Score	Score	Reworkability Score
Indicating on the product how it should be opened and make access points obvious	1	7	0.134615385	7	0.134615385
Ensuring that joints and fasteners are easily accessible	3	8	0.461538462	8	0.461538462
Maintaining stability and part placement during disassembly	5	8	0.769230769	8	0.769230769
Minimizing the number and variety of joining elements	4	5	0.384615385	5	0.384615385
Ensuring that destructive disassembly techniques do not harm people or reusable components	5	7	0.673076923	7	0.673076923
Ensuring reusable parts can be cleaned easily and without damage	5	9	0.865384615	9	0.865384615
Ensuring that incompatible materials are easily separated	4	6	0.461538462	6	0.461538462
Making component interfaces simple and reversibly separable	2	9	0.346153846	9	0.346153846
Organizing a product or system into hierarchical modules by aesthetic, repair, and end-of-life protocol	3	9	0.519230769	9	0.519230769
Implementing reusable/swappable platforms, modules, and components	5	9	0.865384615	9	0.865384615
Condensing into a minimal number of parts	3	7	0.403846154	7	0.403846154
Specifying compatible adhesives, labels, surface coatings, pigments, etc	4	6	0.461538462	5	0.384615385
Employing one disassembly direction without reorientation	2	7	0.269230769	7	0.269230769
Specifying all joints so that they are separable by hand or only a few, simple tools	1	8	0.153846154	8	0.153846154
Minimizing the number and length of operations for detachment	2	7	0.269230769	7	0.269230769
Marking materials in molds with types and reutilization protocols	1	9	0.173076923	9	0.173076923
Using a shallow or open structure for easy access to subassemblies	2	9	0.346153846	9	0.346153846
Total Reworkability score at production station 'j'	52	130	7.557692308	129	7.480769231

		Station 9		Station 10	
17 disassembly guidelines	Weight	Score	Reworkability Score	Score	Reworkability Score
Indicating on the product how it should be opened and make access points obvious	1	6	0.115384615	6	0.115384615
Ensuring that joints and fasteners are easily accessible	3	7	0.403846154	7	0.403846154
Maintaining stability and part placement during disassembly	5	7	0.673076923	7	0.673076923
Minimizing the number and variety of joining elements	4	5	0.384615385	5	0.384615385
Ensuring that destructive disassembly techniques do not harm people or reusable components	5	4	0.384615385	4	0.384615385
Ensuring reusable parts can be cleaned easily and without damage	5	9	0.865384615	9	0.865384615
Ensuring that incompatible materials are easily separated	4	6	0.461538462	6	0.461538462
Making component interfaces simple and reversibly separable	2	8	0.307692308	8	0.307692308
Organizing a product or system into hierarchical modules by aesthetic, repair, and end-of-life protocol	3	8	0.461538462	8	0.461538462
Implementing reusable/swappable platforms, modules, and components	5	8	0.769230769	8	0.769230769
Condensing into a minimal number of parts	3	6	0.346153846	6	0.346153846
Specifying compatible adhesives, labels, surface coatings, pigments, etc	4	5	0.384615385	5	0.384615385
Employing one disassembly direction without reorientation	2	6	0.230769231	6	0.230769231
Specifying all joints so that they are separable by hand or only a few, simple tools	1	7	0.134615385	7	0.134615385
Minimizing the number and length of operations for detachment	2	6	0.230769231	6	0.230769231
Marking materials in molds with types and reutilization protocols	1	8	0.153846154	8	0.153846154
Using a shallow or open structure for easy access to subassemblies	2	8	0.307692308	8	0.307692308
Total Reworkability score at production station 'j'	52	114	6.615384615	114	6.615384615

		Station 11		Station 12	
17 disassembly guidelines	Weight	Score	Reworkability Score	Score	Reworkability Score
Indicating on the product how it should be opened and make access points obvious	1	5	0.096153846	4	0.076923077
Ensuring that joints and fasteners are easily accessible	3	6	0.346153846	5	0.288461538
Maintaining stability and part placement during disassembly	5	6	0.576923077	6	0.576923077
Minimizing the number and variety of joining elements	4	4	0.307692308	3	0.230769231
Ensuring that destructive disassembly techniques do not harm people or reusable components	5	3	0.288461538	2	0.192307692
Ensuring reusable parts can be cleaned easily and without damage	5	7	0.673076923	6	0.576923077
Ensuring that incompatible materials are easily separated	4	6	0.461538462	6	0.461538462
Making component interfaces simple and reversibly separable	2	7	0.269230769	6	0.230769231
Organizing a product or system into hierarchical modules by aesthetic, repair, and end-of-life protocol	3	8	0.461538462	7	0.403846154
Implementing reusable/swappable platforms, modules, and components	5	6	0.576923077	6	0.576923077
Condensing into a minimal number of parts	3	5	0.288461538	4	0.230769231
Specifying compatible adhesives, labels, surface coatings, pigments, etc	4	5	0.384615385	5	0.384615385
Employing one disassembly direction without reorientation	2	6	0.230769231	6	0.230769231
Specifying all joints so that they are separable by hand or only a few, simple tools	1	6	0.115384615	5	0.096153846
Minimizing the number and length of operations for detachment	2	5	0.192307692	4	0.153846154
Marking materials in molds with types and reutilization protocols	1	7	0.134615385	7	0.134615385
Using a shallow or open structure for easy access to subassemblies	2	7	0.269230769	6	0.230769231
Total Reworkability score at production station 'j'	52	99	5.673076923	88	5.076923077

		Station 13		Station 14	
17 disassembly guidelines	Weight	Score	Reworkability Score	Score	Reworkability Score
Indicating on the product how it should be opened and make access points obvious	1	3	0.057692308	2	0.038461538
Ensuring that joints and fasteners are easily accessible	3	4	0.230769231	3	0.173076923
Maintaining stability and part placement during disassembly	5	5	0.480769231	5	0.480769231
Minimizing the number and variety of joining elements	4	3	0.230769231	3	0.230769231
Ensuring that destructive disassembly techniques do not harm people or reusable components	5	2	0.192307692	1	0.096153846
Ensuring reusable parts can be cleaned easily and without damage	5	6	0.576923077	5	0.480769231
Ensuring that incompatible materials are easily separated	4	6	0.461538462	5	0.384615385
Making component interfaces simple and reversibly separable	2	5	0.192307692	4	0.153846154
Organizing a product or system into hierarchical modules by aesthetic, repair, and end-of-life protocol	3	7	0.403846154	6	0.346153846
Implementing reusable/swappable platforms, modules, and components	5	4	0.384615385	2	0.192307692
Condensing into a minimal number of parts	3	4	0.230769231	4	0.230769231
Specifying compatible adhesives, labels, surface coatings, pigments, etc	4	5	0.384615385	5	0.384615385
Employing one disassembly direction without reorientation	2	5	0.192307692	4	0.153846154
Specifying all joints so that they are separable by hand or only a few, simple tools	1	4	0.076923077	3	0.057692308
Minimizing the number and length of operations for detachment	2	3	0.115384615	2	0.076923077
Marking materials in molds with types and reutilization protocols	1	6	0.115384615	5	0.096153846
Using a shallow or open structure for easy access to subassemblies	2	5	0.192307692	3	0.115384615
Total Reworkability score at production station 'j'	52	77	4.519230769	62	3.692307692

		Station 15		Station 16	
17 disassembly guidelines	Weight	Score	Reworkability Score	Score	Reworkability Score
Indicating on the product how it should be opened and make access points obvious	1	2	0.038461538	2	0.038461538
Ensuring that joints and fasteners are easily accessible	3	3	0.173076923	3	0.173076923
Maintaining stability and part placement during disassembly	5	5	0.480769231	5	0.480769231
Minimizing the number and variety of joining elements	4	3	0.230769231	3	0.230769231
Ensuring that destructive disassembly techniques do not harm people or reusable components	5	1	0.096153846	1	0.096153846
Ensuring reusable parts can be cleaned easily and without damage	5	5	0.480769231	5	0.480769231
Ensuring that incompatible materials are easily separated	4	5	0.384615385	5	0.384615385
Making component interfaces simple and reversibly separable	2	4	0.153846154	4	0.153846154
Organizing a product or system into hierarchical modules by aesthetic, repair, and end-of-life protocol	3	6	0.346153846	6	0.346153846
Implementing reusable/swappable platforms, modules, and components	5	2	0.192307692	2	0.192307692
Condensing into a minimal number of parts	3	4	0.230769231	4	0.230769231
Specifying compatible adhesives, labels, surface coatings, pigments, etc	4	5	0.384615385	5	0.384615385
Employing one disassembly direction without reorientation	2	4	0.153846154	4	0.153846154
Specifying all joints so that they are separable by hand or only a few, simple tools	1	3	0.057692308	3	0.057692308
Minimizing the number and length of operations for detachment	2	2	0.076923077	2	0.076923077
Marking materials in molds with types and reutilization protocols	1	5	0.096153846	5	0.096153846
Using a shallow or open structure for easy access to subassemblies	2	3	0.115384615	3	0.115384615
Total Reworkability score at production station 'j'	52	62	3.692307692	62	3.692307692

		Station 17		Station 18	
17 disassembly guidelines	Weight	Score	Reworkability Score	Score	Reworkability Score
Indicating on the product how it should be opened and make access points obvious	1	2	0.038461538	1	0.019230769
Ensuring that joints and fasteners are easily accessible	3	3	0.173076923	3	0.173076923
Maintaining stability and part placement during disassembly	5	5	0.480769231	4	0.384615385
Minimizing the number and variety of joining elements	4	3	0.230769231	3	0.230769231
Ensuring that destructive disassembly techniques do not harm people or reusable components	5	1	0.096153846	1	0.096153846
Ensuring reusable parts can be cleaned easily and without damage	5	5	0.480769231	4	0.384615385
Ensuring that incompatible materials are easily separated	4	5	0.384615385	5	0.384615385
Making component interfaces simple and reversibly separable	2	4	0.153846154	4	0.153846154
Organizing a product or system into hierarchical modules by aesthetic, repair, and end-of-life protocol	3	6	0.346153846	6	0.346153846
Implementing reusable/swappable platforms, modules, and components	5	2	0.192307692	2	0.192307692
Condensing into a minimal number of parts	3	4	0.230769231	3	0.173076923
Specifying compatible adhesives, labels, surface coatings, pigments, etc	4	5	0.384615385	5	0.384615385
Employing one disassembly direction without reorientation	2	4	0.153846154	4	0.153846154
Specifying all joints so that they are separable by hand or only a few, simple tools	1	3	0.057692308	3	0.057692308
Minimizing the number and length of operations for detachment	2	2	0.076923077	1	0.038461538
Marking materials in molds with types and reutilization protocols	1	5	0.096153846	5	0.096153846
Using a shallow or open structure for easy access to subassemblies	2	3	0.115384615	3	0.115384615
Total Reworkability score at production station 'j'	52	62	3.692307692	57	3.384615385

Vita

Juan Saavedra was born in Texcoco, Estado de Mexico, Mexico. I did my undergrad in the University of Texas at El Paso and graduated in 2010 with a B.S. in Industrial Engineering. During this time I worked at the College of Engineering as a Peer Advisor for all the undergraduate students of Industrial Engineering. I was president of the Institute of Industrial Engineers UTEP chapter. During this time we participated in two regional conferences submitting papers that were about: Simulation of a manufacturing line and Inventory optimization using genetic algorithms.

I will graduate from UTEP with a M.S. in Manufacturing Engineer in 2012. During this time I was co-author of the paper "Quality Control of Bio Scaffold Using Intelligent Data Mining" that will be presented in the ISERC 2012 Conference.

Since 2010 I have been working with Johnson & Johnson in the Medical Devices and Diagnostic sector. I have worked in three different areas: Quality, Manufacturing and Supply chain. This gave me the ability to understand all the aspects of a business and has let me understood how is it that many departments interact in order to achieve the goal of satisfying the client on time and with the quality that is desired. Currently I am working at General Labels & Printing in El Paso, Tx as Quality engineer responsible of the entire supply chain quality of the organization.

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This thesis/dissertation was typed by Juan A. Saavedra.